

# Red Giant Mass-Loss: Studying Evolved Stellar Winds with *FUSE* and *HST*/STIS

A dissertation submitted to the University of Dublin  
for the degree of Doctor of Philosophy

**Cian Crowley**

Supervisor: Dr. Brian R. Espey  
Trinity College Dublin, July 2006

---

SCHOOL OF PHYSICS  
UNIVERSITY OF DUBLIN  
TRINITY COLLEGE DUBLIN



*For Mam and Dad*

# Declaration

I hereby declare that this thesis has not been submitted as an exercise for a degree at this or any other University and that it is entirely my own work.

I agree that the Library may lend or copy this thesis upon request.

Signed,

---

Cian Crowley

July 25, 2006.

# Publications

**Crowley, C.**, Espey, B. R., & McCandliss, S. R., 2006, *In prep.*, ‘*FUSE* and *HST*/STIS Observations of the Eclipsing Symbiotic Binary EG Andromedae’

# Acknowledgments

I wish to acknowledge and thank Brian Espey, Stephan McCandliss and Peter Hauschildt for their contributions to this work. Most especially I would like to express my gratitude to my supervisor Brian Espey for his enthusiastic supervision, patience and encouragement. His help, support and advice is very much appreciated. In addition, the helpful and insightful comments and advice from numerous people, including, Graham Harper, Philip Bennett, Alex Brown, Gary Ferland, Tom Ake, B-G Anderson and Dugan With-erick, were invaluable and again, very much appreciated. Also, a special word of thanks for their viva comments and feedback for Alex Brown and Peter Gallagher.

This work was supported by Enterprise Ireland Basic Research grant SC/2002/370 from EU funded NDP. The *FUSE* data were obtained under the Guest Investigator Program and supported by NASA grants NAG5-8994 and NAG5-10403 to the Johns Hopkins University (JHU). The NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer is operated for NASA by the JHU under NASA contract NAS5-32985. STIS data were obtained under the Guest Observer program STSI-GO0948701 provided by NASA through a grant to JHU from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Kait photometric data were obtained with the kind help of Weidong Li.

# Summary

The changes that a star undergoes during the dying process are the most dramatic of its lifetime. These changes result in the most important interactions between a star and its environment, indeed it is in this area of research that some of the most challenging astrophysical problems still remain. For most stars, mass-loss becomes significant when they approach the end of their lives and enter the red giant evolutionary phase. This mass is lost in the form of a relatively dense and slow-moving wind which enriches the interstellar medium with material that has been processed inside the star and which is required for the formation of new stars and planets. However, despite the importance and ubiquity of these winds much remains unknown about the outflow conditions and characteristics and, furthermore, the physical processes which drive the mass-loss are unknown. Indeed, the mass-loss question remains arguably the most important outstanding problem of stellar astrophysics. For isolated giant stars, the diagnostics that can be obtained from observations are limited, with only disk-averaged information being directly observable. Spatially resolved observational constraints, in particular within the wind acceleration zone at the base of the outflow and close to the stellar photosphere, are required.

This thesis presents a series of 20 *FUSE* (*Far Ultraviolet Spectroscopic Explorer*) and *HST*/STIS (*Hubble Space Telescope*/Space Telescope Imaging Spectrograph) observations of the bright symbiotic system EG Andromedae. The system consists of a low-luminosity white dwarf and a mass-losing, non-dusty M2.4 red giant star. The main motivation behind obtaining these ultraviolet spectra is to derive spatially resolved information on the giant wind in order to understand the mass-loss and wind heating mechanisms at work in evolved giants. The orbital elements of the binary are well understood and the dwarf star is known to undergo eclipse every 482 days. The ultraviolet observations follow the white dwarf continuum through periodic eclipses by the wind and chromosphere of the giant, providing a unique, *spatially resolved* diagnosis of the circumstellar gas in absorption against the attenuated dwarf continuum. The atomic transitions in the ultraviolet wavelength region enable both the hot, ionised gas close to the dwarf and also the cooler material in the wind to be diagnosed. In addition, optical spectra and photometry are presented.

Analysis of high and low-resolution optical spectra shows that the atmospheric structure of the giant star is not severely perturbed, either radiatively or tidally, by the presence of the binary companion. It emerges that, although the photosphere is heated slightly and the atmosphere is elliptically distorted on the 7-8% level, these effects are minimal. The

photospheric spectrum remains similar to that of isolated stars and the atmosphere can be modelled as a normal giant. The photometry shows pulsational activity of the giant which is typical of similarly evolved stars, as well as relatively large periodic variations in the U-band.

The ultraviolet spectral variations are dominated by the effects related to the eclipse of the dwarf by the giant atmosphere and wind. The uneclipsed spectra are dominated by the dwarf continuum with emission lines from an ionised portion of the giant wind superimposed on the continuum. The high ionisation features, such as the O VI resonance doublet (which is present as a variable, broad wind profile) diagnose the hot gas close to the dwarf component. This feature is variable on hourly timescales. During total eclipse of the hot component, the spectrum is dominated by emission lines originating from both the giant chromosphere and the extended photoionised section of the cool wind. Spectra observed at stages of partial eclipse display a host of low-ionisation, narrow absorption lines, with transitions observed from lower energy-levels up to  $\sim 5$  eV above ground. This absorption is due to chromospheric/wind material along the line of sight, with most lines being due to transitions of Si II, P II, N I, Fe II and Ni II. Photoionisation modelling shows that the white dwarf radiation does not dominate the wind acceleration region of the giant, and that any derived thermal and dynamic wind properties are most likely representative of isolated red giants.

Analysis of the wind absorption features provides spatially resolved information throughout the base of the wind. The wind is found to be isothermal throughout the region that is probed, with a derived Fe II excitation temperature of  $\sim 8,000$  K. The ionisation level along each line of sight is observed to be constant and symmetric around eclipse and hydrogen remains predominately neutral. The absorption spectra are modelled successfully assuming collisional excitation and over 4,000 lines are identified and modelled. No molecular features are observed in the wind acceleration region despite the sensitivity of *FUSE* to molecular hydrogen. The terminal wind velocity is found to be  $75 \text{ km s}^{-1}$  and the mass-loss rate to be on the order of  $10^{-8} M_{\odot} \text{ yr}^{-1}$ .

The damped wings of the hydrogen transitions define the ultraviolet continuum shape at absorbed phases and allow a mapping of the distribution of material around the giant. This information is used to derive a wind velocity profile that is incompatible with a low-order beta law and implies a delayed onset of acceleration. This result is confirmed by a photoionisation analysis of each sightline. The small-scale structure of the wind is found to be clumpy, with the flocculi having scale dimensions of  $\sim 0.2$  solar radii. Further analysis shows that the wind acceleration is unrelated to the presence of dust or molecular/atomic opacity, but is likely to be related to photospheric pulsations.

# Contents

|                                                               |              |
|---------------------------------------------------------------|--------------|
| <b>Contents</b>                                               | <b>vi</b>    |
| <b>List of Figures</b>                                        | <b>ix</b>    |
| <b>List of Tables</b>                                         | <b>xviii</b> |
| <b>List of Acronyms</b>                                       | <b>xix</b>   |
| <b>1 Red Giant Mass-loss and Symbiotic Stars</b>              | <b>1</b>     |
| 1.1 Stellar Evolution and Mass-loss . . . . .                 | 2            |
| 1.1.1 Evolution to the Red Giant Branch . . . . .             | 2            |
| 1.1.2 Stellar Photospheres, Chromospheres and Winds . . . . . | 4            |
| 1.1.3 Overview of Known Wind Driving Mechanisms . . . . .     | 10           |
| 1.1.4 Relevance to Other Fields of Study . . . . .            | 12           |
| 1.2 Symbiotic Stars . . . . .                                 | 12           |
| 1.3 This Thesis . . . . .                                     | 14           |
| 1.3.1 Probing Giant Winds with Symbiotic Stars . . . . .      | 15           |
| 1.3.2 Relationship to Isolated Giants . . . . .               | 16           |
| 1.3.3 Outline of this Thesis . . . . .                        | 17           |
| <b>2 Target Star, Observations and Data Processing</b>        | <b>19</b>    |
| 2.1 The Choice of Binary System . . . . .                     | 19           |
| 2.2 EG Andromedae . . . . .                                   | 21           |
| 2.3 The Ultraviolet Observing Program . . . . .               | 24           |
| 2.4 <i>FUSE</i> . . . . .                                     | 24           |
| 2.4.1 Data Processing and Instrumental Effects . . . . .      | 27           |
| 2.5 EG And <i>FUSE</i> Data . . . . .                         | 27           |
| 2.6 <i>HST</i> /STIS . . . . .                                | 29           |

|          |                                                            |           |
|----------|------------------------------------------------------------|-----------|
| 2.7      | EG And STIS Data . . . . .                                 | 30        |
| 2.8      | Optical Observations . . . . .                             | 32        |
| 2.8.1    | Low Resolution Data . . . . .                              | 32        |
| 2.8.2    | High Resolution Data . . . . .                             | 33        |
| 2.8.3    | Photometric Data . . . . .                                 | 33        |
| <b>3</b> | <b>The Giant Photosphere: Observations and Modelling</b>   | <b>34</b> |
| 3.1      | Optical Data and Analysis . . . . .                        | 35        |
| 3.1.1    | Low Resolution Data . . . . .                              | 35        |
| 3.1.2    | High Resolution Data . . . . .                             | 39        |
| 3.2      | Photospheric Modelling . . . . .                           | 42        |
| 3.2.1    | The PHOENIX Model . . . . .                                | 45        |
| 3.3      | Photometry . . . . .                                       | 45        |
| 3.4      | Mg II h and k Lines . . . . .                              | 47        |
| 3.5      | Conclusions . . . . .                                      | 48        |
| <b>4</b> | <b>Modelling the UV Spectral Variations</b>                | <b>50</b> |
| 4.1      | The Ultraviolet Observations: The Eclipse Effect . . . . . | 50        |
| 4.2      | Non-Eclipse Related Variations . . . . .                   | 55        |
| 4.2.1    | Broad P-Cygni Features . . . . .                           | 56        |
| 4.2.2    | Broad Emission Lines . . . . .                             | 58        |
| 4.2.3    | Origin of the High Velocity Features . . . . .             | 59        |
| 4.3      | Nebular Emission . . . . .                                 | 62        |
| 4.3.1    | C III Emission in the FUSE data . . . . .                  | 64        |
| 4.3.2    | O III Recombination lines . . . . .                        | 65        |
| 4.4      | Modelling the System . . . . .                             | 65        |
| 4.4.1    | Photoionisation Modelling . . . . .                        | 67        |
| 4.4.2    | Hydrodynamical Models . . . . .                            | 69        |
| <b>5</b> | <b>The Red Giant Wind in Absorption</b>                    | <b>74</b> |
| 5.1      | Analysis of the Wind Absorption . . . . .                  | 75        |
| 5.2      | Wind Ionisation and Overall Structure . . . . .            | 81        |
| 5.2.1    | Molecular Lines . . . . .                                  | 82        |
| 5.3      | Wind Temperature and Excitation . . . . .                  | 83        |
| 5.4      | Modelling the Column Density Variations . . . . .          | 84        |
| 5.5      | Large-Scale Wind Structure . . . . .                       | 86        |
| 5.6      | Small-Scale Wind Structure . . . . .                       | 87        |

---

|          |                                                     |            |
|----------|-----------------------------------------------------|------------|
| <b>6</b> | <b>Implications for Stellar Mass-Loss</b>           | <b>90</b>  |
| 6.1      | Physical Conditions . . . . .                       | 90         |
| 6.1.1    | The Extended Chromosphere in Emission . . . . .     | 91         |
| 6.2      | Large-Scale Structure . . . . .                     | 92         |
| 6.2.1    | Wind Acceleration . . . . .                         | 92         |
| 6.2.2    | Photoionisation Models . . . . .                    | 97         |
| 6.2.3    | $\beta$ Laws . . . . .                              | 99         |
| 6.3      | Small-Scale Structure . . . . .                     | 99         |
| 6.4      | Implications for Wind Driving Mechanisms . . . . .  | 100        |
| <b>7</b> | <b>Conclusions and Future Work</b>                  | <b>103</b> |
| 7.1      | Future Work . . . . .                               | 107        |
|          | <b>Bibliography</b>                                 | <b>112</b> |
| <b>A</b> | <b>Absorption Line Spectroscopy</b>                 | <b>119</b> |
| A.1      | Equivalent Widths and the Curve of Growth . . . . . | 119        |
| A.2      | Profile Fitting . . . . .                           | 123        |
| A.3      | Apparent Optical Depth Technique . . . . .          | 124        |
| <b>B</b> | <b>Wind Absorption Fits</b>                         | <b>125</b> |

# List of Figures

- 1.1 Schematic HR diagrams. The diagram on the left shows the position of main-sequence stars with different radii and masses. The diagram on the right shows the evolution of a low-mass star across the HR diagram. At stage [1], the objects progresses from a protostar to a main-sequence object. As the collapsing core enters hydrostatic equilibrium it forms into a spherical rotating object and begins to burn hydrogen in the core, officially the point at which it becomes a main-sequence star (stage [2]). The majority of its life is spent at stage [2], after which it begins fusing helium in the core and evolves up the RG branch (stage [3]). The star undergoes further internal changes, becomes more luminous and the mass-loss becomes higher until, eventually, the star reaches the tip of the AGB (stage [4]). At this point, so much mass has been lost that the core of the star becomes visible, nuclear burning no longer occurs, and the contracting core releases thermal energy and evolves to stage [5] (where many planetary nebulae are located). Finally the star progresses down the white dwarf cooling track (stage [6]) until the core remains a degenerate, cool, low-luminous body. . . . 3
- 1.2 **Left:** Seven thousand light years distant, the planetary nebula Abell 39 spans six light-years in diameter. The object has progressed through the main-sequence and red giant evolutionary phases to its present state where the hot exposed core ionises those outer layers that it expelled thousands of years previously. **Right:** Artist's impression of a symbiotic system with the white dwarf accreting material from the cool, red companion. . . . 13
- 1.3 **Left:** Artist's impression of FUSE in orbit. The background image is the galaxy M31, as viewed in the ultraviolet by the GALEX satellite. (Graphic courtesy JHU FUSE Project.) **Right:** The Hubble Space Telescope in its low-earth orbit 569 km above the Earths surface. This picture was taken after the second servicing mission in 1997. (Image courtesy of NASA.) . . . 17

- 
- 2.1 A model of the spectrum of a typical symbiotic star showing the contribution of the different components to the spectrum. The dotted lines display the individual contributions of the white dwarf (black), the photoionised nebula (blue) and the red giant component (red). The summed spectrum from all the components is displayed with the solid black line. The units of flux are arbitrary. . . . . 23
- 2.2 View of EG And perpendicular to the orbital plane. Points correspond to the dwarf position for the *FUSE* and *HST* observations. Observer's view is from the bottom and the scale is in units of solar radii. Also see Table 2.2. 25
- 2.3 Schematic diagram of *FUSE*. Each side has a SiC and LiF-coated telescope mirror. Light from these mirrors is reflected and dispersed by a grating with the same type of coating. A 2-d image of the dispersed spectrum is then recorded on two micro-channel detectors. . . . . 26
- 2.4 *FUSE* spectra of EG And for each of the 8 channels over a single orbit. Note the effect of the worm on the flux level over the wavelength region of 1140-1180 Å in the Lif1B spectrum (third panel down). Compare this to the Lif2a spectrum of the same wavelength region which is not affected by the worm (fifth panel down). These observations were obtained on the final orbit of a 5 orbit observing sequence (Observation number C169019). 28
- 2.5 **Top:** A schematic view of the optical design of HST. **Bottom:** A simplified schematic showing the major mechanisms and detectors of STIS. A medium-resolution echelle mode light path is also shown. (Both graphics courtesy of STScI.) . . . . . 30
- 3.1 A multi-wavelength spectrum of EG And stretching from the *FUSE* wavelength region into the optical. The optical region is dominated by the spectrum of the late-type giant. The overplotted data (red) is an averaged spectrum composed of observations of a number of M3 III spectral standards. The close match to the symbiotic giant spectrum suggests that the giant component is relatively undisturbed by the presence of the WD. Note high giant/dwarf luminosity ratio of the stellar components. . . . . 36
- 3.2 Displayed are the low-resolution optical STIS spectra of EG And that were obtained with the G430L grating. The data are contemporaneous with the ultraviolet echelle data and allow the behaviour of the giant to be monitored. . . . . 37

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |    |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.3 | To facilitate viewing of the variations in the G430L spectra, the difference between each spectrum and the August 2002 spectrum are displayed. The ultraviolet echelle data is binned and appended to the optical data to view the changes over the combined wavelength range. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                            | 38 |
| 3.4 | Sections of the high-resolution APO echelle data are plotted in black. Overplotted in blue is the spectrum of the M2 III spectral standard HD 148349. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 41 |
| 3.5 | High-resolution RITTER data of EG And at a number of different phases. The data (red) are overplotted on the first RITTER spectrum (black) in each panel to facilitate the viewing of spectral changes. While the Hydrogen Balmer profile (formed in the photoionised region of the outer giant wind) is observed to vary, the narrow absorption features (formed in the giant photosphere) remain constant (the far-reaches of the red giant wind (close to the dwarf) are heavily influenced by the dwarf radiation, the atmosphere of the giant appears relatively unperturbed). The data in black were obtained at phase $\phi=0.04$ , while the data in red cover phases $\phi=0.05$ to $\phi=0.83$ (top to bottom). . . . . | 43 |
| 3.6 | Differential magnitudes of EG And for (from top to bottom) UVBR. The left panel contains the KAIT data plotted against UV phase with the Skopal data plotted in red. The right panel contains the same data, but phase-wrapped. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 46 |
| 3.7 | Plots of the residual data after the subtraction of a fit to the ellipsoidal variation (period of 240 days; half of the orbital cycle). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 47 |
| 3.8 | Mg II resonance line at 2804 Å plotted in the rest frame of EG And. The Mg II resonance doublet is commonly used to diagnose the terminal velocities of cool winds. The derived value for the terminal velocity of the giant in EG And of 75 km s <sup>-1</sup> is marked on the plot. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                    | 48 |
| 4.1 | <i>FUSE</i> spectra of EG And at quadrature (black) and near eclipse (red). . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 52 |
| 4.2 | A similar set of uneclipsed and eclipsed STIS spectra. In the both plots the y-axis is plotted on a log scale to facilitate display of the strong emission lines. Both datasets are smoothed for clarity. Artifacts in the data are marked with an asterisk. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 52 |
| 4.3 | A graphical representation of the spectral variations in the <i>FUSE</i> EG And data. The flux levels are represented by colour intensities and are displayed on a log scale. The data are phase-wrapped and the flux intensities are linearly interpolated through phases where no data is present. Spectral artifacts are marked with an asterisk. . . . .                                                                                                                                                                                                                                                                                                                                                                      | 53 |

- 4.4 A graphical representation of the STIS ultraviolet data produced using the same methods as with Figure 4.3. Figure 4.3 displays all of the *FUSE* data whilst the the top panel shows the full ultraviolet STIS dataset. The middle panel and lower panels display sections of the same data on a larger scale. . . . . 54
- 4.5 Plots of the O VI (left panel) and P V (right panel) resonance line profiles (from uneclipsed phases) in velocity space in the EG And rest frame. The O VI profiles are reconstructed from clean regions (free of narrow absorption lines) from each component of the optically thick doublet, while the P V profile is the 1117 Å feature. These variations are not related to orbital phase, and the profiles are observed to switch between P-Cygni and inverse P-Cygni form. Although the profiles reach different extents in velocity space, it is apparent that they vary in tandem. These profiles trace clumpy, dense material located close to the dwarf star. The narrow emission component of the P V profile which is located at the rest velocity line is a nebular emission component superimposed on the wind profile. . . 57
- 4.6 Plots of the He II 1640 recombination line at three orbital phases. In the top panel note that the profile is composed of a wide base and a narrower core component. Also note the much narrower O I] 1641 Å emission line. From radial velocity measurements and photoionisation modelling (described later in this chapter) I find that the broad He II component is located close to the dwarf. In the partially eclipsed spectrum displayed in panel 2 the overlying wind absorption from Fe II is apparent. Overplotted (dashed line) with an offset is an Fe II absorption model, thermally excited to a chromospheric temperature of 8000 K. The bottom panel displays the extent to which the He II emitting regions have been eclipsed at  $\phi=0.04$ . The emitting region is therefore close to the dwarf and is located along the axis between both components. The dashed vertical lines correspond to the rest wavelengths of the lines in the red giant rest frame. . . . . 59
- 4.7 Measured radial velocities from fits to the broad component of the He II 1640 Å line (asterisks) and to the 1641 O I] (squares) line. Overplotted are the expected radial velocity curves for material associated with the red giant (dashed) and dwarf (solid) assuming a giant to dwarf mass-ratio of 3.5 and using the orbital elements derived by Fekel et al. (2000) for the giant. . . . . 60

- 4.8 Profiles of FUSE and STIS observations of the P V, N V and O VI resonance transitions. Individual profiles of the N V and O VI doublets are complicated by overlying narrow absorption and emission features from other species. The profiles shown here are reconstructed from both members of the doublet using regions free of the narrow features. The *FUSE* and STIS observations took place within 5 days of each other.  $P^{+4}$  has a lower ionisation energy than the other species - note the extent of its profile compared to the other two features. . . . . 61
- 4.9 Plots of the Si IV 1393 and S IV] 1416 velocity profiles observed with *STIS* at phase  $\phi=0.50$ . The left panel shows the permitted resonance line at  $\lambda$  1393.76Å, while the semi-forbidden line at 1416.90Å is plotted in the right. Both lines are plotted in the rest frame of EG And. The high density broad line region emits only in the permitted lines. . . . . 62
- 4.10 Sections of FUSE spectra around the O VI 1032, 1036 doublet. Within each panel the spectra plotted in red were observed one *FUSE* orbital period ( $\sim 90$  minutes) later than the data plotted in black. Note that while the narrow interstellar absorption features remain constant, the broad O VI profiles vary dramatically over this very short time-span. The dashed vertical lines correspond to the rest wavelengths of the O VI lines in the stellar rest frame. . . . . 63
- 4.11 The variations observed in the nebular densities against orbital phase. The densities shown here are derived using the flux intensities of the [O III]  $\lambda 2321$  / (O III]  $\lambda 1660$  + O III]  $\lambda 1666$ ) flux intensity ratios. Diagnostics from other ions produce similar eclipse effects. . . . . 64
- 4.12 The 1175 Å C III multiplet as observed with *FUSE* at phases  $\phi = 0.79$  (top) and  $\phi = 0.05$  (bottom). Also plotted (dashed and with an offset for clarity) is a quiet solar spectrum of the same multiplet, shifted to the rest frame of EG And. The solar spectrum displays the components of the multiplet close to their optically thin ratios. . . . . 65
- 4.13 Sections of uneclipsed *FUSE* spectra of EG And taken at almost identical orbital phases (black -  $\phi=1.79$ ; red -  $\phi=3.79$ ), but two orbital epochs apart. The spectra are almost identical except for the high-ionisation transitions. This is due to material close to the giant which undergoes variations unrelated to orbital phase. In general the material not located very close to the hot component remains stable over the different observed orbital cycles. 67

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |    |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.14 | Results of a CLOUDY photoionisation modelling along the binary axis of both stars. The calculation is stopped when the electron temperature goes below 4,000K. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 70 |
| 4.15 | Contribution functions of selected emission lines derived from the same photoionisation model as described in Figure 4.14. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 71 |
| 4.16 | Hydrodynamical model published by Walder & Folini (2000) for a binary system with similar systemic parameters to EG And. Although the outflow is severely disturbed at large distances into the wind, the density is very low and this material is not diagnosed in the absorption lines of EG And. The region of interest (within the binary separation) appears relatively undisturbed. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                              | 72 |
| 4.17 | A close-up of the model shown in Figure 4.16, displayed are the locations of the dwarf (green) and the giant (red). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 73 |
| 5.1  | Plots of the ratios of an uneclipsed FUSE spectrum to eclipsed <i>FUSE</i> spectra for 3 different degrees of eclipse. This plot basically removes the unchanging features (such as interstellar absorption lines) and displays only the spectral variations. The spectra are observed at increasing degree of eclipse from top to bottom. Note how the wind absorption lines strengthen and the continuum decreases with respect to the template quadrature spectrum. Most of the absorption features at these wavelengths originate from excited states of Fe <sup>+</sup> , P <sup>+</sup> , O <sup>+</sup> and Ni <sup>+</sup> . . . . .                                                                                                                                                                                   | 76 |
| 5.2  | The top panel shows two <i>FUSE</i> spectra of EG And. The uneclipsed spectrum was taken at quadrature and is an unobscured view of the dwarf where the absorption lines are all interstellar (flux is offset by $+3 \times 10^{13}$ for clarity). The absorbed spectrum was taken part-way during eclipse ( $\phi=0.10$ ) and a fit is overplotted (red). The fit was generated by placing absorbing material in the line of sight to the uneclipsed spectrum. The second panel shows the Fe II contribution to the fit while the bottom panel shows the H I contribution along with a number of other species (in this wavelength region mostly N I, P II and Ni II. Note that the blue wing of Lyman $\alpha$ defines the continuum shape. The Fe II model was generated using atomic data from Raassen & Uylings . . . . . | 78 |

- 
- 5.3 Plots of the complete *FUSE* dataset for EG And. Overplotted are the H I absorption models superimposed on a fit to the continuum of the template spectrum (red). The plotting of the template spectrum highlights the variations in the continuum that are unrelated to phase. The data are binned for clarity. . . . . 79
- 5.4 Plots of the complete STIS ultraviolet dataset for EG And, similar to Figure 5.3. . . . . 80
- 5.5 Plot of the continuum flux at a line free region (at  $\sim 1160 \text{ \AA}$ ) against orbital phase is displayed in the left panel. The right panel shows the same data plotted against the reduced phase. Triangular points represent STIS data and crosses represent *FUSE* data in both plots. Filled datapoints represent ingress data and open symbols define egress data for the panel on the right. The observed asymmetry between ingress and egress datapoints diagnoses the asymmetry in the distribution around the giant. . . . . 83
- 5.6 By measuring the apparent absorbing column for a range of lines coming from different lower levels, it is possible to examine the excitation structure in the gas. Here is an excitation diagram of Fe II derived from one of the STIS spectra. The solid line corresponds to a total Fe II column of  $7 \times 10^{16} \text{ cm}^{-2}$  and a temperature of 7,500 K. The lower and higher dashed lines correspond to the same column but to a temperature of 6,500 K and 8,500 K respectively. . . . . 84
- 5.7 Models of the column density variations of Fe I (black), Fe II (red), Fe III (green) and Fe IV (blue) assuming a Vogel wind acceleration. Overplotted are the column densities derived from the data. There are no transitions diagnosing the  $\text{Fe}^{3+}$  column densities. Note that material which is not affected by the dwarf radiation is not included in the column densities, therefore the sections of the line of sight which are unaffected by the dwarf radiation does not contribute to the columns. This accounts for the discrepancy between the model and the datapoints for more eclipsed phases. See text for further details. . . . . 86
- 5.8 Column densities of neutral hydrogen as a function of orbital phase. The red datapoints are derived from fits to low resolution *IUE* data. The black datapoints are derived from *FUSE* and STIS data where the uncertainties are of the order of the size of the datapoints. There is evidence for an asymmetry in the material around the giant, which is most likely due to a mechanical redistribution of the material by the motion of the dwarf. . . . 87

- 5.9 Example plots of the variation of the narrow wind line profiles from STIS (top panel; where the dashed lines correspond to the line centres at the EG And rest velocity) and *FUSE* (lower panel) spectra. Note the structure that is resolved in the STIS profiles. This structure remains unresolved in the lower resolution *FUSE* spectra, however the relative constancy of the profiles observed over a 3-day-time period (lower three spectra) place upper limits on the variability and unevenness of the outflow. . . . . 89
- 6.1 **Left:** Model of the HI column density falloff as a function of distance from the giant primary in EG And overplotted against the H I columns derived from *FUSE* and STIS egress data. Note the deviation of the model from the datapoints at  $b \sim 3.5 R_{RG}$  corresponding to the distance where the hydrogen is ionised by the white dwarf. **Right:** Plot of the run of the velocity profile of the giant derived from the model shown on the left using an inversion technique. Note the deviation of the velocity profile from  $\beta$  laws, commonly used to parameterise the wind profile in late giants. . . . 94
- 6.2 The predicted densities in the wind plotted against distance above the photosphere for a range of different wind acceleration models. The dashed lines correspond to different  $\beta$ -laws whilst the red line displays the density profile of a wind with a Vogel type acceleration. The blue line also corresponds to a Vogel wind acceleration, but with a mass-loss rate an order of magnitude less than the other models. The derived H I column densities are rather uncertain outside the impact parameter range  $\sim 2.1 - 3.2 R_{RG}$ . . . . . 96
- 6.3 Models of the column density variations of Fe I (black), Fe II (red), Fe III (green) and Fe IV (blue), similar to that presented in Figure 5.8. The upper panel assumes a Vogel wind acceleration whereas the lower panel assumes a  $\beta=1$  wind model and the same mass-loss rate ( $7.5 \times 10^{-8} M_{\odot}$ ). Note that material which is not affected by the dwarf radiation is not included in the column densities, therefore the sections of the line of sight which are unaffected by the dwarf radiation does not contribute to the columns. This accounts for discrepancies at more eclipsed phases. . . . . 98
- 7.1 **Left:** Sections of *FUSE* spectra of BF Cyg. (Black: uneclipsed, Blue: partially eclipsed) **Right:** *FUSE* spectrum of BF Cyg (black) plotted against an eclipsed spectrum of EG And (blue). Even though the orbital phases are different, it is apparent that the ionisation structure and composition of both winds are very similar. . . . . 109

- 7.2 Plot of derived wind laws for the giants in EG And (black) and SY Mus (blue) using the Abel inversion technique. Overplotted in red are some low-order  $\beta$ -laws. Note the similarity of the profiles for both symbiotic giants. Although the delayed onset of the wind acceleration profile seems to be a real effect, it remains to be seen whether the sharpness of the velocity increase is an artifact of binarity. . . . . 110
- A.1 Curve-of-growth diagram illustrating the regions of validity for each of the equivalent-width approximation formulae. The numeric solution is in red, and the approximations are in black. Overplotted are the equivalent widths derived from direct numerical integration of model molecular hydrogen lines for  $b = 1, 2, 4, 8$ , and  $16 \text{ km s}^{-1}$ . The solid grey horizontal line at the middle of the graph indicates roughly the boundary between resolved and unresolved (instrumentally broadened) line profiles for *FUSE* data, assuming that the *FUSE* resolution is  $R=20,000$ . . . . . 121
- A.2 **Left.** Absorption lines generated for a theoretical atom to illustrate the profiles obtained for different sections of the COG - ie. unsaturated, saturated and again saturated but where the Lorentzian wings dominate. **Right.** Interstellar HI Lyman  $\alpha$  absorption towards the line of sight to EG And. The line is obviously situated on the square root region of the COG. Overplotted is a model with  $N_{HI}=2.5 \times 10^{20} \text{ cm}^{-2}$ . . . . . 122
- A.3 In black are theoretical profiles obtained with an instrument with infinite resolution; overplotted in red are the same profiles after convolution with a Gaussian corresponding roughly to the LSF of the *FUSE* instrument. The convolution with the instrumental profile can mask line saturation. . . . . 123
- A.4 The top three panels show theoretical absorption line profiles (black line traces a transition stronger than the red lines), whilst the lower panels show the corresponding AOD profiles. The lines shown on the left display no sign of saturation, while the differing AOD profiles for the AOD data at middle and on the right do show saturation. This is diagnosed by the differing strengths of the AOD profiles. . . . . 124

# List of Tables

|     |                                                                                                                                                                                                                                        |    |
|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.1 | EG And Parameters. References - KP02- Keyes & Preblich (2004); MNSV91- Muer-<br>set et al. (1991); VNM92- Vogel et al. (1992); FJHS00- Fekel et al. (2000); B00- Bel-<br>czyński et al. (2000); WV97- Wilson & Vaccaro (1997). . . . . | 22 |
| 2.2 | EG And <i>FUSE</i> and STIS observations. Ephemeris from Fekel et al. (2000). See<br>Figure 2.2 for a graphical representation. . . . .                                                                                                | 31 |

# List of Acronyms

|      |                                                                        |
|------|------------------------------------------------------------------------|
| AGB  | <b>A</b> symptotic <b>G</b> iant <b>B</b> ranCh                        |
| APO  | <b>A</b> pache <b>P</b> oint <b>O</b> bservatory                       |
| AU   | <b>A</b> stronomical <b>U</b> nit                                      |
| CCD  | <b>C</b> harge <b>C</b> oupled <b>D</b> evice                          |
| FGB  | <b>F</b> irst <b>G</b> iant <b>B</b> ranCh                             |
| FUSE | <b>F</b> ar <b>U</b> ltraviolet <b>S</b> pectroscopic <b>E</b> xplorer |
| FUV  | <b>F</b> ar <b>U</b> ltraviolet                                        |
| FWHM | <b>F</b> ull <b>W</b> idth at <b>H</b> alf <b>M</b> aximum             |
| FWZI | <b>F</b> ull <b>W</b> idth at <b>Z</b> ero <b>I</b> ntensity           |
| HST  | <b>H</b> ubble <b>S</b> pace <b>T</b> elescope                         |
| IDL  | <b>I</b> nteractive <b>D</b> ata <b>L</b> anguage                      |
| IRAF | <b>I</b> mage <b>R</b> eduction and <b>A</b> nalysis <b>F</b> acility  |
| ISM  | <b>I</b> nterstellar <b>M</b> edium                                    |
| IUE  | <b>I</b> nternational <b>U</b> ltraviolet <b>E</b> xplorer             |
| KAIT | <b>K</b> atzmann <b>A</b> utomated <b>I</b> maging <b>T</b> elescope   |
| LTE  | <b>L</b> ocal <b>T</b> hermal <b>E</b> quilibrium                      |
| MAMA | <b>M</b> ulti- <b>A</b> node <b>C</b> hannel <b>A</b> rray             |
| NUV  | <b>N</b> ear <b>U</b> ltraviolet                                       |
| RG   | <b>R</b> ed <b>G</b> iant                                              |
| STIS | <b>S</b> pace <b>T</b> elescope <b>I</b> maging <b>S</b> pectrograph   |
| WD   | <b>W</b> hite <b>D</b> warf                                            |

# 1

## Red Giant Mass-loss and Symbiotic Stars

The materials required for the formation of planets, solar-like systems and, eventually, life were synthesised from hydrogen and helium within previous generations of stars. However, the question as to how the majority of this material is unlocked from the stellar gravity and transported outwards remains what is arguably *the* most important outstanding problem of stellar astrophysics (e.g. Harper, 1996). The bulk of the very heavy elements are delivered to the interstellar medium (ISM) by rare <sup>1</sup> stellar explosions known as supernovae and, indeed, these events are well studied. However, the vast majority of carbon, nitrogen and oxygen (CNO) and other light elements originate in the dense winds of stars in the red giant (RG) stage of evolution. Indeed, in the solar neighbourhood these stellar winds replenish up to 3/4 of the interstellar medium. However, despite the fact that these stars produce the bulk of CNO in the universe, the mass-loss processes in these objects are not understood. Furthermore, the gas dynamics and physical conditions in the layers above the stellar surface cannot be accurately modelled and reliable observational information is sparse.

In this introductory chapter, the mass-loss problem is outlined in some detail. These evolved objects are placed in an evolutionary context and both the historical and current status of the research in this field is discussed. The class of stellar binary objects known as

---

<sup>1</sup>supernovae rates of only  $\sim 1$ -2 per century in our galaxy

symbiotic stars are introduced, followed by a description of how the analysis of ultraviolet observations of these systems will be utilised in this work to gain an understanding of the red giant mass-loss process.

## 1.1 Stellar Evolution and Mass-loss

With the possible exception of the most compact stellar objects, such as white dwarfs, all stars are known to lose mass in the form of a stellar wind. These mass outflows are detected in a number of differing ways, including observations of classical P-Cygni line profiles<sup>2</sup>, extended circumstellar shells and circumstellar reddening. However, even though mass-loss appears to be ubiquitous across the whole range of stellar types, it is well recognised that the wind generation processes and, indeed, the nature of the winds themselves, depend on the properties and evolutionary status of the host star. In order to place red giant mass-loss in context, it is instructive to examine how stars evolve into these relatively cool and tenuous objects.

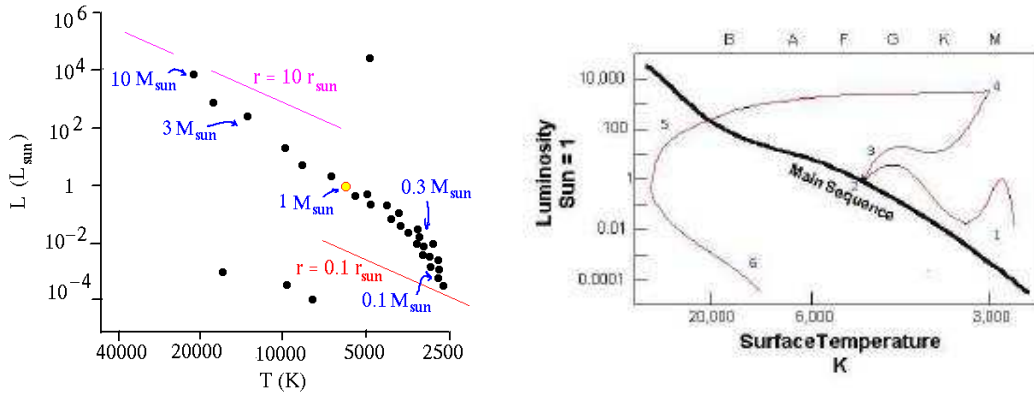
### 1.1.1 Evolution to the Red Giant Branch

When a collapsing condensed core of a molecular cloud becomes hot and dense enough for hydrogen fusion to take place, the protostellar object becomes what is known as a main-sequence star. The main-sequence is a relatively stable evolutionary phase where stars spend up to 90% of their lives. A diagram commonly used to analyse the evolutionary status of stars is the Hertzsprung-Russel (HR) diagram. Essentially, this is a log-log plot of stellar luminosity against temperature. On the HR diagram, the main-sequence stars appear as a broad and densely populated band running from the bottom right to the top left corner (see Figure 1.1, left). As can be seen in Figure 1.1 (left), the majority of the low mass stars (including our own sun) are found in the lower right hand corner of the diagram. The coolest of these stars are designated to have spectral types of K or M. The more massive stars (the hottest of which are designated type O or B), located in the upper left corner, burn their hydrogen supply much faster and spend only a limited amount of time on the main-sequence.

Stellar evolution after the main-sequence depends strongly on the initial mass of the star. Those more massive stars (typically initial masses  $> 8M_{\odot}$ ) require large amounts of energy to counteract the large inward gravitational forces and typically expend their

---

<sup>2</sup>P-Cygni features are characterised by a strong emission line with a corresponding blueshifted absorption feature superimposed. The absorption is produced by material moving away from the star and toward the observer, whereas the emission comes from other parts of the expanding material.



**Figure 1.1:** Schematic HR diagrams. The diagram on the left shows the position of main-sequence stars with different radii and masses. The diagram on the right shows the evolution of a low-mass star across the HR diagram. At stage [1], the object progresses from a protostar to a main-sequence object. As the collapsing core enters hydrostatic equilibrium it forms into a spherical rotating object and begins to burn hydrogen in the core, officially the point at which it becomes a main-sequence star (stage [2]). The majority of its life is spent at stage [2], after which it begins fusing helium in the core and evolves up the RG branch (stage [3]). The star undergoes further internal changes, becomes more luminous and the mass-loss becomes higher until, eventually, the star reaches the tip of the AGB (stage [4]). At this point, so much mass has been lost that the core of the star becomes visible, nuclear burning no longer occurs, and the contracting core releases thermal energy and evolves to stage [5] (where many planetary nebulae are located). Finally the star progresses down the white dwarf cooling track (stage [6]) until the core remains a degenerate, cool, low-luminous body.

hydrogen core after a few million years. The star then moves away from the main-sequence and ‘burns’ helium in its core. The helium is eventually fused into progressively heavier elements until the core is finally composed of iron. Eventually, the remains of the stellar envelope is ejected during the course of a dramatic and high-energy supernova explosion, leaving the core to collapse to form a neutron star or black hole.

Less massive stars (initial masses  $< 8M_{\odot}$ ) spend a much greater amount of time on the main-sequence (up to billions of years), due to the reduced energy requirements for resisting gravitational contraction. When the hydrogen in the core is eventually exhausted, changes take place in the stellar envelope that are equally as dramatic, although less explosive, than the changes that occur in their high-mass counterparts. The reduced energy generation in the core results in its contraction, which enables ignition of helium fusion in the core. This generates large amounts of energy, allowing the stellar envelope

to cool and expand, resulting in the star's progression up the first giant branch (FGB). For intermediate and low-mass stars, it is in this phase that mass-loss really becomes significant (Schaller et al., 1992) enriching the surrounding region with processed elements.

As the star progresses further up the giant branch, the nuclear processes in the star's interior change fundamentally (with helium being synthesised into progressively heavier elements). This results in large increases in the stellar luminosity and radius, accompanied by a cooling of the surface layers. The structure becomes increasingly pulsationally unstable, with more and more material being lifted off the surface in the form of a massive stellar wind. This wind carries the results of the internal nuclear processes and provides the building blocks for future generations of stars and planetary systems.

After the core helium has been converted to carbon and/or oxygen, the star enters what is known as the asymptotic giant branch (AGB) phase. By the time the star has evolved to this point on the giant branch, enough mass has been lost to enable the formation of a cool, dusty circumstellar shell. The outer layers of the star continue to expand and become cooler, with the amplitude of the pulsations in the stellar atmosphere increasing dramatically. The star leaves the AGB phase when the envelope mass decreases below about  $0.001M_{\odot}$  and the strong mass loss ends. The central core retains its luminosity but contracts, resulting in a corresponding increase in temperature. The increase in temperature results in a large increase in the emission of ultraviolet and x-ray continuum photons, often resulting in the ionisation of the ejected stellar envelope. This process leads to the formation of complex planetary nebulae. An example of one such planetary is shown in Figure 1.2. The core then becomes a hot compact white dwarf (WD) and since it is no longer producing energy, it proceeds down the WD cooling track of the HR diagram. See Figure 1.1 (right) for a graphical view of the evolution of a low-mass star across the HR diagram.

## 1.1.2 Stellar Photospheres, Chromospheres and Winds

### 1.1.2.1 Stellar Photospheres

The photosphere of a star is the layer of the stellar atmosphere that we know most about; it is generally the layer that we can directly observe. It is defined as the region where the optical depth reaches unity, where the atmosphere becomes transparent and the photons have a reasonable chance of escaping directly from the star and making the journey across space. Although the depth of this layer will vary with wavelength (especially close to the wavelengths of strong atomic transitions), for a star like the sun, the photospheric layer is reasonably well defined. However, due to their lower temperatures and surface gravities,

and also due to their pulsations and heavy mass-loss, evolved giant stars do not have such a clear boundary. By contrast, the atmosphere is extended, inhomogeneous and at some point becomes a strong outflow of gas (and possibly dust). For such objects, the nature and extent of the photosphere are more difficult to characterise.

Classifications of giant stars are usually based on the photospheric molecular and atomic features that are observed in the visible and infrared regions of the spectrum<sup>3</sup>. The presence and strengths of these spectral features are primarily dependent on the temperature, chemical abundance and gravity in the photosphere, and it is these physical parameters that are generally used to characterise stellar atmospheres. Due to the fact that the photospheres of most giant stars are cool enough ( $T \leq 4,500$  K) for molecules to form, the appearance of the spectrum from the optical to the far-infrared (IR) is heavily influenced by absorption bands of molecular species. Several molecules present such a wealth of spectral lines that they become a pseudo-continuous opacity source. At optical wavelengths, oxygen-rich giants show strong bands of TiO and VO. For S stars, which have approximately equal amounts of oxygen and carbon, the most characteristic band on display is that produced by ZrO. In carbon-rich (C) stars, all molecular bands are from carbon compounds. The observation that many photospheric molecular features are due to *either* carbon *or* oxygen based molecules can be understood in terms of the favourable energetics for formation of the CO molecule. The majority of carbon and oxygen in stellar photospheres therefore exists as CO which is very readily formed, leaving the remains of whichever species is more abundant to form molecules with other species. In the infrared, most M stars have strong absorption by H<sub>2</sub>O, CO, SiO and OH. For a detailed description of observations of the photospheres of cool stars see Gray (1976).

The fact that molecules can form in the low density photospheric environment of cool stars is the prime reason why the modelling of giant atmospheres can be such a difficult process. It is important that the large range of molecular opacities are taken into account, in addition to the usual opacity sources such as H<sup>-</sup>. Furthermore, for many strong atomic and molecular transitions the LTE (Local Thermodynamic Equilibrium) approximation becomes invalid at the low densities present in giant photospheres, further complicating the computational modelling. When modelling most stars the atmospheric layers can be assumed to be in a plane-parallel geometry and a one dimensional approximation is usually sufficient. However, for extended giant stars, a plane-parallel atmosphere is not appropriate. Thus, full radiative transfer treatment is required. In addition to these com-

---

<sup>3</sup>Although there are also further sub-divisions based on their pulsational behaviour (irregular, semi-regular or Mira-like) or on properties of the circumstellar environment (e.g. OH/IR stars showing OH masering and a large IR excess).

plications, strong mass-loss and atmospheric pulsations further complicate the structure, making the difficulties in modelling these objects apparent. Despite these problems, recent advances in computational hardware and modelling techniques have made it possible to model these photospheres to reasonably high degrees of reliability.

### 1.1.2.2 Evolved Stellar Winds & Chromospheres: An Historical Perspective

Although optical prism observations of novae and massive hot stars in the 19<sup>th</sup> Century established that strong outflows from stars do exist, the fact that red giants have stellar winds was not solidly established until Deutsch (1956) presented his observations of the binary system  $\alpha$  Her. The system consists of an M5 giant in a wide orbit with a secondary binary system containing two hotter dwarf stars. Deutsch noticed that the spectrum of the secondary could be used as ‘*a very convenient probe*’ to analyse different regions of the M star’s outer wind in absorption. He found velocity-shifted wind absorption lines that were present in the spectrum of the circumstellar envelope of the M star, and also in the spectrum of the secondary. Since the orbital separation is very large, these features must be due to gas that has escaped from the M star and envelopes both components, thus providing evidence for mass-loss from a red giant. Further studies of mass-loss from giants was primarily based on the observations of low-velocity ( $10 - 30 \text{ km s}^{-1}$ ), blue-shifted circumstellar absorption features of low-ionisation species in M giants. Detailed reviews of the early studies of red giant winds had been presented by Deutsch (1960), Reimers (1975), Reimers (1977) and Goldberg (1979). The question however, as to what lay between the photosphere and the cool outer portions of the wind was not addressed.

Taking the sun as an example, what lies outside of the photosphere is the region known as the chromosphere. This is a region, approximately 2500 km thick, which sees a rise in temperature from  $\sim 5,600$  to  $\sim 10,000$  K, even though the density continues to decrease. Moving outwards, this layer is followed by the transition region, where the temperature rises sharply until the corona is reached. The corona and is an extremely hot (millions of degrees) and tenuous region that extends outwards to the interstellar medium.

Following the launch of *IUE* (*International Ultraviolet Explorer*) the important diagnostic transitions in the ultraviolet wavelength region could be observed for a range of evolved stars. These spectra provided evidence for the existence of some, or all, of these layers in cool giants. Many studies of cool giants based on *IUE* data (e.g. Carpenter, 1986; Stickland & Sanner, 1981) revealed the presence of a rich ultraviolet emission line spectrum (e.g. lines of C II, O I, Mg II and Fe II), characteristic of chromospheric conditions. Stencel (1981) reviewed the evidence for the extension of this chromospheric region over several stellar radii, contrary to the narrow chromosphere present in the sun. He states:

*‘It seems physically appealing that among red giants which show no evidence for hot coronae, the chromosphere occupies a volume homologous to that of coronae in warmer, higher gravity stars.’* Indeed Carpenter et al. (1985) went on to find that there exists *‘a clear difference in the radial extent of the chromospheres around coronal and noncoronal stars. The former stars appear to have very thin chromospheres (of no more than 0.1 percent of the photospheric radius), while the latter stars have chromospheres extending, on average, out to 2.5 photospheric radii.’* The case is not clear though. Luttermoser et al. (1994) finds that for their chromospheric models of an M6 giant the *‘chromospheric emission features are formed relatively close to the star ( $\leq 1.05$  giant radii)’*. It is therefore apparent, that for cool giants, the extent of the chromosphere and the physical conditions within it are still not fully identified.

The coolest giant stars do not display evidence of circumstellar material heated to temperatures exceeding those expected in chromospheres. However, it emerged from the analysis of the ultraviolet and X-ray observations in the late 1970s and early 80s that some cool photospheric giant stars do display emission lines, characteristic of coronal conditions (Antiochos et al., 1986; Ayres et al., 1981; Linsky & Haisch, 1979). It was suggested that cool stars can be divided into two very broad categories, coronal and non-coronal stars. As reviewed by Carpenter (1998) ....*‘The first group (coronal stars) include active stars such as flare stars, all cool dwarfs, giants earlier than K2, and supergiants earlier than about G8. The outer atmospheres of these stars are similar to that of the sun in that they exhibit a chromospheric temperature rise above the photosphere (to temperatures  $\sim 5,000 - 10,000$  K), above which is located a hotter transition region (temperatures  $\sim 10^5$  K), and then an even hotter corona (temperatures  $\sim 10^6$  K).....The second group (non-coronal stars) includes giants later than K2 and supergiants later than G8. The outer atmosphere of these stars show the same chromospheric temperature rise as the coronal stars, but in general show little or no evidence of transition regions or coronae.’* This division positions the majority of red giants as non-coronal objects. However, it was soon discovered that there were intermediate objects, the so-called hybrid stars (Hartmann et al., 1980; Reimers et al., 1996). These stars have spectral types placing them in the non-coronal category, although they display evidence for the existence of high temperature circumstellar material. Nevertheless, this modified categorisation still places red giant M stars (which include all AGB stars) firmly in the non-coronal category. Multiple dividing lines and refinements on the classification are discussed by Reimers et al. (1996).

The only directly observable information available for point-source stars are disk-averaged global properties, such as the mass-loss rate and the terminal wind velocity (and even these values are notoriously difficult to measure for normal isolated red giants).

Generally, in order to gain information on the spatially resolved structure of the outer layers of isolated stars, a model of the circumstellar material must be assumed a priori. In order to gain a more direct knowledge of the chromospheric and wind structure, researchers in the 1980s again looked towards the benefits of observing binary systems; this time in the ultraviolet with *IUE* and more recently the *HST* (*Hubble Space Telescope*). The first in a large series of papers analysing the *IUE* observations of the  $\zeta$  Aurigae and VV Cepheid binary systems was published by Hempe (1982). The main results of these studies are summarised in a number of review articles (e.g. Baade, 1990, 1998; Carpenter, 1992; Dupree & Reimers, 1987; Guinan, 1990; Harper, 1996; Linsky et al., 2000; Reimers, 1987). These ultraviolet studies of eclipsing binaries cast light upon the temperature structure, radiative processes and physical distribution of the circumstellar material. However, as noted by Linsky et al. (2000), it was often difficult to disentangle what effects the hot companion star was having on the giant wind; the most notable problem being the complex ionisation structure generated by the ultraviolet continuum of the secondary. *‘The ionisation structure in the wind is complex.....The properties of the wind are time-dependent.....the mass-loss is variable on a time-scale of several months, the wind density does not repeat from orbit to orbit’*. Harper et al. (2005) also find that *‘the wind from  $\zeta$  Aur does not accelerate as fast as those inferred in single stars of similar spectral type’*, implying that the presence of the companion may significantly alter the wind acceleration profile. It is therefore necessary, when using the binary technique, to try and understand, as much as it is possible, to what extent the companion star is altering the giant’s wind. However, as noted by Baade (1998), *‘the UV binary technique permits us to examine the physical properties of the tenuous layers of these stars unobtainable by other means.’* He concludes that *‘It results from these studies that circumstellar envelopes of cool, evolved stars are more complicated than previously expected.’*

### 1.1.2.3 Evolved Stellar Winds and Chromospheres: Current State of Research

The advances made towards understanding the chromospheres and winds of evolved stars in the 1960s, 70s and 80s began to stall in the early 90s, and today much remains unknown. The case for cool evolved stars is in stark contrast to those stars of different spectral types. For hot massive luminous stars, the radiation pressure on the outer layers of the star is known to impart energy into the outer layers and to drive the mass-outflows (e.g. Owocki, 1994). For main-sequence solar-like stars, where the rates of mass lost are much less ( $\sim 10^{-13} M_{\text{sun}}$ ), the hot tenuous winds are predominantly driven by Alfvén waves through

coronal holes (e.g. Lamers, 1997)<sup>4</sup>. However, for the majority of red giant stars the basic mass-loss processes at work are not understood. Indeed, for stars of spectral types between K0 II-III and M5-M6 II-III, much remains unknown about the regions above the visible photosphere and the transportation of the material that is processed inside these objects to the interstellar medium (e.g. Judge & Stencel, 1991).

For those stars approaching the tip of the AGB, the stellar winds are thought to be driven in a two step process. At stellar distances where dust can form (typically at least  $5 R_{RG}$ ), radiation pressure on dust and subsequent dust-gas collisions can explain the observed wind properties. Stellar pulsations are thought to levitate matter out to regions conducive to dust formation. This combination of pulsations and subsequent radiation pressure on dust can, in theory, account for the large mass loss rates observed in heavily evolved giants. However, much of our knowledge of AGB stellar winds comes from the circumstellar shells around the objects, and is not observed from the wind acceleration region itself. These stars can be totally obscured by the dust which absorbs efficiently in the visible region of the spectrum. These dust shells often produce maser emission<sup>5</sup> of SiO, OH and H<sub>2</sub>O far out in the stellar wind. Both molecular emission lines and masers can be imaged, giving detailed information about the extent and shape of the outer limits of the wind and circumstellar shell. However, this technique only provides information on the outermost part of the wind, where the material has cooled sufficiently to allow dust and molecules to form and where the wind is strongly affected by the ambient medium. Observational information on the inner part of the wind is still sparse and is required in order to test the hypothesis that radiation pressure on dust is the primary instigator of mass-loss in these objects. For instance, although working models exist where dust and gas are initially driven by shocks and where the photospheric radiation pressure on dust expels the material from the star, Judge & Stencel (1991) suggest that *‘dust formation is not the primary instigator of mass-loss from most cool giants.’* Their empirical analysis of the global thermodynamic requirements of the outer atmospheres of a range of cool giants finds that while dust plays an important role in AGB mass-loss, it only dominates the stellar wind when the star reaches the very last phase on the AGB and becomes an infrared carbon star. They conclude that *the energy fluxes required to drive the winds of K and later giants, both with and without detectable dust, may be independent of the dust shell optical depths....the primary process(es) supplying the energy leading to mass-loss*

---

<sup>4</sup>For a full discussion of the various type of wind driving mechanisms and the regimes in which they dominate see Lamers & Cassinelli (1999).

<sup>5</sup>masering (microwave amplification by stimulated emission of radiation) is a common formation mechanism for producing strong, narrow emission lines in the molecular circumstellar envelopes of AGB stars. See Diamond (2002); Lamers & Cassinelli (1999) and references within for details.

*from cool giants require(s) energy fluxes that increase rather smoothly with evolutionary phases, until the star becomes an infrared carbon star.* Evidently, the case for AGB mass-loss is not clearcut and much work remains to be carried out.

AGB stars only account for a fraction of all red giants and the situation is even more uncertain for those stars on the first ascent of the red giant branch. These stars do not possess significant cool, dusty circumstellar shells and their pulsations are orders of magnitude weaker. Clearly the strong winds that are observed in these stars pose major problems for theorists. With the continuing improvement in stellar atmosphere modelling and computational power, it is reliable observational constraints that are required to provide the impetus needed to gain a solid understanding of this problem.

### 1.1.3 Overview of Known Wind Driving Mechanisms

The most important wind-driving theories are briefly outlined in this section. For a detailed treatment see Lamers & Cassinelli (1999). There are a number of different mechanisms that can, in theory, drive a wind from a star. Many of these theories originated in the 1950s and 60s when attempts were made to explain the origin of the solar wind. It was at this time that Eugene Parker suggested that flows of material from the sun could be driven by gas pressure gradients, resulting in the so-called solar wind.

#### 1.1.3.1 Coronal Winds

In solar-like stars, the temperature rise directly above the photosphere is thought to be due to the dissipation of mechanical energy or the reconnection of magnetic fields originating in the convection zone below the photosphere. Since normal stars with a photospheric temperature less than  $\sim 6,500$  K are thought to possess convective zones, it follows that chromospheres and coronae could, in principal, exist around all cool stars. The existence of this hotter material above the photosphere can produce a gas pressure gradient that can accelerate an outflow from the star. Coronal winds produce high-velocity outflows with much lower mass-loss rates than those produced by other driving mechanisms. These winds are only important in solar-like stars where no other wind mechanism contributes to the mass-loss.

#### 1.1.3.2 Sound Wave Driven Winds

The convection zones of cool stars generate acoustic waves in their photospheres which can propagate outwards carrying wave energy to the outlying material. This produces a wave pressure in the stellar atmosphere which can in theory drive a wind from the star.

However, these sound waves can only effect the mass-loss rates of very low gravity stars, and only then if certain stringent conditions hold. The importance of this process (or lack of) is not fully understood.

#### 1.1.3.3 Dust Driven Winds

The fact that a large excess of infrared flux is observed in many AGB stars led to the idea that this emission was due to dust formed in the stellar wind and that the radiative forces on this dust could actually drive the outflow. In this mechanism, the dust absorbs the photospheric radiation, which heats the dust and results in energy being radiated isotropically in the infrared. However, in addition to carrying energy, the photons also carry momentum, and when the radiation from the star is absorbed by the dust, this momentum is transferred to the dust particle. Since the radiation field of the star is directional, the result is an accelerating flow of material moving outwards from the star.

This wind-driving mechanism results in a slow ( $\sim 10\text{-}30\text{ km s}^{-1}$ ), but massive outflow. However, it is only important for heavily evolved AGB stars where the material is cool enough for dust to form, and also where the luminosity to mass ratio of the star is large enough so that the outward forces exceed the gravitational forces. It is thought that the process is very efficient in large-amplitude pulsating AGB stars (Miras) where the pulsations can levitate material out to distances where dust can form and be subsequently acted upon by the photospheric radiation.

#### 1.1.3.4 Line Driven Winds

Line driven winds are important for hot, luminous stars (i.e. OB stars, hot main-sequence stars, giants, supergiants, white dwarfs). These stars emit most of their continuum radiation in the ultraviolet - the spectral region where lots of strong resonance transitions of common elements are located. The opacity in these absorption lines is much stronger than in the continuum and the large radiation force on ions in and above the photosphere turns out to be very effective at driving a stellar wind.

#### 1.1.3.5 Alfvén Wave Driven Winds

Since Parker's original wind predicted only a steady, radial, structureless outflow, driven by gas pressure gradients in the corona, the observation of temporal and spatial variation in the solar wind remained unexplained until 1965. It was then that Parker refined his theory to include open magnetic field structures which could do work on the wind and where the wind characteristics would depend strongly on the field conditions at the base

of the outflow. Alfvén wave driven winds typically have very high terminal velocities (solar wind streams up to  $\sim 700 \text{ Km s}^{-1}$ ) and are important for stars from all over the HR diagram.

#### 1.1.4 Relevance to Other Fields of Study

The rates at which stars lose matter to the interstellar medium is of central importance in both stellar and galactic evolution. Mass-loss from stars can profoundly influence their evolution and, in many cases, even decide their eventual fate. The evolution of the star is influenced most dramatically in cases where the mass-loss time scale is comparable to the core evolution time scale, or when the cumulative mass-loss is comparable to the initial stellar mass.

In the case of galactic chemical evolution, mass-loss from stars plays an even more crucial role. Evolved giant stars in particular play a vital role in contributing large amounts of processed material to the ISM, out of which new generations of stars will form. This enriched gas is also the material from which stars and planets form, hence the need to understand mass-loss in order to understand the initial conditions present for star and planetary formation.

It is apparent that the lack of a theory of mass-loss with predictive power further amplifies uncertainties in stellar and galactic evolution models. However, it is also important to gain a full understanding of the mass-loss and physical processes at work in evolved giants for its own sake. Overall, it is desirable to be able to predict stellar mass-loss rates from first principles.

## 1.2 Symbiotic Stars

Prior to the advent of space-based observatories, symbiotic systems were a poorly understood phenomenon. Optical spectra revealed a continuum typical of a cool, evolved giant star with characteristic low-ionisation atomic and molecular absorption features such as Ca I, Ca II, Na I, Fe I,  $\text{H}_2\text{O}$ , CN, CO, TiO and VO. What made these stars peculiar was the presence of high ionisation (ionisation potential (IP)  $> 20 \text{ eV}$ ) emission lines that are typically observed in hot gaseous nebulae. It was not until the late 1970's and early 80's that UV observations with *IUE* confirmed the presence of an additional far-UV (FUV) radiation source, thus proving the binary nature of these sources.

It is now accepted that symbiotic objects are binary systems typically consisting of a hot white dwarf or subdwarf in orbit with a late-type giant star primary. The red giant loses material in the form of a relatively slow (typically  $\sim 10 - 100 \text{ km s}^{-1}$ ), dense wind,



**Figure 1.2: Left:** Seven thousand light years distant, the planetary nebula Abell 39 spans six light-years in diameter. The object has progressed through the main-sequence and red giant evolutionary phases to its present state where the hot exposed core ionises those outer layers that it expelled thousands of years previously. **Right:** Artist's impression of a symbiotic system with the white dwarf accreting material from the cool, red companion.

and this material is photoionised by the hot WD ( $T_{WD} \sim 10^5$  K) continuum to produce a rich nebular spectrum. The high-ionisation emission lines found in the spectra of these objects typically diagnose electron densities of  $n_e \sim 10^9 \text{ cm}^{-3}$  and are thought to originate in a part of the atmosphere/wind of the cool giant which is ionised by the hot companion. The red giant continuum dominates the optical and infra-red spectral regions while the continuum observed in the ultra-violet is primarily due to the hot component. Since their discovery, symbiotics have been studied extensively, primarily with the purpose of further understanding stellar evolution. For a general overview of symbiotic stars and their features see Kenyon (1986) and Mikolajewska et al. (1988).

Most of these objects display brightness variations of 0.5–1.0 magnitudes over periods of months to years, with some undergoing 2–4 magnitude eruptions, some of which last years. In some cases these periodic variations can be attributed to orbital variations (binary periods are typically  $\sim 1–3$  years for non-dusty binaries) or changes in the giant itself (i.e. pulsations). The larger variations and irregular brightness increases are attributed to thermonuclear detonation of material accreted from the giant's wind onto the surface of the hot star. For a discussion of possible outburst mechanisms in symbiotics see Mikolajewska & Kenyon (1992).

At present only  $\sim 200$  of these objects are known with most residing in the Milky Way. A handful are situated in the Magellanic Clouds and in the Draco dwarf galaxy, both of

which are satellite galaxies to our own. The actual number of symbiotics is difficult to ascertain, with estimates for our galaxy ranging from 3,000 to 30,000 (Yungelson et al., 1995). The relative scarcity of these systems can be understood by looking at the phases of evolution that the two components must be located in. The symbiotic phenomenon will only be observed for the period of time that one component of a binary system has evolved to become a hot, dense WD and the other is still a large, low-gravity giant, losing mass to its surroundings. Even accounting for the different evolutionary scenarios, this phase is expected to last at most  $\sim 10^6$  years. This time frame is short in comparison to stellar evolution timescales.

Symbiotic binary systems are important objects to understand for a number of reasons. There is evidence that long-period, widely separated symbiotics may be evolutionary precursors to those planetary nebulae which display complicated patterns of ionised material, where the nebula is often thought to be excited by a well-separated white dwarf pair. Symbiotic stars are also often suggested as candidates for the progenitors to type Ia supernovae. It is therefore highly desirable to place these objects in an evolutionary scenario, thus placing constraints on stellar evolution models.

These binaries also permit the study of material in extreme conditions which cannot be studied elsewhere. Gas temperatures in the space between the two stars can range from  $\sim 10^4$  K in the giant's wind to  $\sim 10^6$  K in the shocked region where the hot and cool winds collide. This produces an extremely rich emission and absorption spectrum in the relatively uncharted FUV spectral region. Therefore, these stars provide ideal testbeds from which to gain information about analysis techniques, spectral diagnostics and atomic data in the UV. This spectral region will become even more important when the next generation of space telescopes come online, whose instruments will routinely obtain high-quality spectra of galaxies possessing large redshifts that shift their UV features to optical wavelengths.

Finally, and most relevant to this thesis, the evolved giant stars that are present in symbiotic systems provide one of the more efficient means of enriching the universe with processed material. The unique configuration of the hot, compact ionising star in close proximity to the mass-losing giant presents an ideal opportunity to gain an understanding of mass-loss processes involved.

## 1.3 This Thesis

In much the same vein as Deutsch's original observations of  $\alpha$  Her, this thesis aims to further the understanding of evolved star mass-loss through observations of a binary

system, in this case a symbiotic binary. Those symbiotic systems which are observed to undergo eclipse provide an opportunity to obtain *spatially resolved* information on the giant's extended atmosphere and wind. The presence of the dwarf star, combined with knowledge of the orbital parameters, make it possible to use the secondary as an orbiting ultraviolet-bright backlight. Therefore, ultraviolet observations, if taken at well chosen orbital phases, allow the study of the circumstellar material in absorption along differing lines of sight through the wind.

### 1.3.1 Probing Giant Winds with Symbiotic Stars

The role of eclipsing binaries in providing localised information on circumstellar conditions has long been recognised and has been discussed earlier in this chapter. *IUE* studies of  $\zeta$  Aurigae and VV Cephei systems have been particularly useful in examining the chromospheres and winds of giants and supergiants (e.g. Baade, 1990; Reimers, 1987). However, a number of factors suggest that the study of symbiotic systems holds advantages over the study of other binary systems:

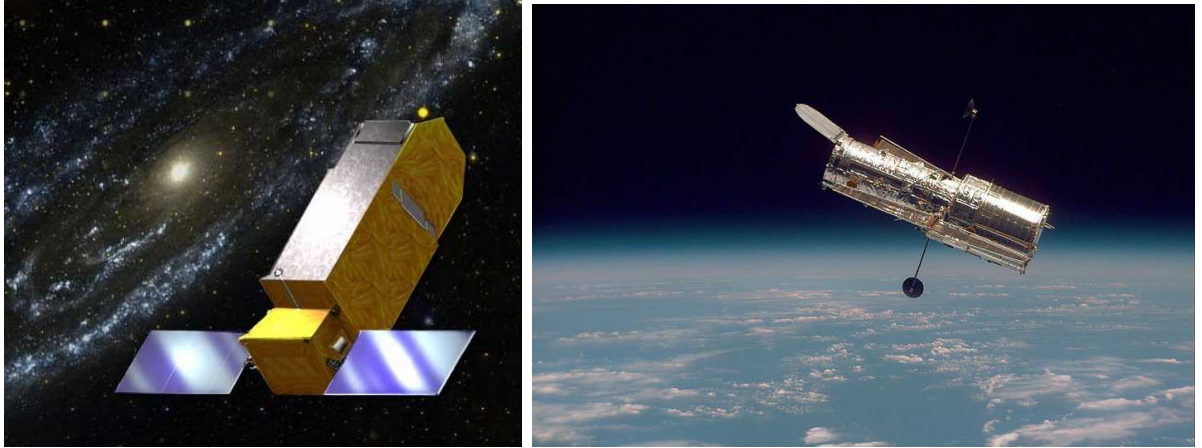
- The small diameter of the dwarf relative to the giant (typically  $\sim 0.0002\%$ ) provides a narrow, pencil beam view through the outer layers of the giant.
- Unlike many other binaries, the two components in symbiotic systems have entirely different spectral characteristics and can be easily disentangled. The giant continuum does not contribute in the far ultraviolet and the high-velocity, high-ionisation material close to the dwarf is easily distinguished from the low-velocity, low-ionisation giant wind features. In binaries with similar components, it is often difficult to disentangle the wind features.
- The dwarf provides a bright UV continuum source upon which varying absorption from the cool circumstellar gas is superimposed. The FUV and UV is especially rich in resonance and diagnostically informative atomic and molecular transitions which would not be visible without the presence of the strong UV continuum.
- Many symbiotics have been well studied across all wavelengths and the orbital elements and geometrical parameters of a large number are well known.

This study is based on a rich ultraviolet spectral dataset obtained with the *FUSE* and *HST*/STIS (*Hubble Space Telescope*/Space Telescope Imaging Spectrograph) observatories (see Figure 1.3). Observations at orbital phases where the white dwarf is located behind a portion of the cool wind take advantage of the finite size of the hot component to probe

different layers of the circumstellar material in absorption. Utilising the high quality of the *FUSE* and STIS data (far superior to the *IUE* datasets; discussed in Chapter 2), it is possible to obtain high enough signal to noise and spectral resolution to resolve the narrow phase-dependent wind absorption features that are superimposed on the UV continuum. This was not possible with *IUE*. The multi-phase observations, coupled with the high spectral resolution of the data, permits the separation of absorption features that are intrinsic to the system from the interstellar features through a direct analysis of those features which shift in sympathy with the period of the binary. In addition, material can be associated with particular regions in the system by inference from the line width and ionisation level, and also by direct measurement of the radial velocity changes in the line positions. Spectra taken at opposing quadratures will show the largest velocity shifts and the observations at minimum phase impose constraints on the inclination angle and the physical extent of the nebular line-emitting regions. The spectra where cool wind absorption features are visible present an opportunity to map the atomic level populations for complex atoms/ions such as Fe II and Ni II, as well as a chance to diagnose the ionisation structure of the circumstellar material. Analysis of the profile shapes and variability of these absorption features can provide information on the dynamics and small-scale structure of the wind. It is also possible to derive information on the large-scale distribution of the wind, and indeed its velocity profile, by analysing the variation of the absorption features, in particular the strong neutral hydrogen transitions. This data can provide spatially resolved observational constraints on the wind throughout the wind-base and acceleration region - precisely the information required by models.

### 1.3.2 Relationship to Isolated Giants

Although it is obvious that the presence of a hot, ionising star will certainly perturb the outer regions of the giant wind to a certain extent, these effects can be minimised by appropriate choice of stellar system (discussed further in the following chapters). However, in order to determine if any derived wind properties can be applied to isolated stars it needs to be quantified by how much the giant is disturbed by the dwarf, both radiatively and tidally. With this in mind the giant star will also be observed and analysed using the same methods as one would apply to a normal isolated star. Analysis of the ultraviolet spectra obtained when the dwarf is eclipsed by the giant makes it possible to view the giant in much the same terms as one would view an isolated star in the ultraviolet. This is especially true for those transitions traditionally used for the diagnosis of chromospheric material (i.e. Mg II 2796 Å, 2804 Å and C II 2226 Å). However, it is in the optical wavelength region that the atmospheres of giant stars are typically observed. This thesis



**Figure 1.3:** **Left:** Artist's impression of *FUSE* in orbit. The background image is the galaxy M31, as viewed in the ultraviolet by the *GALEX* satellite. (Graphic courtesy JHU *FUSE* Project.) **Right:** The Hubble Space Telescope in its low-earth orbit 569 km above the Earth's surface. This picture was taken after the second servicing mission in 1997. (Image courtesy of NASA.)

presents photometric coverage through *UBVR* filters of the binary system as well as high resolution optical spectra which enables the properties of the giant star to be analysed. Photoionisation modelling is also employed in an attempt to test the influence of the WD radiation on the giant wind and to build a model of the binary to use it as a framework for deriving intrinsic cool giant wind properties. Finally, the derived wind and atmospheric parameters are compared to those predicted for isolated stars by the state of the art stellar atmosphere code, PHOENIX.

### 1.3.3 Outline of this Thesis

In *Chapter 2*, the parameters of the chosen binary system are described and the ultraviolet and optical dataset upon which this work is based.

*Chapter 3* deals with the analysis of both the low and high-resolution optical data, as well as the UVBR photometry. The radiative and tidal effects of the dwarf on the structure of the giant atmosphere are examined, and the extent to which the giant star is similar to normal, isolated stars is discussed. The photospheric parameters are determined and the structure is modelled using the PHOENIX stellar atmosphere code.

*Chapter 4* presents the general variations observed in the ultraviolet dataset and develops a working model for the system whereby the influence of the hot component on the cool circumstellar material of the giant star can be assessed.

In *Chapter 5*, an in-depth analysis of the giant wind in absorption is detailed and the variety of techniques which are used to derive the thermal and dynamic conditions and physical extent and distribution of the wind are explained.

In *chapter 6*, the significance of the absorption analysis is explored, and the implications for the theories of mass-loss from evolved stars are discussed.

*Chapter 7* summarises the accomplishments of the work and suggest possible directions that future studies should take in order to further understand the mass-loss problem.

# 2

## Target Star, Observations and Data Processing

To most effectively eclipse-map the outflow from the cool star, it is essential that a suitable binary system is chosen. In this chapter the attributes that such a system must have are outlined and the parameters of the chosen binary star are described. Information on the multi-wavelength observations and also details of the techniques that will be utilised in order are also presented. The chapter finishes with a discussion on how the results and conclusions drawn will have the potential to further our understanding of the conditions and physical mechanisms at work in extended giant atmospheres.

### 2.1 The Choice of Binary System

To successfully use the binary technique to study mass-loss, it is necessary to choose a suitable system that fulfils a number of criteria. These criteria are discussed below.

In order to measure the absorption that diagnoses the cool material in the circumstellar environment of the red giant, there must be sufficiently high signal to noise ( $S/N$ ) in the ultraviolet continuum. In order to provide a sufficient number of ultraviolet photons, the target system must be located relatively close-by, and should be free of large amounts

of obscuring dust, both intrinsic to the system, and also along the line of sight. The choice of an S-type symbiotic, where the primary has not yet lost enough mass to enable the formation of a cool, dusty circumstellar shell, ensures that the system will be free of extinction caused by dust associated by the system. In any case, observations of an S-type symbiotic star is preferred to that of a dusty D-type system. D-type symbiotics contain a more evolved mira-like primary which has evolved onto the AGB, where the wind dynamics are different from those of normal red giants, and the orbital periods tend to be longer. The less evolved S-type primaries most likely contain a giant star on the first ascent of the red giant branch, where dust does not appreciably contribute to the wind acceleration<sup>1</sup>. Choice of a system which is both close to earth, and also out of the plane of the galaxy, reduces the attenuation due to dust along the line of sight.

The orbital period of the system must not be large in comparison to the lifetimes of the observing instruments, or indeed to the duration of the observing cycles. Choosing a system with a relatively short orbital period ensures the acquisition of a dataset with a more complete phase-coverage. Many binary systems, including D-type symbiotics, have orbital periods on the timescale of decades. For such long-period binaries, the lifetime of the observatory and/or its instruments will place constraints on the completeness of the orbital phase coverage. The choice of a binary with an orbital period of one to two years makes it possible to test the stability of the system by making observations at similar phases, but different orbital epochs. These repeat observations enable any events unrelated to orbital phase to be identified. In addition, the process of obtaining observing time with observatories with one year observing cycles is greatly complicated if the observing program extends over a large number of proposing cycles.

The system must also be as stable as possible, permitting the distinction to be made between those variations that are due to orbital phase and those that are due to phase-independent effects. Many symbiotics and other binaries are extremely active objects.

---

<sup>1</sup>Locating the position of a star on the giant branch is not usually a trivial matter. Generally if an isolated giant is chemically peculiar it can be described as being in the thermally pulsating AGB phase (e.g. Iben & Renzini, 1983). Also if a low-mass M star has a luminosity greater than  $\sim L_{BOL} = 10^{3.5} L_{\odot}$ , then it is almost certainly on the AGB (Lattanzio, 1991; Scalo, 1976). A low-mass M star is almost certainly on the AGB if it has a circumstellar shell (i.e. as observed with sub-millimetre telescopes) because the integrated mass-loss on the first giant branch is insufficient to produce a thick shell (e.g. Drake, 1986, and references within). For late K and M stars with luminosities  $\lesssim 10^{3.5} L_{sun}$  the timescale for evolution up the FGB is typically 7-8 times that of the timescale for AGB evolution (Lattanzio, 1991). So, even without information on the presence of a circumstellar shell, it is apparent that most chemically normal K and M giants in this luminosity range are on the first ascent of the giant branch. As noted by Judge & Stencel (1991) ‘...this corresponds to the assumption that stars later than M5 III are mostly on the AGB ( $T_{eff} \lesssim 3,500 K$ ), and earlier spectral types are mostly on the FGB.’

Often the secondary components are heavy accretors of the primary's wind, with nuclear detonation periodically occurring on the star's surface. These outbursts are typically observed as large increases in fluxes across all wavelength regions, accompanied by decreases in the fluxes of the high-ionisation emission lines (this is attributed to a shrouding on the hot gas close to the dwarf). Because the primary goal of this work is to observe a giant wind which is as undisturbed as possible, it is apparent that the choice of a quiescent, non-outbursting system is desirable.

The orbital parameters of the binary must be well known. In order to transform results derived at orbital phases into spatially-resolved information on the giant's wind, it is necessary to know the orbital elements. The orbits of many S-type symbiotics are well-understood.

In order to minimise the effects of the hot star radiation field on the giant wind, the luminosity ratio of the hot to cool star should be as low as possible. Those systems where the hot component is of comparable luminosity to the cool component have giant winds which are greatly modified by the ionising companion. Indeed, in some cases, the photoionised portion of the cool wind can almost engulf the primary component.

The analysis of variable absorption lines is greatly complicated if the features are blended with absorption features that are of interstellar origin. Although it is theoretically possible to remove these features using the uneclipsed observations as templates, the analysis is greatly simplified if the radial velocity of the binary system is well separated from that of the intervening interstellar clouds.

Finally, the inclination of the orbital plane of the binary must be high enough so as the two component stars are observed to eclipse. Taking all these considerations into account, the prime candidate for such an ultraviolet monitoring program is the S-type symbiotic binary, EG Andromedae.

## 2.2 EG Andromedae

The quiescent symbiotic star EG And (HD 4174, SAO 36618) is well documented in the literature (e.g. Munari, 1993; Oliverson et al., 1985; Skopal et al., 1991, 2004; Smith, 1980; Stencel, 1984; Tomov, 1995; Vogel, 1993; Vogel et al., 1992; Wilson & Vaccaro, 1997) and is considered a prototype for stable, non-dusty symbiotic stars. Indeed it was observed extensively with *IUE* where the ultraviolet eclipse effect was used to study the dimensions and wind of the giant star (Vogel, 1991; Vogel et al., 1992). The object is one of the closest and brightest symbiotic systems and consists of a hot, low luminosity white dwarf (Muerse et al., 1991) with an M2.4 giant primary which is on the first ascent of

| Parameter      | Value               | Reference |
|----------------|---------------------|-----------|
| RG temperature | $\sim 3,700$ K      | KP02      |
| WD temperature | $\sim 75,000$ K     | MNSV91    |
| RG Luminosity  | $\sim 950$ $\odot$  | VNM92     |
| WD Luminosity  | $\sim 16$ $\odot$   | VNM92     |
| Period         | 482.6 days          | FJHS00    |
| Separation     | $\sim 4.2$ $R_{RG}$ | VNM92     |
| RG Radius      | $\sim 75\odot$      | VNM92     |
| Inclination    | $> 70^0$            | VNM92     |
| $V_{mag}$      | $\sim 7.1$          | B00       |
| Orbit          | circular            | WV97      |
| E(B-V)         | 0.05                | MNSV91    |

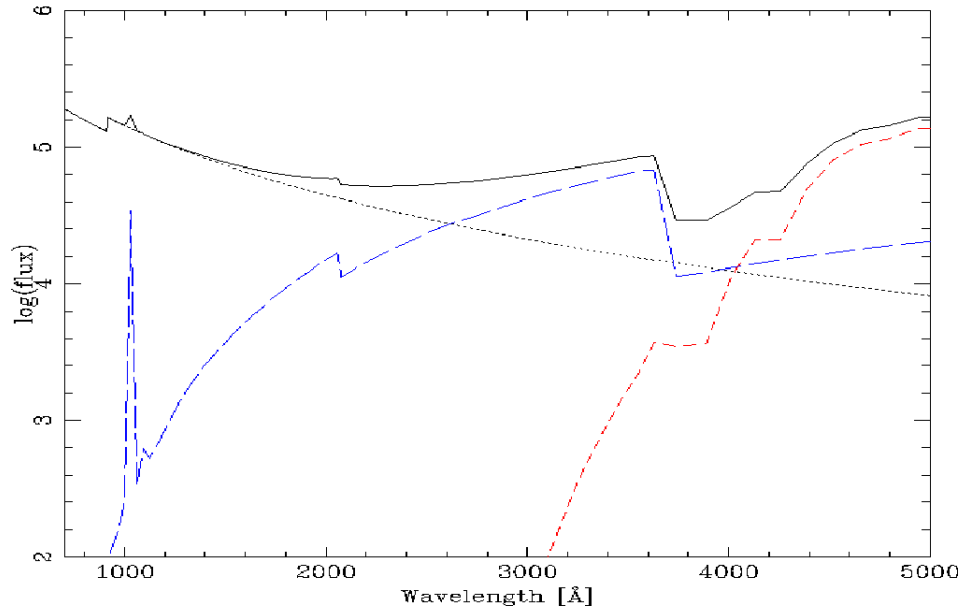
**Table 2.1:** *EG And Parameters.* References - KP02- Keyes & Preblich (2004); MNSV91- Muerse et al. (1991); VNM92- Vogel et al. (1992); FJHS00- Fekel et al. (2000); B00- Belczyński et al. (2000); WV97- Wilson & Vaccaro (1997).

the red giant branch (Kenyon & Fernandez-Castro, 1987; Keyes & Preblich, 2004). The optical spectrum of the giant is very similar to that of isolated M3 spectral standards (see Chapter 3) and far-infrared data from *IRAS* show fluxes very similar to normal isolated red giants (Kenyon et al., 1986). Due to the low-luminosity of the dwarf, the giant’s atmosphere is not greatly affected by the presence of the ionising companion. In fact radio measurements confirm that the ionised region around the dwarf is relatively small and does not dominate the cool wind (Schmid, 2003; Seaquist & Taylor, 1990).

The ultraviolet continuum is known to undergo periodic variations although the system has never been observed to undergo outburst. This periodic variation is attributed to the ultraviolet source being eclipsed by the atmosphere of the primary component (Vogel, 1991) and has been observed extensively over several orbital epochs by *IUE*. Fekel et al. (2000) have determined an accurate orbit for the system based on radial velocity measurements of molecular lines originating in the giant’s photosphere. System parameters are detailed in table 2.1.

The high systemic radial velocity ( $-95$  km s $^{-1}$  relative to heliocentric) permits the wind absorption features to be easily distinguished from interstellar absorption features ( $\sim -30$  km s $^{-1}$  relative to heliocentric), thereby removing the complications that arise when systemic features are merged with interstellar features.

It is also worth noting that the red giant is a member of a binary system, in which mass-transfer between the components has possibly taken place at some stage of the binary evolution. Since both objects formed from common interstellar material at the same time, it follows that the white dwarf component must have been the more massive of the two and evolved more rapidly than its companion. It is thus not inconceivable that large amounts of heavily processed material could have been transferred from the more



**Figure 2.1:** A model of the spectrum of a typical symbiotic star showing the contribution of the different components to the spectrum. The dotted lines display the individual contributions of the white dwarf (black), the photoionised nebula (blue) and the red giant component (red). The summed spectrum from all the components is displayed with the solid black line. The units of flux are arbitrary.

evolved star to its companion during its evolution from red giant to white dwarf. If this was the case then the surface abundances of the red giant would certainly be abnormal and the star could not be taken to be representative of isolated giants. However, it is thought that the material lost by the more evolved star has mostly dissipated into the interstellar medium by the time that the binary reaches the symbiotic phase, and that the cool wind and red giant surface remain relatively uncontaminated. From the analysis of ultraviolet emission line fluxes of a sample of symbiotic stars, Nussbaumer et al. (1988) found that the abundances of the material surrounding the giant are typical of those found in the photospheres of isolated giants. In addition, photospheric abundances of EG And are found to be normal in this study (see Chapter 3).

Reviewing the attributes of the system, most especially noting the low interstellar extinction, the absence of circumstellar dust (Kenyon et al., 1986; van Buren et al., 1994), the low dwarf luminosity and the proximity of the binary, it is apparent that EG And is an ideal candidate for an ultraviolet wind analysis.

## 2.3 The Ultraviolet Observing Program

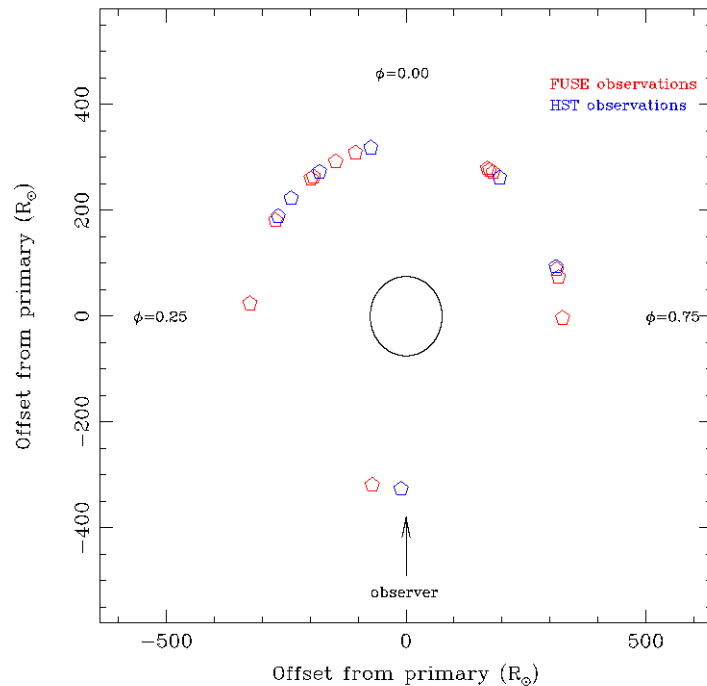
The ultraviolet observing program was designed to cover orbital phases both in and out of eclipse, as well as to test the stability of the system and the repeatability of observations over orbital time-scales. The timing of the observations was designed to include unabsorbed phases (i.e. inferior conjunction and quadrature) as well as phases close to total eclipse, and also, a series of ingress and egress observations, where the strengths of the wind absorption features increase and decrease respectively.

A key point of this work is that the uneclipsed spectra provide a template for comparison with the absorbed spectra as well as providing diagnostics of the hot component and the material close to it. Comparison of the uneclipsed with the absorbed data allows the diagnosis of the absorbing material, namely the giant wind. Analysis is simplified by using the uneclipsed spectra as they enable the study of the *ratios* of spectra to analyse the variations, removing the need to model the unabsorbed continuum, emission and interstellar absorption. The observations where the dwarf is occulted provide restrictions on the geometry of the system and on the location and size of the line emitting regions. In addition, diagnostics can be obtained from the chromospheric emission features which are not blended with emission components from the photoionised region of the wind at eclipse. We have obtained 20 ultraviolet observations of the system between January 2000 and December 2003. These include phases when the dwarf was eclipsed, uneclipsed and at various different stages of ingress and egress. Phase  $\phi = 0.0$  is defined as the point at where the dwarf is at superior conjunction, and is completely eclipsed by the giant, ie. ultraviolet minimum. See Figure 2.2 for a schematic diagram showing the positions of the dwarf star at the time of the ultraviolet observations.

The combined *FUSE* and STIS echelle wavelength coverage (905 Å - 3100 Å) provides access to the transitions of many important atomic and molecular species, including those of the low-ionisation species expected to be present in the giant wind and those diagnosing the hotter gas associated with the dwarf.

## 2.4 *FUSE*

The *FUSE* satellite was launched on June 24, 1999 into a circular 768 km orbit. The Johns Hopkins University in Baltimore, Maryland, who developed *FUSE* for NASA, are responsible for the operation of the observatory. It is funded by NASA with additional support from the French and Canadian space agencies, but through the Guest Investigator program observing time is made available through a competitive peer-reviewed proposal



**Figure 2.2:** View of EG And perpendicular to the orbital plane. Points correspond to the dwarf position for the *FUSE* and *HST* observations. Observer's view is from the bottom and the scale is in units of solar radii. Also see Table 2.2.

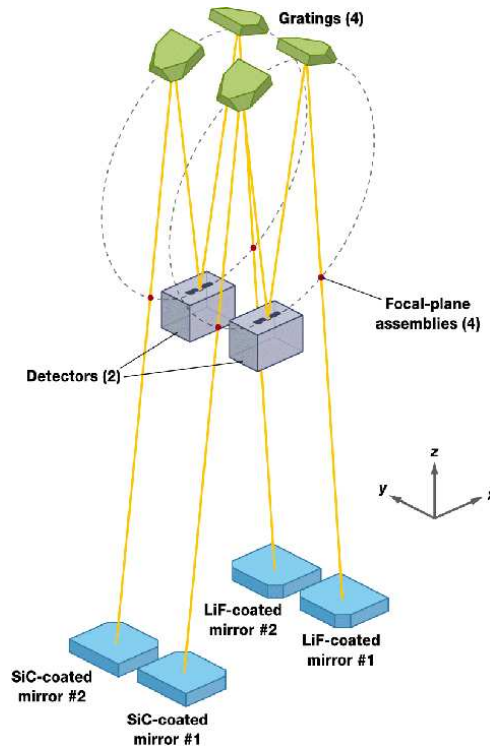
process to investigators worldwide.

*FUSE* offers a reasonably high resolving power of  $\lambda/\Delta\lambda \sim 15,000 - 20,000$  and is the only current observatory covering the spectral region 905-1187 Å. Indeed, since the failure of the electronics on STIS in August 2004 *FUSE* is the only instrument presently providing high resolution spectra in the ultraviolet region of the spectrum. The instrument and operations have been fully described by Moos et al. (2000) and Sahnou et al. (2000).

The far-ultraviolet wavelength region covered by *FUSE* is a crucially important spectral region, especially for diagnosing the differing material in symbiotic systems. The wavelength band contains many important resonance transitions of low-ionisation species, in addition to containing transitions diagnosing the hotter gas in these systems. Some of the strongest lines in symbiotics are CIII 977, CIII\* 1176, OVI 1032, 1038, PV 1117, 1128, SIV 1062, 1072, 1073, SVI 933, 944 (Å). The O VI 1032 1036 Å features are extremely useful for diagnosis of the hot, ionised material. The presence of these strong ( $A \sim 4 \times 10^8 \text{ s}^{-1}$ ) resonance lines of an abundant element in a highly ionised state (ionisation potential = 138.1 eV) permits analysis of the highly ionised material closest to the dwarf. In addition to covering diagnostically important transitions, observations in the FUV directly

probe the continuum of the hot component. The contribution from the cool giant and nebular recombination continua at frequencies this high are essentially negligible. The importance of observing symbiotic systems at these low wavelengths is made apparent by the model spectrum of a typical symbiotic star displayed in Figure 2.1, where the WD spectrum is visible only at very blue wavelengths.

The *FUSE* instrument itself consists of four co-aligned prime-focus telescopes and Rowland-circle spectrographs; see Figure 2.3 for a schematic diagram. Each optical path (or channel) consists of a mirror, a Focal Plane Assembly, a diffraction grating and a section of a FUV detector. This arrangement means that the instrument has eight segments (four optical channels and four detector segments) where four channels cover the wavelength range 1000-1080 Å and two each over the ranges 900-1000 Å and 1080-1180 Å.



**Figure 2.3:** Schematic diagram of *FUSE*. Each side has a SiC and LiF-coated telescope mirror. Light from these mirrors is reflected and dispersed by a grating with the same type of coating. A 2-d image of the dispersed spectrum is then recorded on two micro-channel detectors.

Four of the channels have employed silicon carbide (SiC) coatings, providing reflectivity in the wavelength range  $\sim 905\text{--}1000$  Å, while the other four have lithium fluoride (LiF) coatings for maximum sensitivity above 1000 Å. Dispersed light is focused onto two

photon-counting microchannel plate detectors. Point sources can be observed through three different apertures (LWRS,  $30'' \times 30''$ , MDRS,  $4'' \times 20''$  and HIRS,  $1.25'' \times 20''$ ) and with two different photon recording modes, time-tagged (TTAG) and histogram (HIST). The standard aperture for most observations is LWRS and the data is usually recorded using the TTAG mode in which the position and arrival time of each photon is recorded. Non-standard apertures are only used in cases where the highest possible spectral resolution is required. The accumulated photon counting mode (HIST) is used for very bright targets where the memory arrays of the photon counting devices are in danger of being filled before the data can be relayed to earth.

### 2.4.1 Data Processing and Instrumental Effects

The effects of spacecraft motion are corrected with the CalFUSE pipeline which places the data on a heliocentric velocity scale, screens the data for low quality or unreliable data and performs a background subtraction. For information on the *FUSE* pipeline see <http://fuse.pha.jhu.edu/analysis/calfuse.html>.

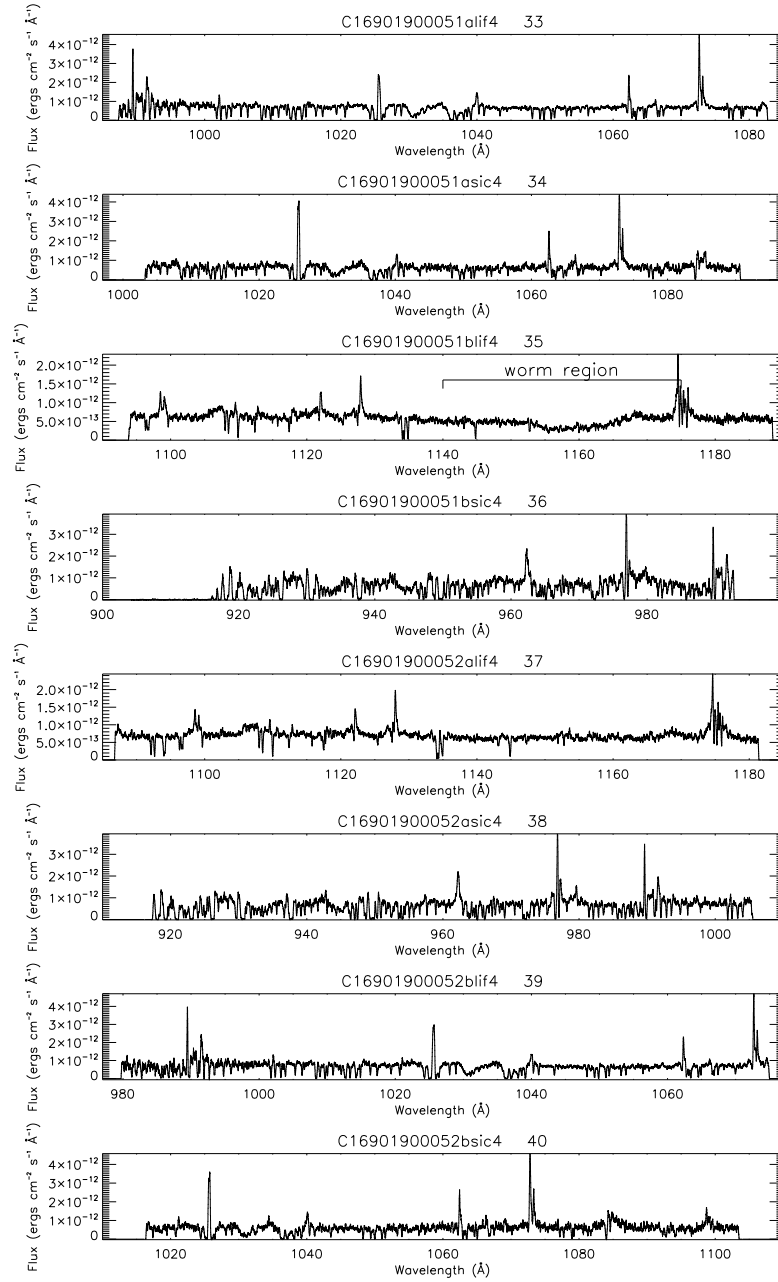
Special care was taken when analysing the *FUSE* data in order to account for some of the instrumental effects that affect *FUSE*. For example, due to a flexing of the optical bench over orbital timescales some channels become misaligned during exposures, leading to the loss of the target for all or part of an exposure in one or more channels. This was corrected by scaling the fluxes for each channel over each orbit to the corresponding flux level observed in the LiF1 channel, which was the guide channel for each observation of EG And.

Another artifact in the data that had to be corrected for is the “worm”, which mainly affects the LiF1b channel. This effect is due to a shadowing by the QE wires at locations over the detectors and can attenuate up to 50% of the flux in the affected wavelength regions. See Figure 2.4 for an example of *FUSE* data of EG And and for a single orbit. The illustrations also show how the worm affects the data. For a full description of all the instrumental effects see the *FUSE* instrument and data handbook<sup>2</sup>.

## 2.5 EG And *FUSE* Data

We have obtained thirteen *FUSE* observations of EG And (see table 2.2). All data were acquired with the target in the large aperture (LWRS;  $30'' \times 30''$ ) in TTAG photon collecting mode over a time period of 3 *FUSE* cycles. The data were reduced and calibrated

<sup>2</sup><http://fuse.pha.jhu.edu/analysis/dhbook.html>



**Figure 2.4:** *FUSE* spectra of EG And for each of the 8 channels over a single orbit. Note the effect of the worm on the flux level over the wavelength region of 1140-1180 Å in the *Lif1B* spectrum (third panel down). Compare this to the *Lif2a* spectrum of the same wavelength region which is not affected by the worm (fifth panel down). These observations were obtained on the final orbit of a 5 orbit observing sequence (Observation number C169019).

with CalFUSE version 3.0.8 (Dixon & Sahnou, 2003). Interstellar absorption lines in the 8 different channels were compared to interstellar features in the STIS data in order to correct for small wavelength offsets due to target drift in the aperture. For most observations the data from each channel were shifted and co-added to increase the signal to noise ratio ( $S/N$ ). However, for those observations where the target was known to drift completely out of the aperture in some channels, the data from each channel were analysed separately. Exposure times were calculated in order to reach continuum  $S/N$  ratios of at least 15 per resolution element for the co-added spectra at wavelength  $\sim 1050$  Å.

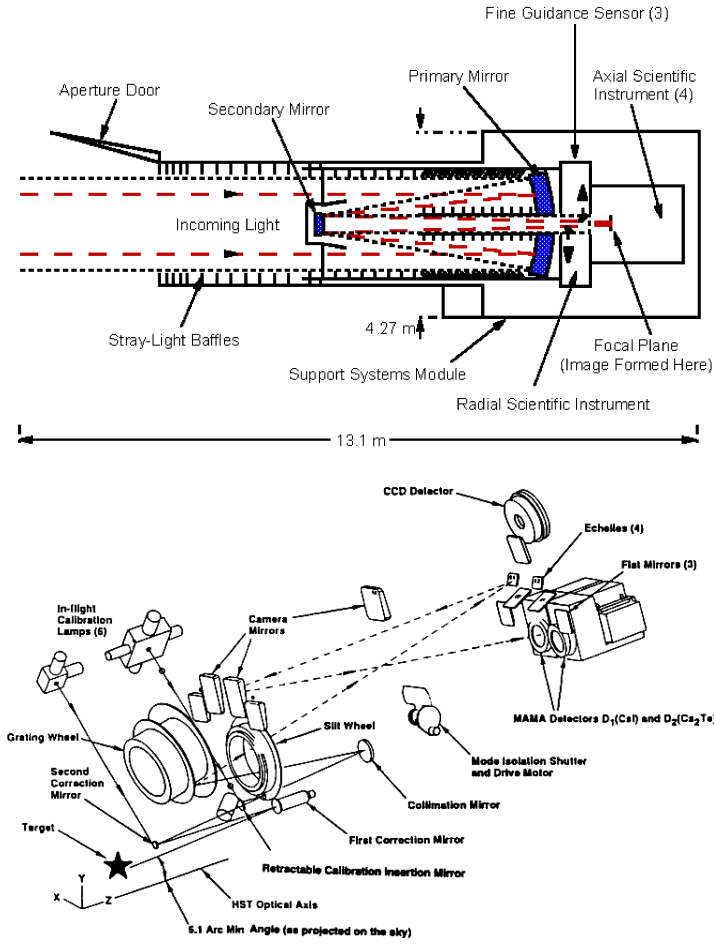
The thirteen *FUSE* spectra provide good orbital-phase coverage, covering phases from close to total eclipse, to partially absorbed spectra, to spectra of the white dwarf unobscured by the giant material. The dataset also contains three observations of the system at very similar phases over 3 separate epochs. These spectra in particular can be used to determine the stability of the system and whether observations taken over different phases can be compared. In addition, three observations at partial eclipse were taken over a time-period of four days, making it possible to study the small-scale distribution of the giant wind.

## 2.6 *HST*/STIS

The *HST* is a multi-instrument observatory containing a 2.4 m reflecting telescope, in orbit at 569 km. The spacecraft contains a number of instruments capable of detecting images and spectra over a wide wavelength region. However, the data for this observing program was obtained using the Space Telescope Imaging Spectrograph (STIS), which was added to *HST* in the second servicing mission in 1997.

The echelle gratings of STIS provide a window on a wavelength region spanning 1150-3100 Å. The bandpass encompasses the transitions of many important atomic and molecular species including neutral and low-ionisation states of H, C, N, O, Si, P, Fe, Ni, Mg, Mn as well as CO and H<sub>2</sub>O. Transitions probing high temperature gas such as C<sup>3+</sup>, Si<sup>3+</sup>, N<sup>4+</sup>, S<sup>3+</sup> and He<sup>+</sup> are also present along with a range of forbidden and semi-forbidden lines which provide valuable nebular diagnostics.

The echelle gratings disperse light in two directions; each spectral order, covering a few Å, is dispersed perpendicular to the wavelength dispersion direction. With this type of grating a large wavelength range can be covered in only one observation and adjacent echelle orders have  $\sim 10\%$  overlap in wavelength. Light dispersed by the echelle gratings is collected by one of the the MAMA photon counting devices. There are two MAMA detectors, the STIS/FUV-MAMA provides coverage from 1150 to 1700 Å and



**Figure 2.5:** Top: A schematic view of the optical design of HST. Bottom: A simplified schematic showing the major mechanisms and detectors of STIS. A medium-resolution echelle mode light path is also shown. (Both graphics courtesy of STScI.)

the STIS/NUV-MAMA provides coverage from 1650 to 3100 Å. A thorough description of the STIS design is provided by Woodgate et al. (1998).

## 2.7 EG And STIS Data

The seven *HST* observations (see Table 2.2) were carried out with the medium resolution echelle gratings (E140M and E230M) of the STIS through the  $0.2'' \times 0.06''$  aperture at the 1425 Å, 1978 Å and 2707 Å central wavelength settings. This resulted in a resolving power of  $R \sim 30,000 - 45,000$  ( $\Delta v \sim 6 - 10 \text{ km s}^{-1}$ ) over the wavelength range  $\sim 1150 - 3100$  Å. The observations were designed to provide sufficient exposure time to achieve a  $S/N$

| Date        | Telescope | Exp. time (Ks) | $\phi_{uv}$ |
|-------------|-----------|----------------|-------------|
| 5 Jan 2000  | FUSE      | 11.0           | 1.79        |
| 6 Aug 2000  | FUSE      | 9.1            | 2.24        |
| 24 Nov 2000 | FUSE      | 5.5            | 2.47        |
| 3 Sep 2001  | FUSE      | 11.1           | 3.05        |
| 14 Sep 2001 | FUSE      | 7.5            | 3.07        |
| 28 Sep 2001 | FUSE      | 9.6            | 3.10        |
| 23 Oct 2001 | FUSE      | 5.6            | 3.16        |
| 23 Aug 2002 | FUSE      | 10.9           | 3.79        |
| 28 Aug 2002 | STIS      | 4.6            | 3.80        |
| 16 Oct 2002 | STIS      | 4.6            | 3.90        |
| 20 Oct 2002 | FUSE      | 8.6            | 3.91        |
| 22 Oct 2002 | FUSE      | 6.7            | 3.91        |
| 23 Oct 2002 | FUSE      | 6.7            | 3.91        |
| 22 Dec 2002 | STIS      | 7.1            | 4.04        |
| 18 Jan 2003 | STIS      | 6.5            | 4.09        |
| 22 Jan 2003 | FUSE      | 3.4            | 4.10        |
| 6 Feb 2003  | STIS      | 7.6            | 4.13        |
| 16 Feb 2003 | STIS      | 7.3            | 4.15        |
| 31 Jul 2003 | STIS      | 4.5            | 4.50        |
| 01 Dec 2003 | FUSE      | 8.9            | 4.75        |

**Table 2.2:** *EG And FUSE and STIS observations. Ephemeris from Fekel et al. (2000). See Figure 2.2 for a graphical representation.*

ratio of at least 15 in the continuum at the central wavelength of the E140M setting. This typically resulted in a combined total of 2 orbits worth of exposure time for all three settings for the unabsorbed phases and a total of 3 orbits for the absorbed phases. The data were reduced within the IRAF environment using the standard Space Telescope Science Institute (STScI) reduction package and routines.

For target acquisition purposes two five second exposures were made using the G430L grating. The spectra are of low resolution ( $R \sim 500$ ) with a wavelength coverage of  $\sim 2900 - 5700 \text{ \AA}$ . The non-standard G430L data reduction is described in a later section of this chapter.

The STIS observations of EG And cover two uneclipsed phases, one at almost total eclipse, and four at phases of partial eclipse. The first STIS observation which was taken at phase  $\phi=3.80$  was taken only five days after one of the *FUSE* observations. These nearly contemporaneous observations provide the opportunity to test the variability of features on short time-scales, as well as making it possible to compare diagnostically important line-profiles over the combined wavelength region (i.e. the resonance lines of O VI, N V and C IV).

## 2.8 Optical Observations

In order to make full use of any wind information derived from the ultraviolet data, it is necessary to have a detailed knowledge of the giant star parameters, and of how the object relates to isolated objects. Cool giant photospheres are typically studied in the optical and infrared wavelength regions where they emit the majority of their photons, where stellar atmosphere models are used to constrain the parameters. Both high and low resolution optical spectra were obtained with different instruments, over varying timescales, in order to study the EG And red giant component.

The optical dataset consists of low resolution spectra obtained with HST and the FAST spectrograph on Mount Whipple, as well as high resolution echelle observations obtained with the 3.5 M telescope at Apache Point Observatory (APO) and the 1 M RITTER telescope. Note that all optical spectra were analysed within the framework of air rest wavelengths. The ultraviolet data were analysed with respect to vacuum wavelengths.

### 2.8.1 Low Resolution Data

A low resolution spectrum of EG And was obtained using the FAST spectrograph mounted on the 1.5 m telescope at the Fred L. Whipple Observatory on Mount Hopkins in Arizona on 3 Jan 1995. These data cover the spectral range  $3800 - 7500 \text{ \AA}$  at a resolution of  $\sim 3 \text{ \AA}$ . The spectrum was calibrated using FAST spectra of several Hayes & Latham (1975) flux standards.

In addition to the echelle data, we also analyse spectra obtained using the long-slit G430L apertures. These low-resolution data span the optical wavelength region of the spectrum where the cooler giant star dominates the spectrum (see Figure 2.1). The acquisition of these data make it possible to monitor the giant star, whose spectral variations can be compared to the variations observed in the ultraviolet data. Due to the brightness of EG And it was possible to make use of the *HST*/STIS target acquisition/peakup data. While these data are usually only used for acquisition purposes, the large flux count made it possible to obtain useful spectra. These data provide spectra within the wavelength range of  $\sim 3200 - 5800 \text{ \AA}$  at a resolution similar to the FAST data.

Since this data is not usually useful for analysis (for dimmer targets), there is no standard reduction procedure. In this case each G430M raw image file was modified to allow CalSTIS to treat it as a G430L image and the header keywords were altered in order for the pipeline to write-out the spectrum. The fluxes were then scaled in order to match the E230M 2707 echelle spectra at the ultraviolet wavelength overlap region and scaled against the B and V band contemporaneous photometry at the long wavelength end of

the spectrum.

### 2.8.2 High Resolution Data

The APO spectra were obtained on July 31 1999 (corresponding to an orbital phase of  $\phi = 0.47$ ), having a spectral resolution of  $R \sim 40,000$ . Using a prism as a cross-disperser, the APO echelle covers all wavelengths from 3500 to 10400 Å spread over 100 orders. On the same night a comparison spectrum was obtained of the high velocity M2 III spectral standard HD 148349 using the same instrumental setup. The telescope and its instrument are fully described by York (1995).

The Ritter Observatory is located on the campus of The University of Toledo. The RITTER data were acquired using an echelle spectrograph on the 1 metre telescope, resulting in 9 echelle orders for each observation, covering the wavelength region around H $\alpha$  at a maximum spectral resolution of  $R \sim 60,000$ . In all, thirteen observations were made of EG And between 1993 and 1995 with orbital phases spanning  $\phi = 0.04$  to  $\phi = 0.83$  (see Figure 3.5 for details).

### 2.8.3 Photometric Data

In addition to the optical spectra, regular UBV $R$  photometry of the binary was obtained between June 2001 and January 2005. The coverage ranged from nightly to weekly, although there are also large gaps in the coverage (few months) during periods when the target was obscured by the sun. The filter images were obtained using the automated 1 M Berkeley Katzman Automatic Imaging Telescope (KAIT), located at the Lick observatory in California. Due to the brightness of the target, short exposures were required, with exposure times for the UBV and  $R$  bands being 60, 7, 1 and 0.5 seconds respectively.

Due to the uncrowded field around EG And it was possible to analyse the images using standard aperture photometry methods<sup>3</sup>. The data received basic processing on site and these images were then further analysed with the APPHOT package in the IRAF (Image Reduction and Analysis Facility) environment, using the standard star HD 4143 as a comparison.

---

<sup>3</sup>See documentation at <http://iraf.noao.edu/docs/photom.html>

# 3

## The Giant Photosphere: Observations and Modelling

This chapter deals with the analysis and modelling of the red giant photosphere, using techniques similar to those that are applied to isolated giant stars. In addition to providing a test of how affected the giant is by the dwarf companion, this analysis provides information on the red giant parameters and evolutionary history. This information makes it possible to quantify the relationship of the giant star in the EG And binary to normal red giants, as well as to define the inner boundary conditions for the stellar wind at the photosphere.

The low and high resolution optical spectra are presented and discussed and the PHOENIX modelling of these data is described. Also presented are the data obtained from the UBVR photometric monitoring of the system and discuss the emission lines which originate in the layers above the photosphere. These features are used to diagnose chromosphere and wind conditions for isolated cool stars and provide another means of testing the strength of the link between symbiotic giants and normal red giants.

## 3.1 Optical Data and Analysis

### 3.1.1 Low Resolution Data

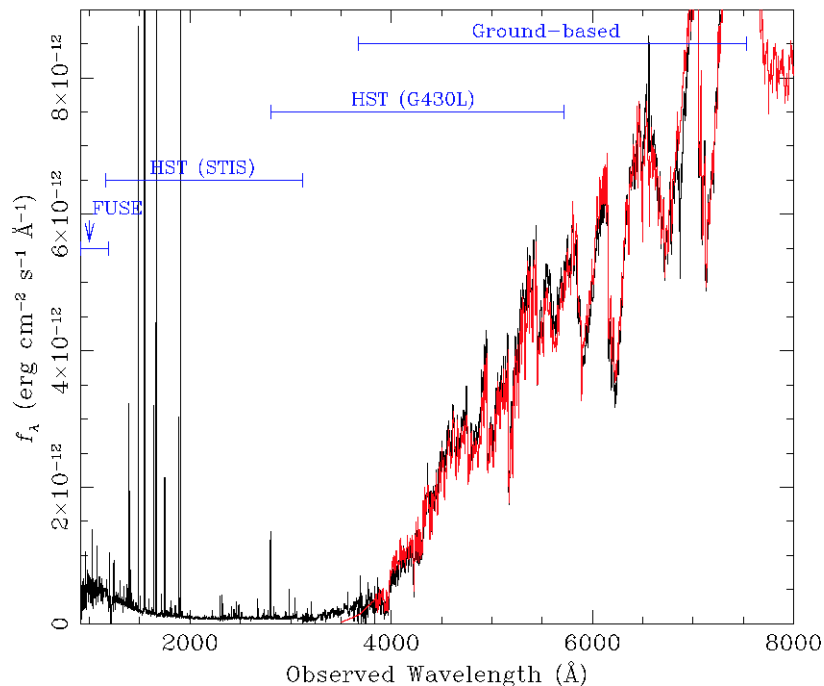
#### 3.1.1.1 FAST data

Analysis of the low resolution optical spectrum of EG And obtained with the FAST spectrograph shows that the spectrum of the giant is not dramatically altered by the presence of the white dwarf. Displayed in Figure 3.1 is a combined spectrum of EG And composed of the FAST data and uneclipsed *FUSE* and STIS spectra. Overplotted in red is a spectrum generated using the average spectra of a number of M3 III spectral standards, which were presented by Fluks et al. (1994) in their survey of bright giants. Both spectra are dominated by strong molecular band absorption (mainly TiO and VO) and the similarity between the spectra in the optical region is readily apparent. To a first approximation at least, this implies that the metallicity of EG And is similar to normal M giants and that the white dwarf radiation does not drastically alter the giant's atmospheric structure. At wavelengths shortward of  $\sim 4000 \text{ \AA}$ , the extra emitting components in the symbiotic spectrum become apparent, with the recombination continua, the white dwarf continuum and the ultraviolet emission lines (originating in the photoionised portion of the giant wind) betraying the binary nature of the system. It is also interesting to note the large difference in the luminosities of the giant (optical flux) and dwarf (ultraviolet flux) for this system.

#### 3.1.1.2 STIS/G430L data

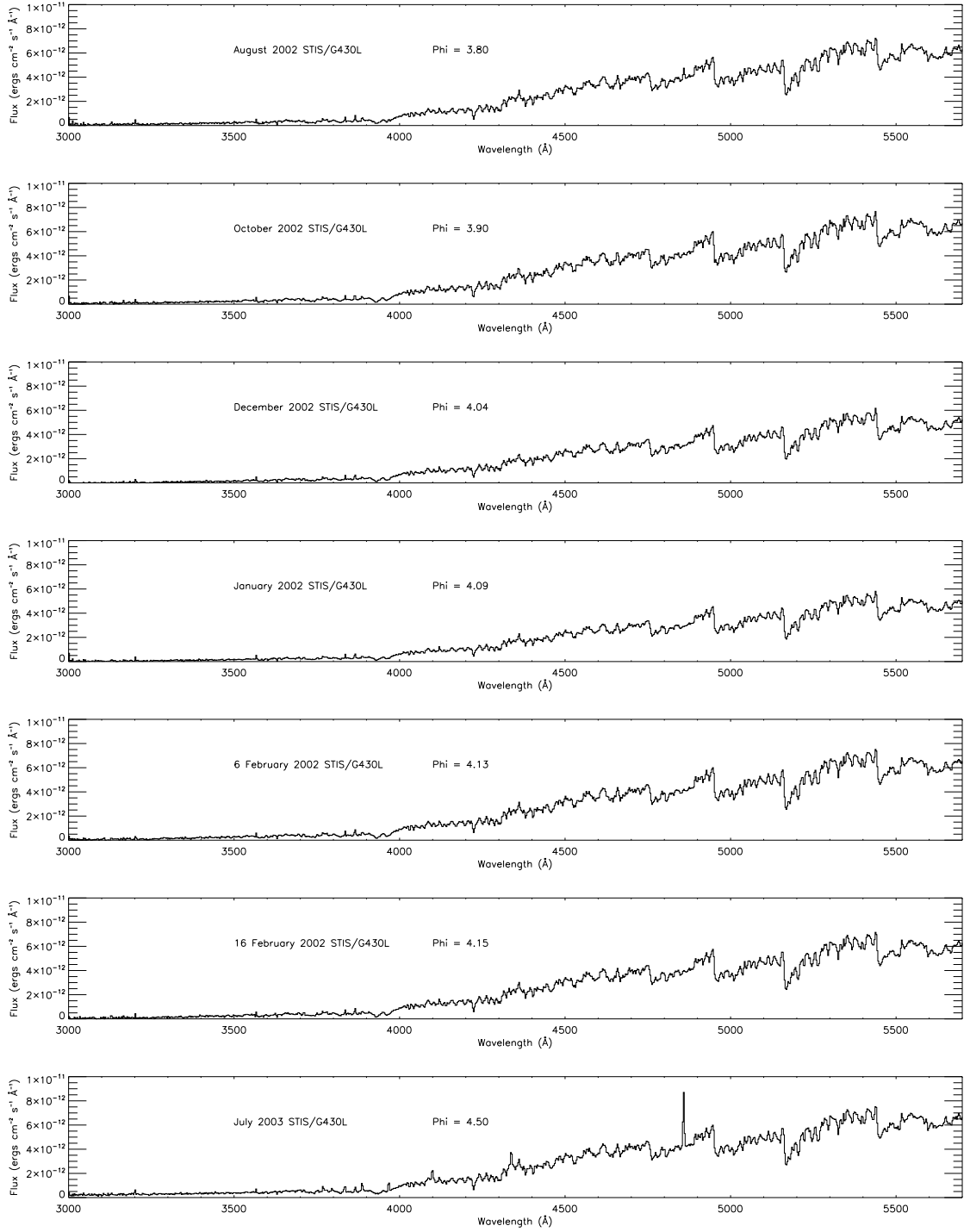
The STIS data were obtained with the G430L grating on board *HST* and provided optical spectra that were contemporaneous to the high-resolution ultraviolet data and are presented in Figure 3.2. This dataset provided an opportunity to test to what extent the eclipse and variations in the hot star affect the giant's atmosphere. The variations in the ultraviolet echelle are presented in Figure 3.3 (see Table 2.2 for observation details). The high resolution ultraviolet data is binned (for clarity) and appended to the optical data. The spectra are subtracted from the reference STIS quadrature ( $\phi=0.80$ ) spectrum to enable the variations to be clearly identified.

The upper five panels in Figure 3.3 display the spectra that were taken at varying degrees of eclipse relative to the August 2002 quadrature spectrum. Note how the ultraviolet continuum is attenuated by varying degrees in all spectra and that the vast majority of the emission features (associated with photoionised material close to the dwarf) are partially eclipsed. The continuum flux in the wavelength region that diagnoses the giant

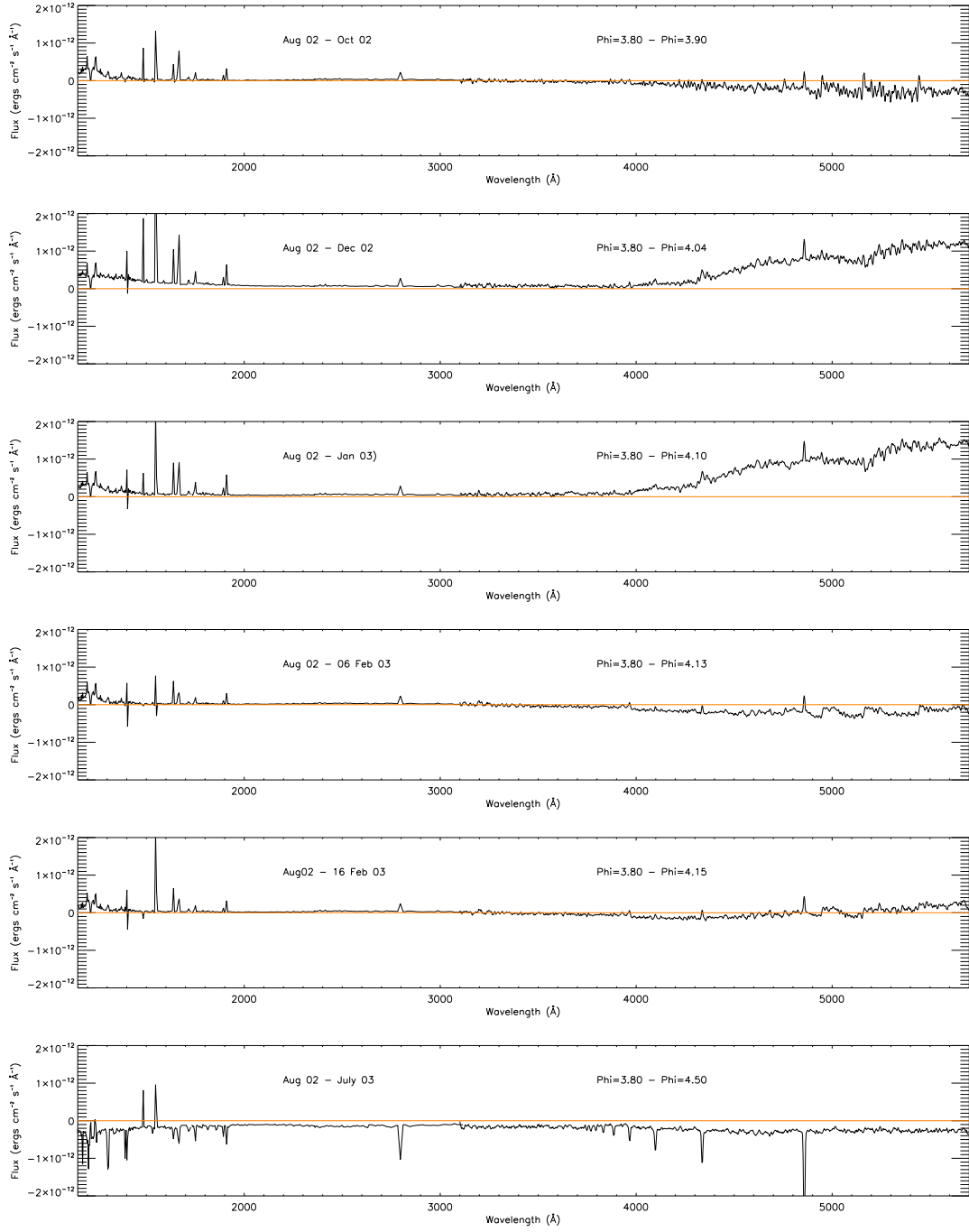


**Figure 3.1:** A multi-wavelength spectrum of EG And stretching from the *FUSE* wavelength region into the optical. The optical region is dominated by the spectrum of the late-type giant. The overplotted data (red) is an averaged spectrum composed of observations of a number of M3 III spectral standards. The close match to the symbiotic giant spectrum suggests that the giant component is relatively undisturbed by the presence of the WD. Note high giant/dwarf luminosity ratio of the stellar components.

( $\lambda \gtrsim 4000 \text{ \AA}$ ) however, does not vary smoothly around the eclipse. The most striking aspects of the changes in this spectral region are the large variations in the fluxes of the continua (however, it must be remembered that the giant is much more luminous than the dwarf, so the relative changes are much less than the displayed data might initially suggest). These variations are unrelated to the eclipse and are consistent with periodic pulsations of the giant that are observed in the photometric data (see section 3.3). Upon closer analysis, it is clear that the shape of the continuum (defined by the blended molecular absorption bands) is also changing, with features such as individual molecular bands changing in strength. These spectral features are primarily sensitive to the metallicity and the temperature of the photosphere. It is therefore apparent that we are observing temperature variations at the photospheric level. A least-squares fitting procedure was applied in order to compare each spectrum with the set of spectral standards published by Fluks et al. (1994) in an effort to quantify the extent of the photospheric variations. It was found that the spectral type varies around the eclipse by  $\sim \pm 2$  sub-spectral types. This



**Figure 3.2:** Displayed are the low-resolution optical STIS spectra of EG And that were obtained with the G430L grating. The data are contemporaneous with the ultraviolet echelle data and allow the behaviour of the giant to be monitored.



**Figure 3.3:** To facilitate viewing of the variations in the G430L spectra, the difference between each spectrum and the August 2002 spectrum are displayed. The ultraviolet echelle data is binned and appended to the optical data to view the changes over the combined wavelength range.

corresponds to a temperature fluctuation of  $\sim 50$  K. It is possible that the temperature changes are related to pulsations (would then also be seen in isolated giants), however, it is most likely that these variations are, at least partially, due to heating by the dwarf radiation field.

### 3.1.1.3 Anomalous July 2003 STIS Spectrum

It can be seen that the STIS spectrum obtained in July 2003 ( $\phi=0.50$ ) displays different characteristics to the other spectra. The July data show flux increases in the continuum (right across the combined ultraviolet and optical wavelength region) relative to the quadrature spectrum. Large increases in the intensities of the nebular emission lines (especially, the hydrogen Balmer recombination lines and the collisionally excited Mg II resonance doublet) are also prominent. In fact, the only features that are weaker than those in the reference spectrum are the emission cores of the high-ionisation C IV and Si IV resonance lines. The large differences that are observed between these two datasets are surprising since both were obtained when the dwarf was out of eclipse and these effects cannot be explained by the eclipse. Since the flux increases occur right across the spectrum, they must be related to the dwarf, to the nebular region where the low-ionisation emission originates and indeed, also to the giant itself.

A modelling of the continuum variation shows that these changes can be explained by an increase in the density of the material close to the dwarf. This increased density (as a result of a temporary increase in the mass-loss rate of the giant) leads to increased accretion onto the dwarf and also to an increase in the emission line fluxes in the vicinity of the white dwarf. A comparison between the optical region of the spectrum and the other displayed spectra show that the increase in the optical flux in the July 2003 spectrum is consistent with the magnitude of the optical flux variations that are occurring in the other spectra. These optical variations are not related to the circumstellar material, but to changes in the atmosphere of the giant (such as pulsational activity). These variations that are observed in the July 2003 STIS data are discussed further in Chapter 6.

## 3.1.2 High Resolution Data

### 3.1.2.1 APO Data

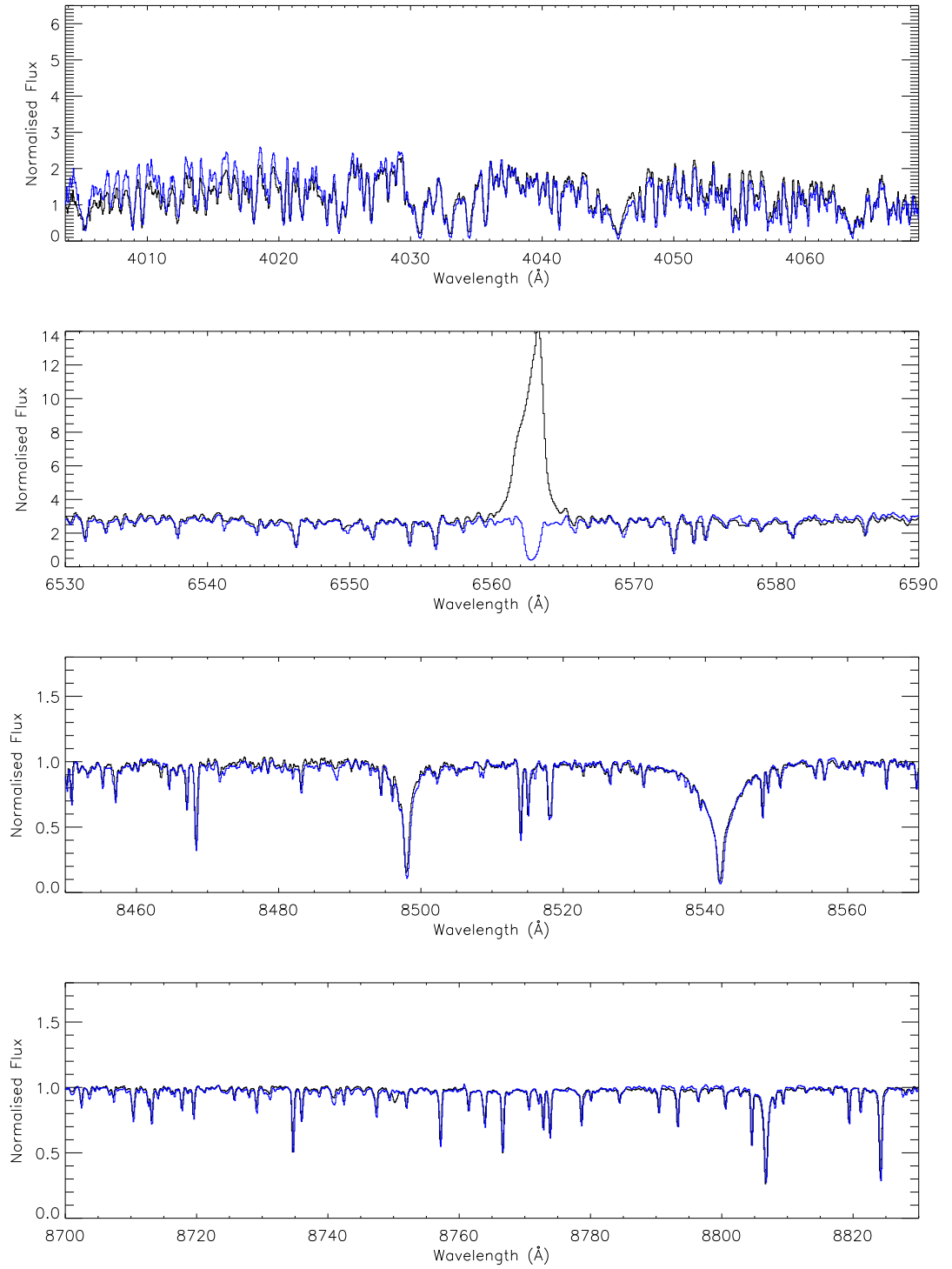
The APO echelle data cover the complete wavelength region from 3,500 Å to 10,400 Å at high resolution. A study of this dataset permits a more in-depth analysis and modelling of the photosphere. However, even prior to a full modelling process, the extent to which the EG And giant is similar to isolated giants can be viewed by a direct comparison of

the EG And APO spectrum with the spectrum taken of HD 148349, which was observed on the same night, and with the same instrument. Displayed in Figure 3.3 are sections of the echelle data of EG And (black) and HD 148349 (blue).

The similarity between both datasets is remarkable over the complete spectral range covered, including wavelength regions around molecular bands (top panel of Figure 3.4 for example), for weak lines from neutral species such as Fe I and Ti I (examples in all panels) and in regions around broadened features such as the Ca II lines in the near-infrared spectral region (third panel from the top). These Ca II lines are sensitive to both the atmospheric pressure (surface gravity) and also to the metallicity. The only large differences between the two spectra are in those regions where EG And displays strong nebular emission lines, such as illustrated in the wavelength region around the hydrogen Balmer line shown in the second panel of Figure 3.3. This emission is due to the binary nature of EG And it is not a photospheric feature. Both stars, therefore, possess very similar photospheric parameters (including metallicity) and since both are high-velocity objects with similar abundances, they most likely belong to the same stellar population.

HD 148349 is a bright (V magnitude  $\sim 5.27$ ), high-velocity ( $+99 \text{ km s}^{-1}$ ) M2 III spectral standard. Dumm & Schild (1998) list the star as having a radius of  $R=83 R_{\odot}$ , a  $T_{eff}=3,720 \text{ K}$ , and a mass of  $M=2 M_{\odot}$ , with optical magnitude of 5.45 magnitudes (with a variability of 0.11 magnitudes). The star is also known to belong to the old disk population (Mennessier et al., 2001), to which EG And also belongs (Wallerstein, 1981), and which agrees with the stellar parameters derived here (section 3.2.1). From a direct viewing of the spectra, it appears that the EG And giant possesses similar parameters. It is also worth noting that a rotational broadening of the narrow absorption lines in the APO EG And data imply a photospheric rotational velocity of  $\sim 7.5 \text{ km s}^{-1}$ . If the system is assumed to be tidally locked and co-rotating (the timescale for this process to occur is short for symbiotics and all can be assumed to co-rotate), then the implied radius of the giant is  $\sim 70 R_{\odot}$ , consistent with that derived from the eclipse geometry (Vogel et al., 1992).

From this spectral comparison, it can be inferred that the atmospheric structure remains relatively unperturbed by the ionising companion. It seems likely that any wind/chromospheric conditions derived from the ultraviolet data can be extrapolated to isolated stars as long as the effect of the dwarf radiation on the wind (which is further away from the photosphere) is understood.



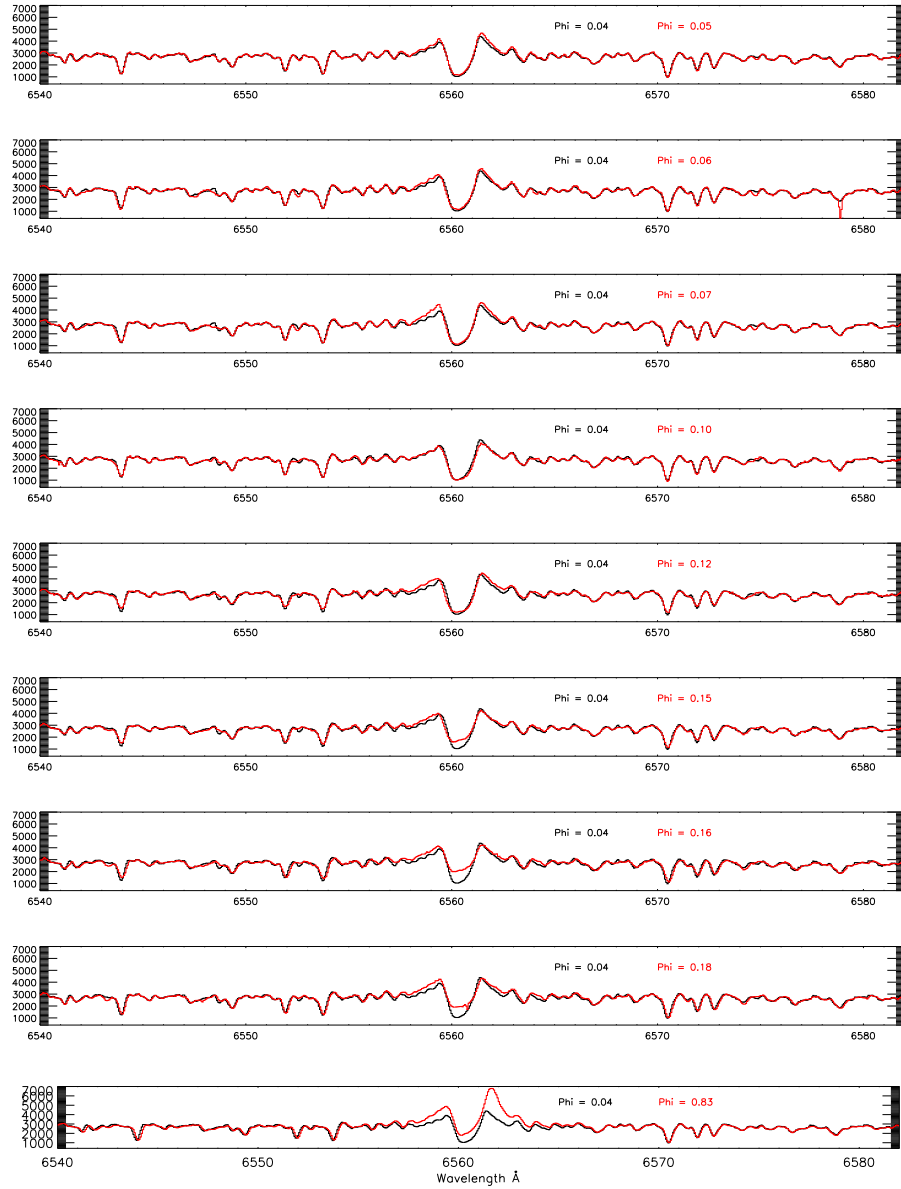
**Figure 3.4:** Sections of the high-resolution APO echelle data are plotted in black. Overplotted in blue is the spectrum of the M2 III spectral standard HD 148349.

### 3.1.2.2 RITTER Data

The high-resolution RITTER spectra sample a time-span of 2 years, spread over 12 observations, however the spectra which provide coverage of the region near the hydrogen  $\alpha$  Balmer feature were all observed within 10 weeks of one another. While the wavelength coverage is very much less than that provided by the APO observation, the repeat RITTER observations provide an opportunity to test for any possible changes occurring in the photosphere, which may or may not be related to orbital phase. It is found that all the repeat spectra are very similar, implying that the photosphere is not undergoing large variations. Example spectra are plotted in Figure 3.4, where the wavelength region close to the hydrogen Balmer feature is displayed. These spectra were observed between 24<sup>th</sup> September 1993 and 2<sup>nd</sup> September 1993, which correspond to the egress orbital phases  $\phi=0.04$  to  $\phi=0.18$ . A series of spectra are plotted (in red, and in temporal order) along with the spectrum obtained closest to eclipse (in black) which is plotted in each panel in order to facilitate easy comparison. Although hydrogen Balmer itself (originating in an ionised section of the red giant wind, near the dwarf) undergoes large changes, the photospheric features stay remarkably constant right throughout egress. Even though the spectral regions covered by the RITTER echelle are not as sensitive to very small temperature changes (that some molecular band strengths diagnose), the fact that the photospheric spectra remain constant over this timescale shows that the structure of the atmosphere is relatively stable throughout the orbital phase space.

## 3.2 Photospheric Modelling

The derivation of photospheric parameters is an iterative process. Traditionally, stellar atmospheres are defined by four main parameters: temperature, surface gravity ( $g$ ), microturbulence and metallicity ( $Z$ ). All of these parameters are interdependent. Thus, it is necessary to iterate on each parameter to find a self-consistent solution. A discussion of the process is treated in Gray (1976). Typically spectral diagnostics that depend strongly on one parameter are chosen to constrain the parameters for the first iteration and a solution can then be found quickly. For cool, extended atmospheres that contain molecules, however, the situation is more complex than it is for hotter stars. In addition to the complications that the presence of molecules introduces into the computational modelling, the molecular features from a large number of blended transitions mutilate the underlying continuum and make identifying the original continuum an uncertain process. Since the strengths of the weak lines are used to obtain stellar parameters, the uncertainty that the molecular opacity introduces to the continuum determination is propagated into



**Figure 3.5:** High-resolution RITTER data of EG And at a number of different phases. The data (red) are overplotted on the first RITTER spectrum (black) in each panel to facilitate the viewing of spectral changes. While the Hydrogen Balmer profile (formed in the photoionised region of the outer giant wind) is observed to vary, the narrow absorption features (formed in the giant photosphere) remain constant (the far-reaches of the red giant wind (close to the dwarf) are heavily influenced by the dwarf radiation, the atmosphere of the giant appears relatively unperturbed). The data in black were obtained at phase  $\phi=0.04$ , while the data in red cover phases  $\phi=0.05$  to  $\phi=0.83$  (top to bottom).

the parameter determination. When one considers the large number of molecular features and the inherent problems that arise due to the lineblends, it is possible to realise that the stellar parameters cannot be obtained as accurately as they can for hotter stars. However, by taking advantage of the latest codes and computational power, it is possible, using spectral synthesis techniques as often as is possible, to determine the stellar parameters.

The initial estimates of the stellar parameters were obtained by using a chi-squared procedure to fit the low-resolution FAST spectrum to a set of Kurucz models (Kurucz, 1993) in a grid that coarsely covered effective temperature, surface gravity and metallicity. The closest fitting Kurucz model atmosphere ( $T_{eff}=3750$  K,  $\log(g)=1$ ,  $Z=-0.5$ ) was then used in conjunction with the latest version of the spectral synthesis and analysis code MOOG (Snedden, 1973) to further analyse the spectrum using atomic data of Kurucz & Bell (1995). The MOOG analysis primarily consisted of using the equivalent widths of Fe I and Ti I absorption features to refine the stellar parameters. Most of the lines that were measured were situated at the long wavelength end of the echelle data near the strong Ca II lines at  $\sim 8,500\text{\AA}$ . This region is remarkably free from telluric lines and at these wavelengths the continuum is least affected by molecular absorption (Munari & Tomasella, 1999).

Unfortunately, the photosphere is too cool for any Fe II absorption features to be measured; thus precluding the use of the traditional method of applying the Fe I/Fe II equilibrium method to constrain the surface gravity. However, the Fe I and Ti I lines could be utilised to refine the effective temperature by requiring that no trend between the derived abundance and the line's excitation potential was present. The microturbulent velocity was then estimated by requiring that the abundance was independent of equivalent width. Although there was scatter in the derived abundances of iron and titanium ( $\sigma \sim 0.3$ ) due to a combination of continuum placement error, atomic data errors and line blending, the metallicity was consistently located in the range from  $Z = -0.6$  to  $-0.3$ .

In an effort to determine the inner boundary conditions for the wind, and indeed to further understand the giant's structure, a further analysis of the APO spectrum was undertaken using the latest stellar atmosphere code that is suitable for cool star modelling. The eventual aim of the modelling was the construction of a static model atmosphere using the PHOENIX stellar atmosphere code. PHOENIX, which is fully described by Brott & Hauschildt (2005, and references within), is a general-purpose state-of-the-art stellar and planetary atmosphere code which offers many advantages over other model atmosphere codes when it comes to modelling cool stars. The code treats dust as well as a large number of molecular and atomic species, and also deviates from the LTE (Local

Thermodynamic Equilibrium) assumption for a number of important species.

### 3.2.1 The PHOENIX Model

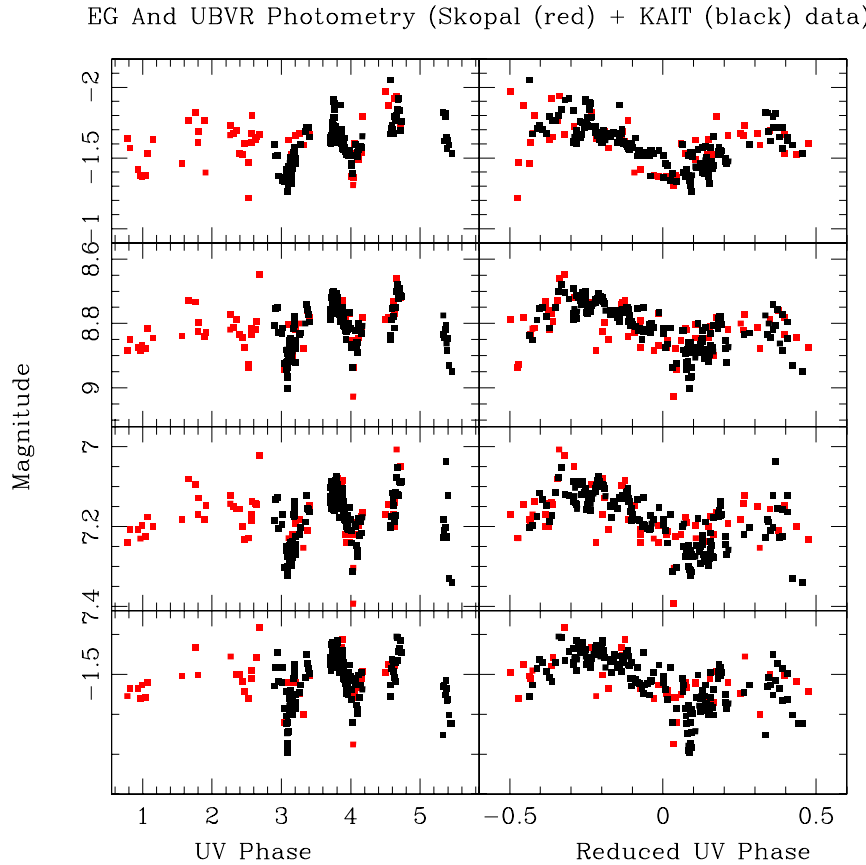
Using the information derived on the stellar parameters from the high resolution spectral analysis, a grid of static PHOENIX model atmospheres were generated and provided by Peter Hauschildt (private communication). The models covered a range of photospheric temperatures, surface gravities and metallicities ( $\Delta T=100$  K,  $\Delta(\log g)=0.5$  and  $\Delta Z=0.2$ ) and a spectrum for each model was generated using a microturbulent broadening parameter of  $2 \text{ km s}^{-1}$ , with a wavelength coverage of 4,000-9,000 Å. These synthetic spectra were compared to selected wavelength regions of the APO spectrum of EG And and, using a chi-squared procedure, the best fit parameters were determined to be  $\log(g)=1.0$  and  $T_{\text{eff}}=3,600$  K, with a metallicity of  $Z=-0.4$  (uncertainties of the order of the grid spacing). The stellar radius implied by the model is  $64 R_{\odot}$ , consistent with the radii determined observationally, within the uncertainties.

## 3.3 Photometry

The *UBVR* photometry spans 3 orbital cycles and provides coverage on weekly and sometimes daily timescales. This provides an opportunity to monitor the behaviour of the giant itself over these timescales, as well as the recombining material that contributes to the U-band. It is the giant's spectrum that completely dominates the optical wavelength region (emission lines contribute only  $\sim 0.1\%$  of the B- and V-band flux), but the hydrogen recombination region emits radiation within the detection range of the U-filter. This recombining material is located relatively close to the dwarf, in the outer region of the giant wind, and means that it is possible to monitor the hot material also, albeit indirectly. The *UBVR* KAIT photometry (differential magnitudes;  $\text{Mag}[\text{standard}]-\text{Mag}[\text{Eg And}]$ ) is presented in Figure 3.6 (black), along with data published by Skopal et al. (2004) (red) for comparison.

From analysis of the data, it emerges that the strongest photometric effect is due to an ellipsoidal distortion of the giant, as previously found by Wilson & Vaccaro (1997). The variation is smooth over phase-space, is present in all filters, and has a period of  $\sim 240$  days, which is half of the orbital period. The magnitude of the variations is consistent with the giant being tidally distorted on the  $\sim 7\text{-}8\%$  level. This is not expected to alter the internal structure of the star significantly (Hauschildt, private communication).

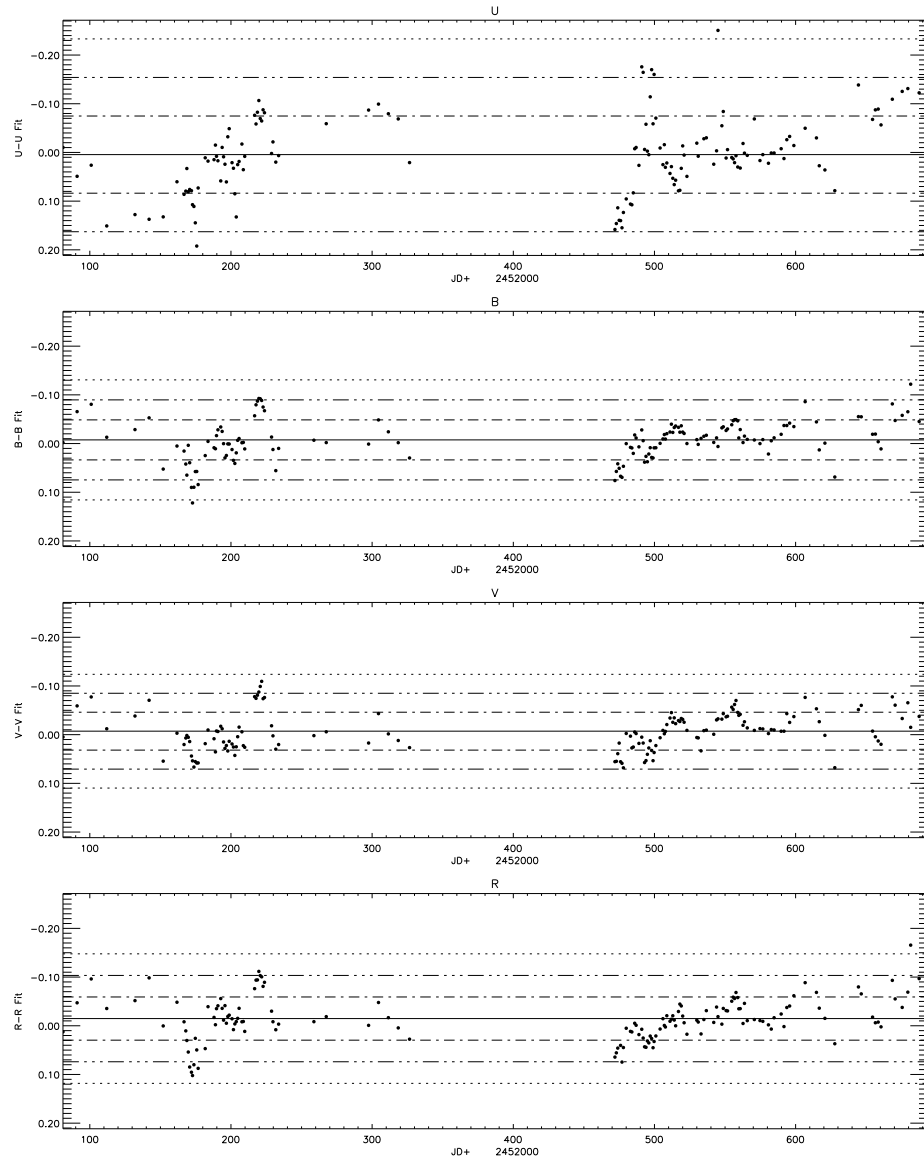
Superimposed on the ellipsoidal variation, are smaller variations displaying a period of  $\sim 28$  days. These variations occur in all filters and are  $\sim 0.1$  in the R band magnitudes



**Figure 3.6:** *Differential magnitudes of EG And for (from top to bottom) UVBR. The left panel contains the KAIT data plotted against UV phase with the Skopal data plotted in red. The right panel contains the same data, but phase-wrapped.*

(see Figure 3.7). These variations are consistent with radial pulsations of the photosphere, where the surface is distorted by  $\sim 2\text{--}3\%$ . Since all stars later than K0 are known to pulsate (Koen & Laney, 2000; Percy et al., 2001; Percy & Parkes, 1998) and the amplitudes increase with spectral type, this observation is not unexpected for an M giant.

The U-magnitude, on the other hand, might be expected to display different characteristics since a significant contribution of the light will originate in the hydrogen recombination region close to the WD. Indeed, although the ellipsoidal and pulsational variations are observed in the U-band, the behaviour is much more erratic and the source undergoes changes in brightness (see Figure 3.7) of up to  $\sim 0.17$  magnitudes. These ‘flares’ are unrelated to orbital phase, but do seem to have a similar period to the pulsational variations that occur in all bands. This is discussed further in chapter 6.

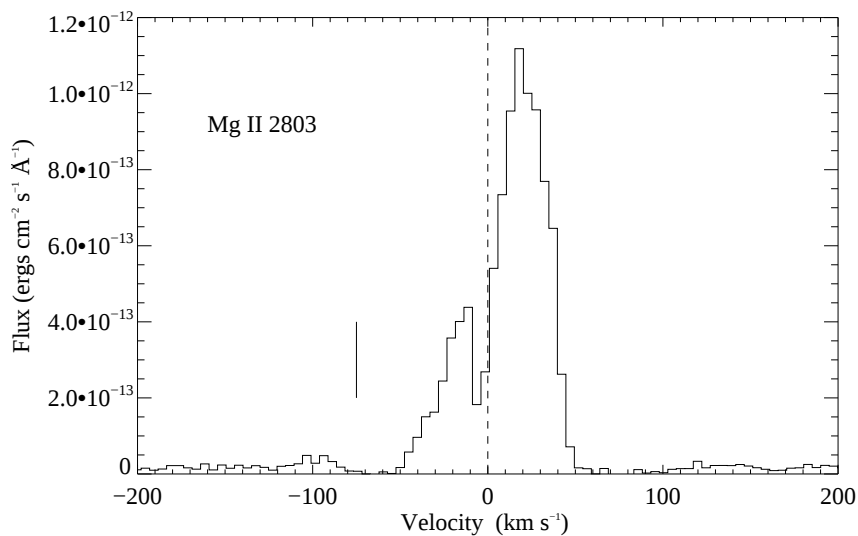


**Figure 3.7:** *Plots of the residual data after the subtraction of a fit to the ellipsoidal variation (period of 240 days; half of the orbital cycle).*

### 3.4 Mg II h and k Lines

The uneclipsed ultraviolet spectra provide an opportunity to view the chromospheric emission lines as they would be observed in isolated stars. The collisionally excited Mg II resonance doublet is a well recognised tracer of cool winds. The fact that  $\text{Mg}^+$  is the predominant ionisation stage of magnesium in cool star chromospheres, in combination with the high probability of radiative decay of the transition ( $\sim 2.5 \times 10^8 \text{ s}^{-1}$ ) makes it a prime diagnostic for determining the terminal velocities of such winds in isolated stars

(Dupree & Reimers, 1987). The Mg II resonance doublet in the eclipsed spectrum is mainly chromospheric in origin and the profile at this phase is the least contaminated by any component from the ionised section of the wind. The position of the dwarf at this orbital phase (almost directly behind the giant) also means that any blue-shifted absorption component superimposed on the chromospheric emission will not be affected by the hot star, and will diagnose the unaffected cool outflow from the giant. Standard measurement of the velocity location of the absorption profile (Dupree & Reimers, 1987) results in a terminal wind velocity for the giant of  $\sim 75 \text{ km s}^{-1}$  (see Figure 3.8).



**Figure 3.8:** *Mg II resonance line at 2804 Å plotted in the rest frame of EG And. The Mg II resonance doublet is commonly used to diagnose the terminal velocities of cool winds. The derived value for the terminal velocity of the giant in EG And of  $75 \text{ km s}^{-1}$  is marked on the plot.*

### 3.5 Conclusions

Analysis of high and low-resolution optical spectra shows that the atmospheric structure of the giant star is not severely perturbed, either radiatively or tidally, by the presence of the binary companion. It emerges that, although the photosphere is heated slightly and the atmosphere is elliptically distorted on the 7-8% level, these effects are minimal. The photospheric spectrum remains similar to that of isolated stars and the atmosphere can be modelled as a normal giant. The photometry shows pulsational activity of the giant, which is typical of similarly evolved stars, as well as relatively large periodic variations in

the U-band. The ultraviolet emission line (i.e. C II 2326 Å and Mg II) fluxes at eclipse approximate those seen in isolated stars. The evidence shows that the giant atmosphere is only slightly disturbed by the presence of the dwarf and that it can be used as a proxy for analysing the circumstellar conditions of red giants in general.

# 4

## Modelling the UV Spectral Variations

Presented in this chapter is an overview of the complete ultraviolet dataset and a discussion of the spectral variations that are observed in the data. The data consist of a multi-component continuum, nebular emission lines and broad wind lines, all of which enable the diagnosis of both the hot gas and the low-excitation absorbing material. All these spectral components undergo dramatic variations, most of which are due to the eclipse of the dwarf star by the cool giant. I will provide an overview of these variations and attempt to place them in the context of a model that permits the separate components of the system to be disentangled. I will pay particular attention to the hot ionised material and in doing so, evaluate the effects of the white dwarf radiation on the red giant and its outflow. The variations of the spectral features in the ultraviolet can be divided into those related to the eclipse and those that are unrelated to the orbit of the binary components.

### 4.1 The Ultraviolet Observations: The Eclipse Effect

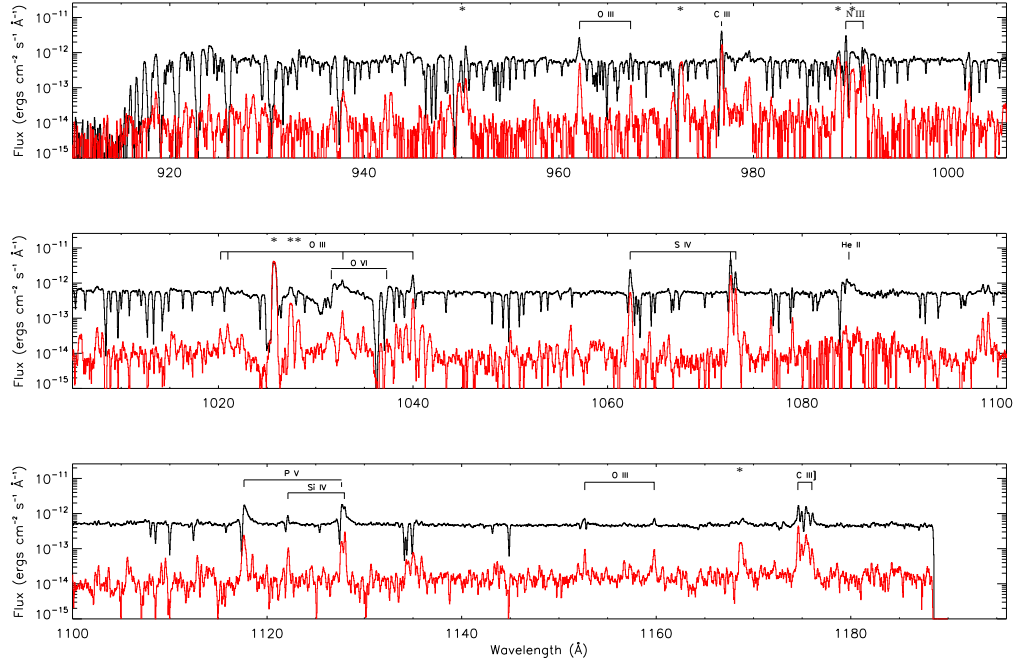
The ultraviolet continuum and emission lines are both modulated by the periodic eclipse of the hot material by the red giant and its extended atmosphere. In those spectra obtained outside of eclipse, the ultraviolet region is dominated by the continuum of the

dwarf. Superimposed on this continuum are emission and absorption features from high-ionisation species and narrow interstellar absorption lines. The continuum is observed to rise towards blue wavelengths into the *FUSE* range where it is severely attenuated by interstellar absorption approaching the Lyman limit. The narrow interstellar absorption lines originate from species such as H I, H<sub>2</sub>, C II, N I, N II, O I, Si II, P II, Ar I and Fe II and are consistent with a warm ( $\sim 500$  K) absorbing cloud with a radial velocity of  $\sim -30$  km s<sup>-1</sup>. In addition, emission and P-Cygni features from species such as C III, N III, O IV, P V, Si IV, and O VI originating from material in the photoionised portion of the giant wind and/or the hot gas close to the dwarf are all prominent in the *FUSE* data outside of eclipse. In the ultraviolet wavelength region covered by STIS, the white dwarf continuum falls off to red wavelengths where the hydrogen recombination continuum also contributes. Permitted and semi-forbidden emission lines from ions such as He II, C II, C III, C IV, N III, N IV, N V, O I, O II, O III, O IV, Mg II, Si IV and Fe II are all prominent.

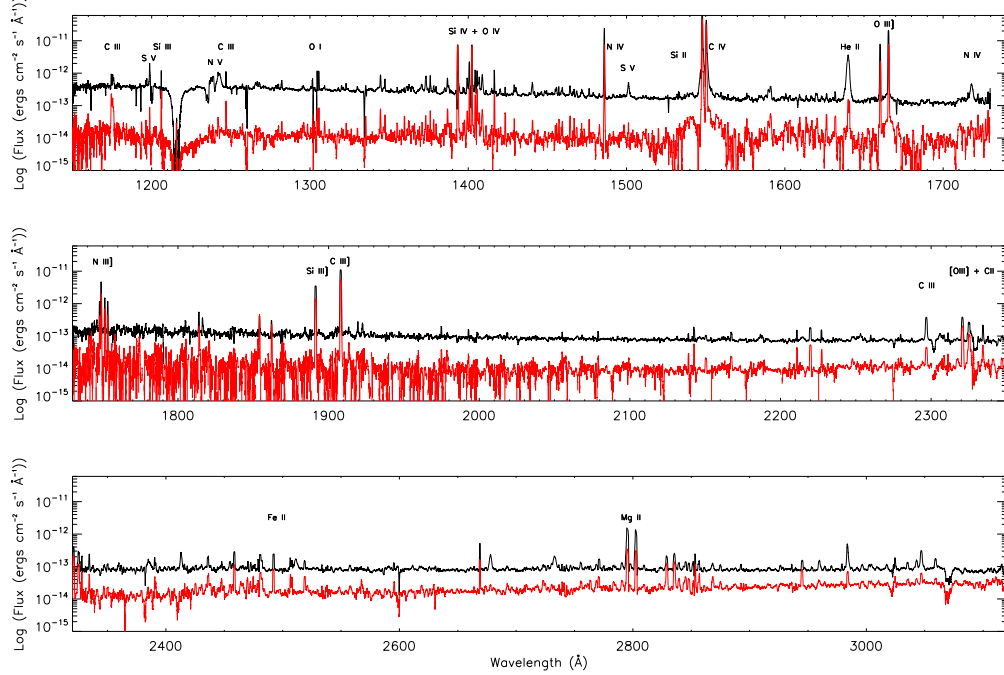
These features are all affected by the eclipse, during which the broad components of the high ionisation lines completely disappear. During eclipsed phases ( $\phi \leq 0.16$ ) the continuum shape is defined by the damped wings of the hydrogen Lyman series transitions as the dwarf is obscured by large amounts of neutral material in the giant's wind. The large increases observed in the hydrogen column densities are accompanied by the appearance of a host of narrow absorption lines from neutral or lowly ionised species. The strength of these features vary in tandem with the strength of the neutral hydrogen lines.

Presented in Figure 4.1 and 4.2 are plots of quadrature and eclipsed spectra taken with *FUSE* and STIS respectively. The fluxes are plotted on a log scale to facilitate display of the strong emission lines. Note especially the eclipse of the ultraviolet continuum and the high, ionisation lines (i.e. He II 1640 Å), whereas lines of species of lower ionisation (i.e. Mg II 2800 Å) are less affected by the eclipse. The increasing strength of the eclipsed continuum towards red wavelengths is also apparent from the STIS spectrum. At red wavelengths the contribution of the dwarf to the continuum decreases and the dominant contributors are the nebular recombination continuum and the continuum of the red giant itself, explaining why the eclipsed continuum is less affected at red wavelengths.

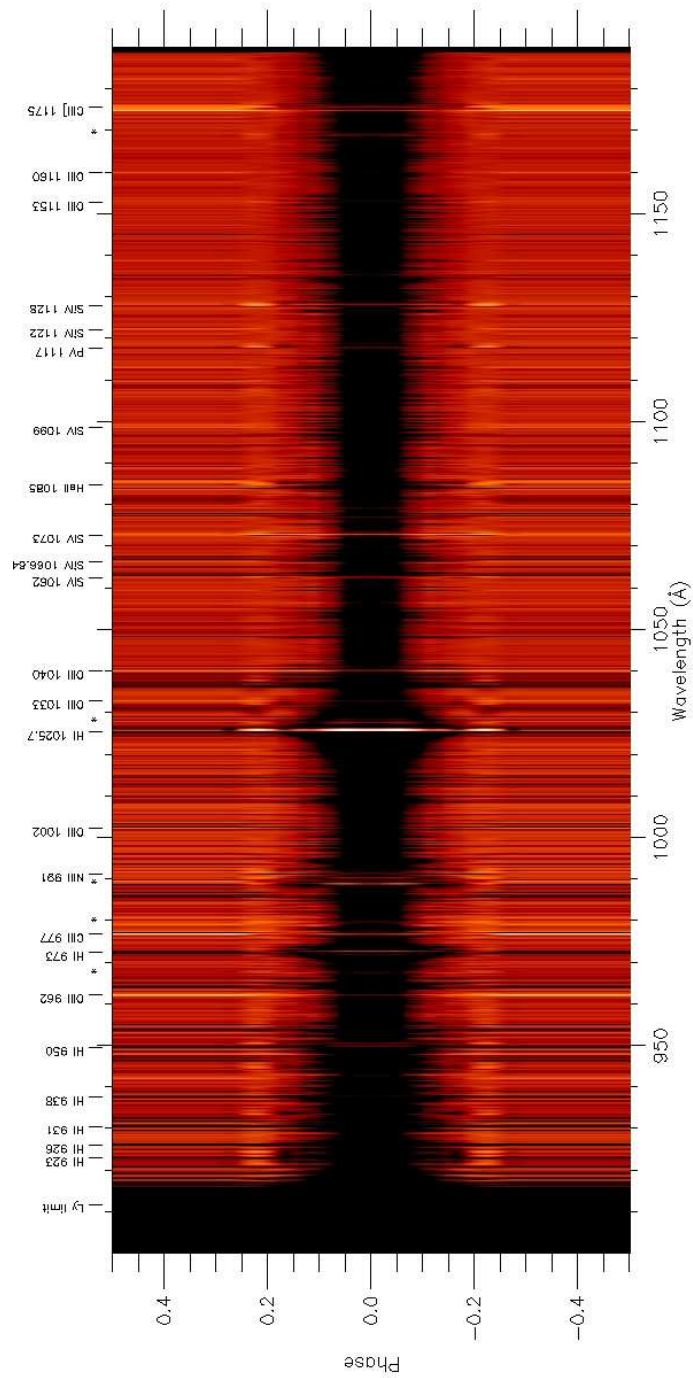
In order to provide an overview of the complete ultraviolet dataset, graphical representations of the variations in the *FUSE* and STIS data were generated, which are presented in Figures 4.3 and 4.4 respectively. The top panel of Figure 4.4 shows the full STIS echelle dataset, the middle panel shows only the E140M data, while the lower panel shows the region of the E140M spectrum close to the He II 1640 Å feature. The flux levels are represented by colour intensities and are displayed on a log scale. The data are



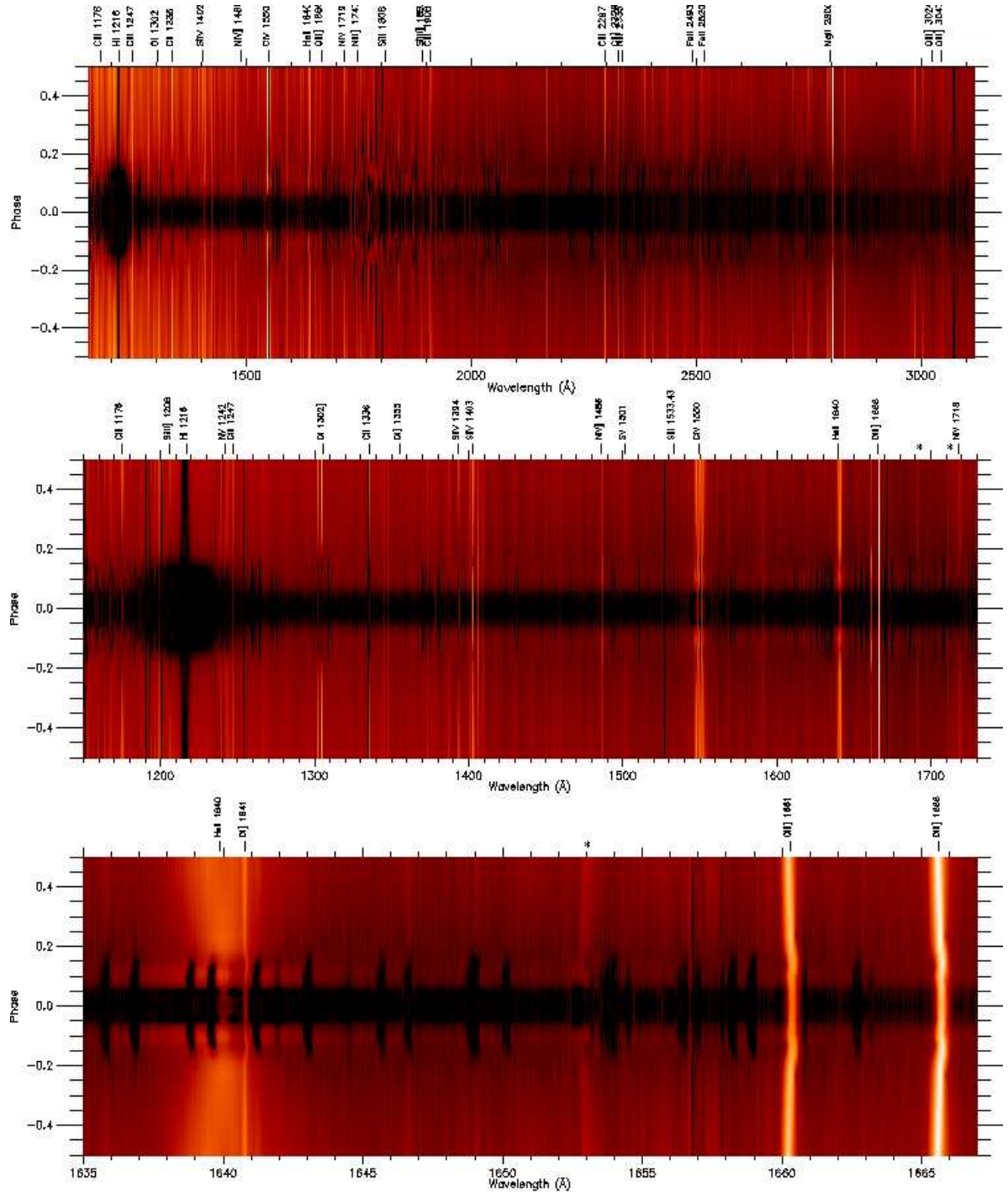
**Figure 4.1:** *FUSE* spectra of EG And at quadrature (black) and near eclipse (red).



**Figure 4.2:** A similar set of uneclipsed and eclipsed STIS spectra. In the both plots the y-axis is plotted on a log scale to facilitate display of the strong emission lines. Both datasets are smoothed for clarity. Artifacts in the data are marked with an asterisk.



**Figure 4.3:** A graphical representation of the spectral variations in the *FUSE* EG And data. The flux levels are represented by colour intensities and are displayed on a log scale. The data are phase-wrapped and the flux intensities are linearly interpolated through phases where no data is present. Spectral artifacts are marked with an asterisk.



**Figure 4.4:** A graphical representation of the STIS ultraviolet data produced using the same methods as with Figure 4.3. Figure 4.3 displays all of the FUSE data whilst the the top panel shows the full ultraviolet STIS dataset. The middle panel and lower panels display sections of the same data on a larger scale.

phase-wrapped and the flux levels are linearly interpolated through those orbital phases where no data is present. The dramatic effects of the eclipse on the ultraviolet data are very apparent in these diagrams. The attenuation of the continuum is observed to continue from mid-eclipse out to phase  $\phi \sim 0.16$ , with the attenuation being stronger close to the H I Lyman transitions. The different effects of the eclipse on different emission lines can be illustrated by examining the lower panel on Figure 4.4. The broad, He II 1640 emission feature originates in material close to the dwarf component, hence the eclipse of this feature is almost complete. In contrast, the O III 1660, 1666 doublet is much less affected by the eclipse of the hot component. This feature originates in an ionised part of the outer wind of the giant which is much more geometrically extended than the He II emitting zone, and therefore much less eclipsed. The appearance of the narrow wind absorption features on the continuum during partially eclipsed phases is also illustrated in this diagram. The majority of these absorption lines in this wavelength region originate from excited levels of the  $\text{Fe}^+$  ion.

The variations which are caused by the eclipse, in particular the appearance of the narrow red giant wind absorption features, will be dealt with fully in Chapter 5. For the remainder of this chapter, those features in the ultraviolet data whose behaviour cannot be explained by the eclipse effect will be analysed. Particular attention is paid to the hot gas close to the dwarf and an attempt is made to quantify the effect of the dwarf radiation on the cool wind and to develop a model for the binary.

## 4.2 Non-Eclipse Related Variations

As discussed above, the general behaviour of the ultraviolet spectral variations can be explained in terms of the eclipse of both the white dwarf and a large portion of the photoionised region of the giant wind by the atmosphere of the giant itself. However, there are also other variations that appear unrelated to the orbital phase. In addition to the variations that are unrelated to orbital phase that were observed in the July 2003 STIS spectrum (that were discussed in the previous chapter), the most striking variations are those of the individual resonance line profiles of the high-ionisation species diagnosing material close to the dwarf star.

It was originally anticipated that the wavelength coverage of *FUSE*, combined with the comprehensive orbital coverage and the high quality of the observations, would permit the identification of white dwarf photospheric features and establish the system as a double-lined spectroscopic binary. However, the only direct observation of the hot star is the ultraviolet continuum which is consistent with a dwarf star with an effective colour

temperature of  $\sim 75,000$  K. The broad components of high-ionisation emission lines from species such as He II, C IV, N IV, N V and S V appear to originate in gas close to the dwarf, however eclipse effects, self-absorption and line blanketing preclude reliable radial velocity measurements and no dwarf photospheric features have been identified. However, analysis of these broad line profiles places this material in very close proximity to the dwarf. I will firstly discuss these resonance profiles that appear in P-Cygni form and the broad lines which have no absorbing component. This is followed by a discussion of the extent and location of this material in the binary.

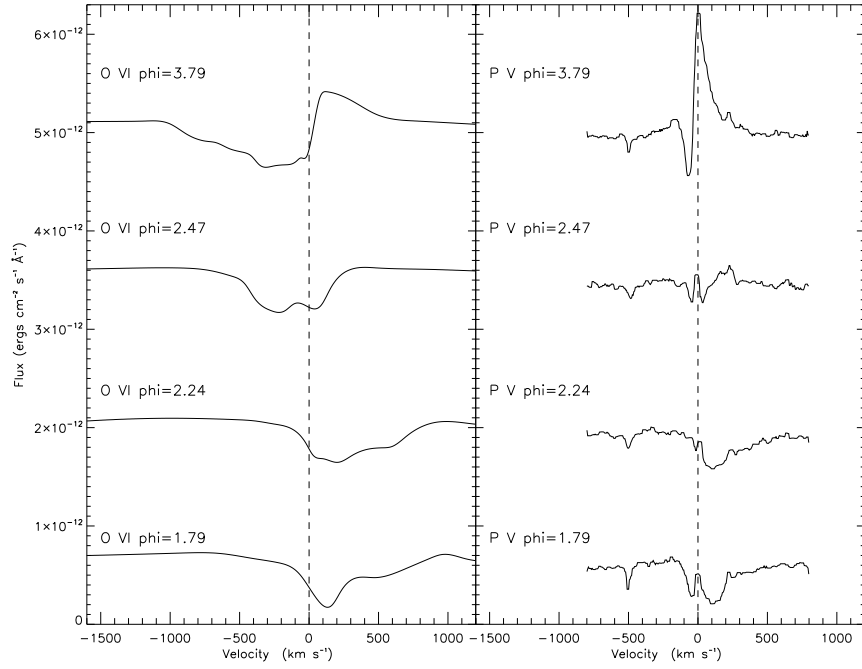
### 4.2.1 Broad P-Cygni Features

A number of permitted, high-ionisation transitions are present in the form of broad emission, P-Cygni or inverse P-Cygni profiles. In some cases, these profiles are blended with a narrow emission component from the nebular region while in others, they are mutilated by interstellar absorption at the blue end of the profile.

The O VI resonance transitions (1032, 1036 Å) represent the highest ionisation transitions in the spectrum and are present as optically thick wind profiles. They are observed to vary between a P-Cygni form, typical of fast ( $\sim 1000$  km s $^{-1}$ ) expanding winds and broad red-shifted absorption profiles typically observed in objects with in-falling material present. The variations are phase-independent and trace instabilities in the region deduced to be close to the white dwarf, as will be explained later in this chapter. See Figure 4.5 for a plot of the O VI profiles at four uneclipsed phases. Also shown are velocity plots of the P V 1117 Å resonance feature at the same orbital phases. Although P $^{+4}$  has a lower ionisation energy than O $^{+5}$  it is apparent that both lines diagnose the same mass-motions, with profiles switching from P-Cygni form to inverse P-Cygni form in tandem.

From the *IUE* observations of EG And, no definitive identification of the N V 1238, 1242 Å emission features was possible, raising the possibility that one of the component stars had an anomalous abundance (Sion & Ready, 1992). However, it is apparent from our STIS spectra that N V emission is present. The profiles are complicated due to self absorption and also due to the fact that the widths of the features ( $\sim 1,000$  km s $^{-1}$ ) are greater than the separation of the doublet. This results in mutilated and overlapping profiles that give the impression of weak emission and an anomalous doublet intensity ratio. The feature disappears during eclipse, which is as expected for gas close to the dwarf.

The C IV 1548, 1550 Å emission feature is the strongest in the ultraviolet spectrum. It is composed of at least two components, a broad base (full width at zero intensity (FWZI) of the convolved doublet  $\sim 1400$  km s $^{-1}$ ) which disappears around eclipse, and a



**Figure 4.5:** *Plots of the O VI (left panel) and P V (right panel) resonance line profiles (from uneclipsed phases) in velocity space in the EG And rest frame. The O VI profiles are reconstructed from clean regions (free of narrow absorption lines) from each component of the optically thick doublet, while the P V profile is the 1117 Å feature. These variations are not related to orbital phase, and the profiles are observed to switch between P-Cygni and inverse P-Cygni form. Although the profiles reach different extents in velocity space, it is apparent that they vary in tandem. These profiles trace clumpy, dense material located close to the dwarf star. The narrow emission component of the P V profile which is located at the rest velocity line is a nebular emission component superimposed on the wind profile.*

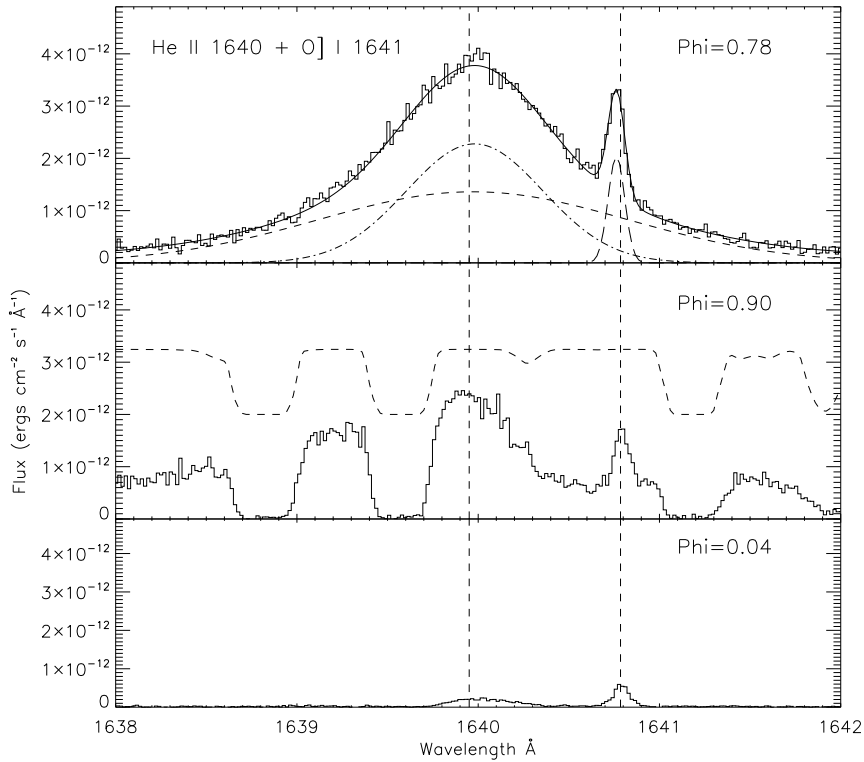
narrower central component which is affected by self absorption. The intra-doublet ratio of the narrow line core deviates from the optically thin 2:1 ratio to give ratios varying from between 1.5 and 1.8, depending on phase. The form of the profile is similar to those of the higher ionisation lines described above, except that the broad profile has a strong nebular emission line core superimposed on it. The C IV profile and its variations are similar in form to other high-ionisation permitted resonance transitions such as S IV and Si IV. A detailed modelling of such resonance line profiles is complicated by the multi-component structure and in many cases self and interstellar absorption. However, it is readily apparent that there are two distinct emitting regions. One in fast-moving gas

close to the dwarf and one which is further away from the dwarf, in an ionised region of the outer red giant wind.

### 4.2.2 Broad Emission Lines

The He II 1640 Å line (formed by recombining  $\text{He}^{+2}$ ) also traces the hotter gas in the system. The emission feature can be decomposed into two Gaussian profiles (see Figure 4.6). The broader component is observed to disappear completely during eclipse, while the emission core is also greatly reduced at phase  $\phi=0.04$ . The profile is greatly affected by a number of narrow Fe II absorption lines during phases of partial eclipse. This explains the asymmetric profiles observed with *IUE* where self-absorption was suggested in order to explain the profile (Sion & Ready, 1992). Due to the high energy of the lower level of the transition (40.8 eV), self-absorption would require large amounts of hot material to be passing intermittently along the line of sight, complicating the model of the system.

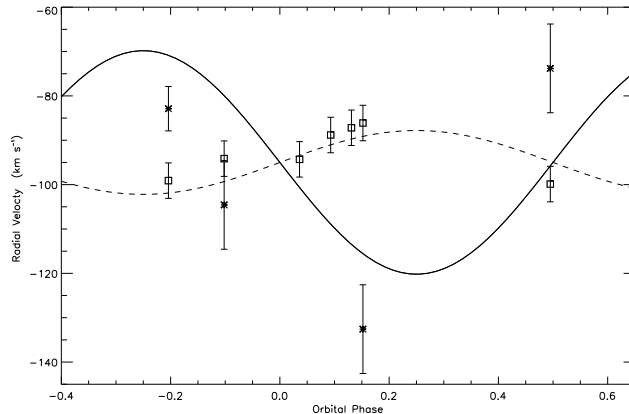
The S V line at 1502 Å (lower level is 15.8eV above ground) and the N IV line at 1718 Å (lower level is 16.2 eV above ground) appear to originate in a similar emitting region to He II. They are of similar width (full width at half maximum (FWHM)  $\sim 300 \text{ km s}^{-1}$ ), vary in the same way and produce radial velocity measurements that vary with phase in the opposite sense to those features associated with the giant. I find that the amplitudes of the radial velocity shifts for lines of the broad components of these permitted lines of He II, S V and N IV are consistent with a dwarf 3 to 4 times less massive than the giant. The lower level of these lines are well above ground, removing complications introduced by self-absorption, and although the profiles are heavily mutilated at eclipsed phases, it is noted that the radial velocities of all three broad components behave similarly. See Figure 4.7 for a plot of the variation of the radial velocities of the broad component of the He II 1640 Å line and the narrow ( $\sim 17 \text{ km s}^{-1}$ ) O I] 1641 Å line with orbital phase. The semi-forbidden O I line shares an upper level with the permitted O I triplet at  $\lambda 1302\text{\AA}$ , all of whose transition probabilities are a factor of  $\sim 10^4$  times higher. Therefore, extremely high optical depths must exist in the line-formation region for an appreciable number of photons to be allowed to escape from the emitting region via the semi-forbidden transition. It is therefore unsurprising that the measured radial velocities for this line match the predicted radial velocity curve for material associated with the giant atmosphere where densities of neutral material are high.



**Figure 4.6:** Plots of the He II 1640 recombination line at three orbital phases. In the top panel note that the profile is composed of a wide base and a narrower core component. Also note the much narrower O I] 1641 Å emission line. From radial velocity measurements and photoionisation modelling (described later in this chapter) I find that the broad He II component is located close to the dwarf. In the partially eclipsed spectrum displayed in panel 2 the overlying wind absorption from Fe II is apparent. Overplotted (dashed line) with an offset is an Fe II absorption model, thermally excited to a chromospheric temperature of 8000 K. The bottom panel displays the extent to which the He II emitting regions have been eclipsed at  $\phi=0.04$ . The emitting region is therefore close to the dwarf and is located along the axis between both components. The dashed vertical lines correspond to the rest wavelengths of the lines in the red giant rest frame.

### 4.2.3 Origin of the High Velocity Features

The observed profiles of the high-ionisation lines can best be understood in terms of the photoionisation and accretion of the red giant wind close to the hot component. The extent of the wind in velocity space depends on the ionisation energy of the species; i.e. the higher ionisation transitions trace higher velocity gas closer to the dwarf. This is illustrated in Figure 4.8 where the profiles were reconstructed with splined fits to both compo-

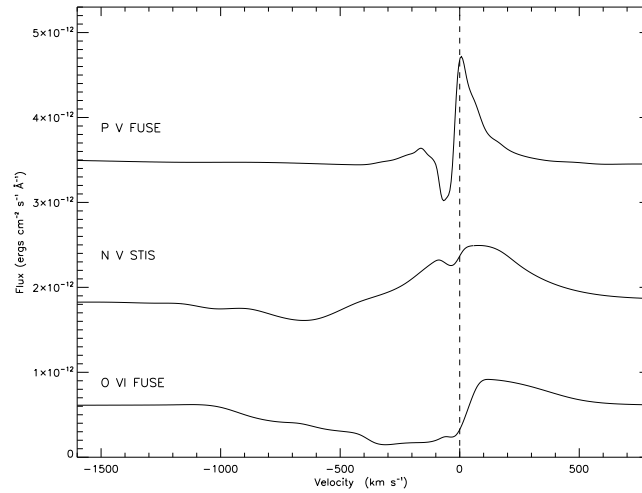


**Figure 4.7:** Measured radial velocities from fits to the broad component of the He II 1640 Å line (asterisks) and to the 1641 O I] (squares) line. Overplotted are the expected radial velocity curves for material associated with the red giant (dashed) and dwarf (solid) assuming a giant to dwarf mass-ratio of 3.5 and using the orbital elements derived by Fekel *et al.* (2000) for the giant.

nents of the doublets in order to exclude self absorption effects and overlying/underlying absorption/emission. A simple photoionisation argument places the higher ionisation material closer to the dwarf, which is where the highest velocities are expected for accreting material. This matches what is observed in the data, and also what is suggested from the radial velocity variations of the unabsorbed broad emission features.

The fact that profiles are observed to switch between P-Cygni and inverse P-Cygni form rules out the existence of a smooth outflow from the hot star. Indeed, for such variations to occur, the material must be reasonably dense and clumpy, suggesting erratic accretion of the cool wind. High densities of this material are also suggested by the absence of broad semi-forbidden line profiles. Unlike some symbiotic objects such as AG Peg (e.g. Nussbaumer *et al.*, 1995), the broad components in EG And are only observed in the permitted lines. The high ionisation semi-forbidden lines exist only as narrow line cores ( $\sim 30 \text{ km s}^{-1}$ ), with no hint of a broad component (see Figure 4.9). Analysis of the Si IV and O IV permitted and resonance multiplets at  $\sim 1400 \text{ Å}$  (Keenan *et al.*, 2002) in particular suggest that the semi-forbidden lines are collisionally suppressed.

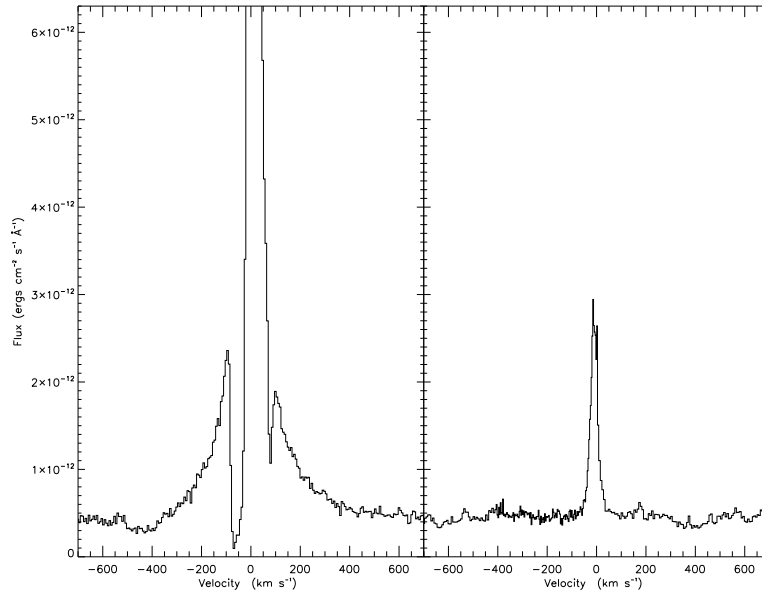
Further evidence for the broad line profiles being due to material being accreted onto the white dwarf comes from the short-timescale variation of the profiles in the *FUSE* spectra. When the uneclipsed *FUSE* spectra are split into their individual orbital exposures, it emerges that in two of the datasets, the resonance profiles of O VI and S VI are observed to shift dramatically over *FUSE* orbital timescales ( $\sim 90$  minutes). Displayed



**Figure 4.8:** Profiles of *FUSE* and *STIS* observations of the *P V*, *N V* and *O VI* resonance transitions. Individual profiles of the *N V* and *O VI* doublets are complicated by overlying narrow absorption and emission features from other species. The profiles shown here are reconstructed from both members of the doublet using regions free of the narrow features. The *FUSE* and *STIS* observations took place within 5 days of each other.  $P^{+4}$  has a lower ionisation energy than the other species - note the extent of its profile compared to the other two features.

in Figure 4.10 are plots of the regions around the *O VI* doublet for two observations. The spectra plotted in red were observed one *FUSE* orbital period later than the data plotted in black. Note that the narrow absorption lines (of interstellar origin) remain static while the broad *O VI* absorption features shift by up to  $\sim 250 \text{ km s}^{-1}$ . The rapid variation of these features is consistent with dense, clumpy material being accreted onto the dwarf component over a very small physical extent. A similar phenomenon is observed in  $\zeta$  Aurigae (binary period  $\sim 972$  days), where the *C IV* resonance profiles change over a time-span of  $\sim 10$  hours (Philip Bennett, private communication).

There is also evidence for an asymmetry in the distribution of hot material around the dwarf. During the phases around eclipse when the broad lines disappear it is apparent that they are modulated asymmetrically around the mid-point of the eclipse. The broad wings of lines such as *He II*, *C IV* and *Si IV* take longer to recover during egress than they do to disappear on ingress. This highlights the asymmetry of the highly ionised region around the dwarf, where the ionising photons can penetrate further into the less dense material in its wake, than they can into the denser wind material that it is moving into. The asymmetry is thus a line of sight effect where we are viewing the wake of the hot

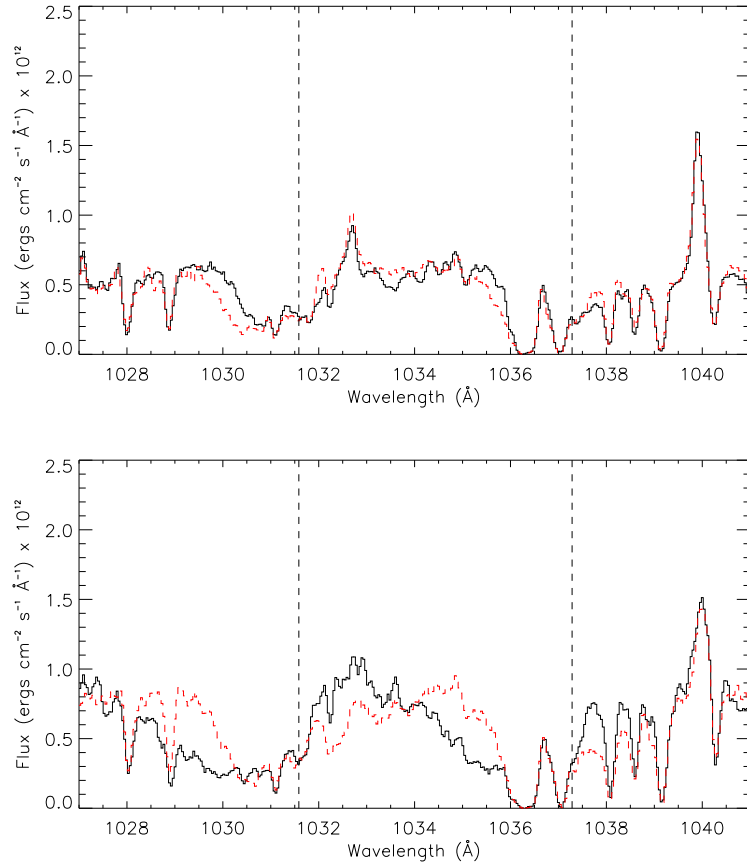


**Figure 4.9:** *Plots of the Si IV 1393 and S IV] 1416 velocity profiles observed with STIS at phase  $\phi=0.50$ . The left panel shows the permitted resonance line at  $\lambda$  1393.76Å, while the semi-forbidden line at 1416.90Å is plotted in the right. Both lines are plotted in the rest frame of EG And. The high density broad line region emits only in the permitted lines.*

component more clearly during ingress phases. Again, for this effect to be noticeable, the source of the high-velocity emission must be located close to the dwarf, otherwise the total eclipse and orbital asymmetry of these features would not be so pronounced.

### 4.3 Nebular Emission

The narrow emission features which originate in the outer region of the red giant, but further from the dwarf than the broad emission features, are now discussed. As presented in Figure 4.1, there are a large number of both strong and weak nebular emission lines characteristic of symbiotic stars in this dataset. These are largely semi-forbidden transitions, although many resonance features also possess a narrow nebular component. A radial velocity analysis of the emission lines places them in an extended portion of the red giant wind. Typical linewidths (FWHM) are  $30 - 50 \text{ km s}^{-1}$ , consistent with a formation region past the initial acceleration region of the expanding wind. This is also in agreement with the picture presented by the photoionisation models of Proga et al. (1998), where a significant red giant wind cross-section is required in order to reproduce

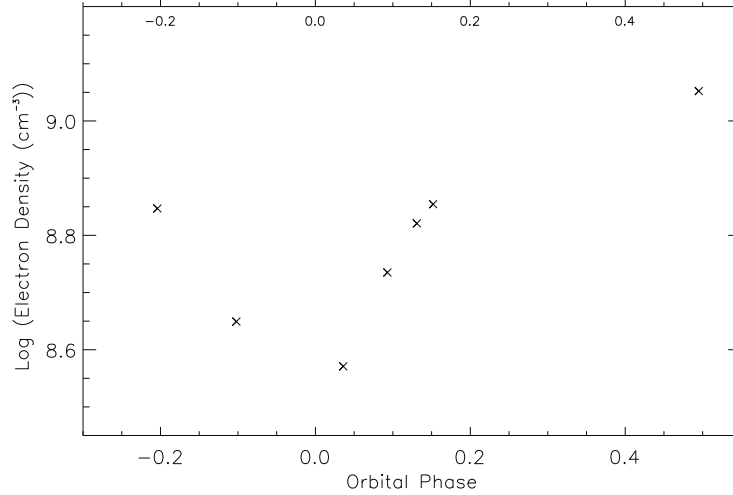


**Figure 4.10:** Sections of *FUSE* spectra around the O VI 1032, 1036 doublet. Within each panel the spectra plotted in red were observed one *FUSE* orbital period ( $\sim 90$  minutes) later than the data plotted in black. Note that while the narrow interstellar absorption features remains constant, the broad O VI profiles vary dramatically over this very short time-span. The dashed vertical lines correspond to the rest wavelengths of the O VI lines in the stellar rest frame.

the observed nebular line strengths in EG And. In addition to undergoing velocity shifts with orbital phase, most of the lines are also strongly modulated by the eclipse, revealing the importance of the white dwarf illumination to their formation.

There are a large number of transitions useful for deriving electron density diagnostics for nebular conditions within the ultraviolet wavelength region (e.g. Czyzak et al., 1986; Feibelman & Aller, 1987). Applying these diagnostics to a range of lines from different species and ionisation energies, a nebular density on the order of  $\sim 10^9 \text{ cm}^{-3}$  is consistently derived for uneclipsed phases. Densities are observed to reduce by a factor of  $\sim 2\text{--}3$  during eclipse, confirming that a large proportion of the core of the ionised nebula is obscured

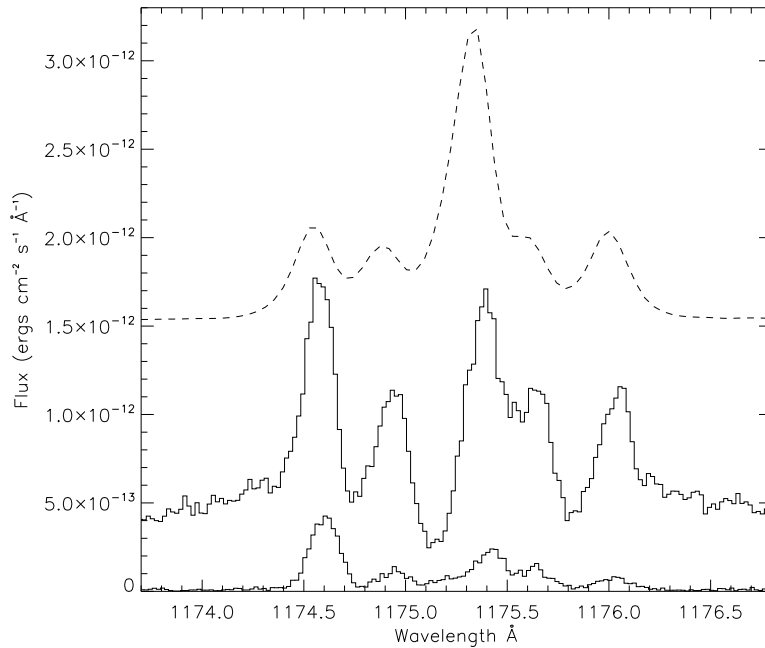
(see Figure 4.11). This places the emitting region along and close to the binary axis.



**Figure 4.11:** *The variations observed in the nebular densities against orbital phase. The densities shown here are derived using the flux intensities of the [O III]  $\lambda 2321$  / (O III]  $\lambda 1660 +$  O III]  $\lambda 1666$ ) flux intensity ratios. Diagnostics from other ions produce similar eclipse effects.*

### 4.3.1 C III Emission in the FUSE data

In theory it is possible to derive the electron temperatures and densities in the C<sup>+</sup>2 emitting regions by applying diagnostic ratios to the many C III lines throughout our data, including the resonance line at 977 Å and the multiplet at 1176 Å. However at all phases the intra-multiplet ratios that are observed for C III  $\lambda$  1176 are far from the optically thin values (see Figure 4.11). In addition to the ratios being changed by optical depth effects, profile modelling suggests that an additional absorption component is present. Since the energies of the lower levels are  $\sim 6.5$  eV above ground, it is conceivable that the levels are populated collisionally in the outer wind. Indeed, the presence of a component that absorbs away from the continuum at maximum ultraviolet phase categorically places at least some of the C III outside the binary orbit. In addition to the multiplet ratios being anomalous, the resonance feature (977 Å) is affected by self-absorption and also interstellar C III and H<sub>2</sub> absorption, therefore I do not use the C III transition in the *FUSE* regions as nebular diagnostics.



**Figure 4.12:** The 1175 Å C III multiplet as observed with *FUSE* at phases  $\phi = 0.79$  (top) and  $\phi = 0.05$  (bottom). Also plotted (dashed and with an offset for clarity) is a quiet solar spectrum of the same multiplet, shifted to the rest frame of EG And. The solar spectrum displays the components of the multiplet close to their optically thin ratios.

### 4.3.2 O III Recombination lines

It is noted that upwards of 15 permitted O III emission lines originating from levels significantly above ground are present in the *FUSE* spectra. To my knowledge, these transitions have only previously been reported for laboratory generated collisional plasmas. The transitions have upper levels with energies typically  $\sim 35$ -50 eV and must trace the recombining  $O^{+3}$  gas in the photoionised portion of the giant's wind. Lines are identified using the line-list published by Petersson (1982).

## 4.4 Modelling the System

These observations provide the most complete set of ultraviolet eclipse observations of any symbiotic system. Indeed the sampling of the eclipse and the high resolution and  $S/N$  of the data enable the study a red giant chromosphere and wind in absorption over a range of differing impact parameters from the photosphere. While it can be deduced from the optical dataset that the atmosphere remains relatively undisturbed by the presence of the

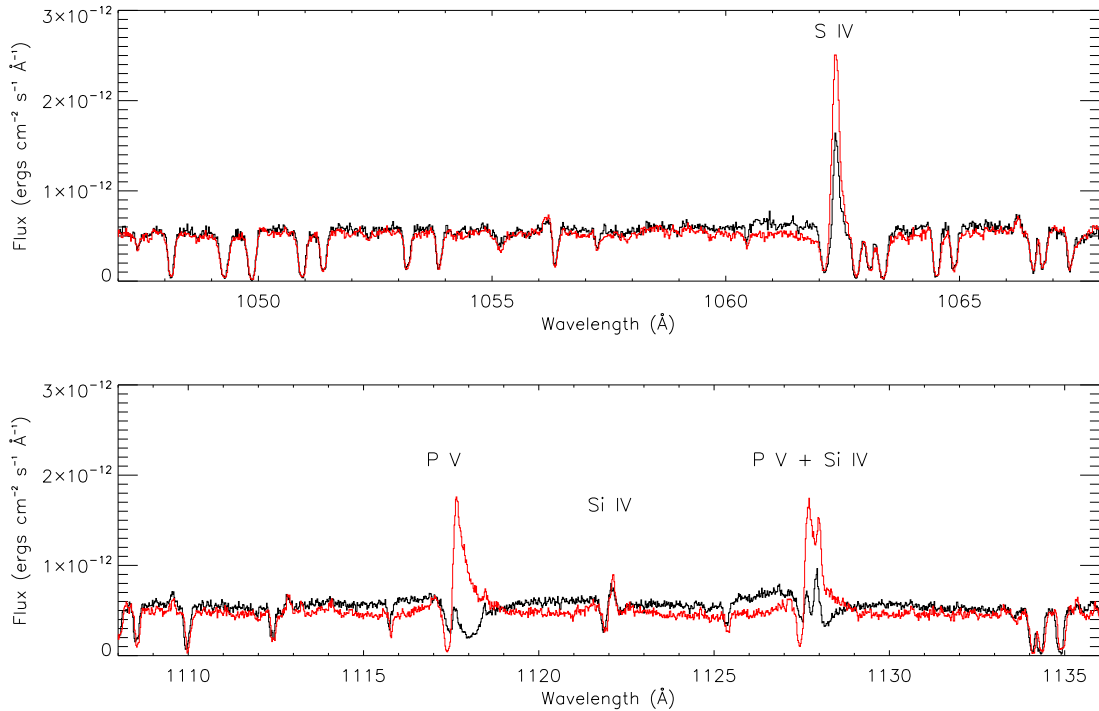
ionising companion, it needs to be clarified by how much the wind *is* affected, and whether the highly variable behaviour of the broad, hot material can be separated from the cool outflow from the giant. For example, if the wind conditions are found to be dominated by the ultraviolet radiation field it would be difficult to draw general conclusions as regards isolated giants based on this type of analysis.

In general terms, we can claim to have a good understanding of the significant spectral variations, which can be explained in terms of the eclipse of the hot component by the photosphere and extended atmosphere and wind of the giant component. I have discussed, however, variations unrelated to orbital phase, such as the behaviour of the profiles of certain high-ionisation features such as the the O VI resonance lines. However, from the analysis of the P-Cygni profiles and the radial velocity analysis of the unabsorbed broad lines, we can conclude that this material is located very close to the dwarf star. These features most likely diagnose dense, clumpy material accreting onto the white dwarf. It follows that this material can be readily separated from the material in the well-behaved cool wind outflow from the red giant.

Indeed, further evidence for this material being confined to a small region around the dwarf comes from examining how close the gas must be to the dwarf in order to be gravitationally accelerated to the observed velocities. Assuming a white dwarf mass of  $0.6 M_{\odot}$  (Vogel et al., 1992) and a gravitationally accelerated velocity of  $300 \text{ km s}^{-1}$  (FWHM of broad He II 1640 component), it emerges that the material must be closer than  $3 R_{\odot}$  from the dwarf's surface, which is less than 1% of the orbital separation. Using a velocity of  $1000 \text{ km s}^{-1}$  (observed in higher ionisation lines such as the O VI resonance profiles), the distance from the dwarf is calculated at being less than a solar radius.

To illustrate that this material is located in a small volume (relative to the system dimensions), sections of two *FUSE* spectra taken at identical orbital phases ( $\phi = 0.79$ ) but at different orbital epochs are displayed in Figure 4.13. It is apparent that both spectra are almost identical with the exceptions of the regions around the high-ionisation, high-velocity lines. These lines are due to Si IV, P V and S IV and are observed to switch from P-Cygni to inverse P-Cygni form. Despite these dramatic changes, the continuum and cool wind features are unaffected. This plot also illustrates the repeatability of the observations of the red giant wind over several epochs.

Further evidence that the giant wind is relatively unperturbed by the white dwarf radiation field lies in the observed ionisation and excitation structure of the different lines of sight through the wind. The ionisation level remains constant throughout the wind acceleration region and is symmetric about eclipse. These observed absorption profiles are much cleaner and simpler to analyse than those obtained from studies of many other



**Figure 4.13:** Sections of uneclipsed *FUSE* spectra of EG And taken at almost identical orbital phases (black -  $\phi=1.79$ ; red -  $\phi=3.79$ ), but two orbital epochs apart. The spectra are almost identical except for the high-ionisation transitions. This is due to material close to the giant which undergoes variations unrelated to orbital phase. In general the material not located very close to the hot component remains stable over the different observed orbital cycles.

eclipsing binaries. In many other cases, the absorption profiles are blended with the spectrum of the background secondary component. Often, the secondary component displays re-emission of scattered photons which fill in the absorption profile and make a full 3-D radiative transfer analysis necessary (Baade et al., 1996, and references within). However, due to the low luminosity of the dwarf, the entirely different spectral characteristics of the stellar components and the relatively low excitation of the wind, the majority of the absorption lines for this dataset can be treated successfully with a pure absorption analysis.

#### 4.4.1 Photoionisation Modelling

The fact that the dwarf is much less luminous than the giant (a factor of  $\sim 60$ ) explains why the white dwarf photons seem to ionise only a small region of the cool wind. However,

in order to analyse this in a quantitative way, the CLOUDY<sup>1</sup> photoionisation code was used to model the effects of the dwarf radiation on the wind. Using the stellar parameters described in Table 2.1 and a wind velocity law found for EG And by Vogel (1991) (characterised by a steep acceleration  $\sim 2.5 R_{RG}$  above the photosphere and hereafter called the Vogel wind law, this is discussed further in chapter 6) I have modelled the structure and conditions in the red giant wind along the binary axis between the two stars. Some of the findings are presented in Figures 4.14 and 4.15.

The top three panels of Figure 4.14 show the effect of the ultraviolet radiation field on the conditions in the outer regions of the red giant wind. The dwarf is located at the left hand side of each panel while the surface of the giant is located on the right. It can be noticed that the wind is heated to a temperature above 20,000K close to the dwarf and drops as the radiation moves into denser material. Note that the hydrogen ionisation boundary is located approximately  $0.7 R_{RG}$  from the dwarf's surface. It is at a distance of  $\sim 1.4 R_{RG}$  that the electron temperature (due solely to the dwarf photoionisation) drops below 4,000K and the calculation is stopped. Beyond this point, the influence of the ultraviolet radiation is minimal. Although, the ionised region does not extend very far into the giant wind, it must be remembered that this calculation was carried out along the binary axis where the wind is densest. For instance, the ultraviolet photons that escape in the opposite direction will ionise a much larger region due to the lower density of material. One can also see from Figure 4.14 the ionisation structure of hydrogen, oxygen and iron along the binary axis. For these plots, the black, red, orange, magenta, green and blue lines correspond to different stages of ionisation with black being neutral and blue corresponding to material that has lost five electrons.

Presented in Figure 4.15 are the contribution functions for a number of emission lines along the binary axis. It can be seen that the high ionisation material associated with O VI and N V resonance lines is located extremely close to the dwarf. The He II and C IV emission features also have a component located close to the dwarf, in addition to a component positioned further into the giant wind. This can explain the two-component profiles which are observed in the spectra for these transitions. For the majority of the nebular emission lines, most of the emitting material is located close to the hydrogen ionisation boundary where the electron density is highest. This is due to a trade-off between the decreasing wind density as one moves further from the giant and the decreasing number of free electrons (due to photoionisation) as one moves further from the dwarf.

The photoionisation model accounts for the relative emission line strengths observed in

---

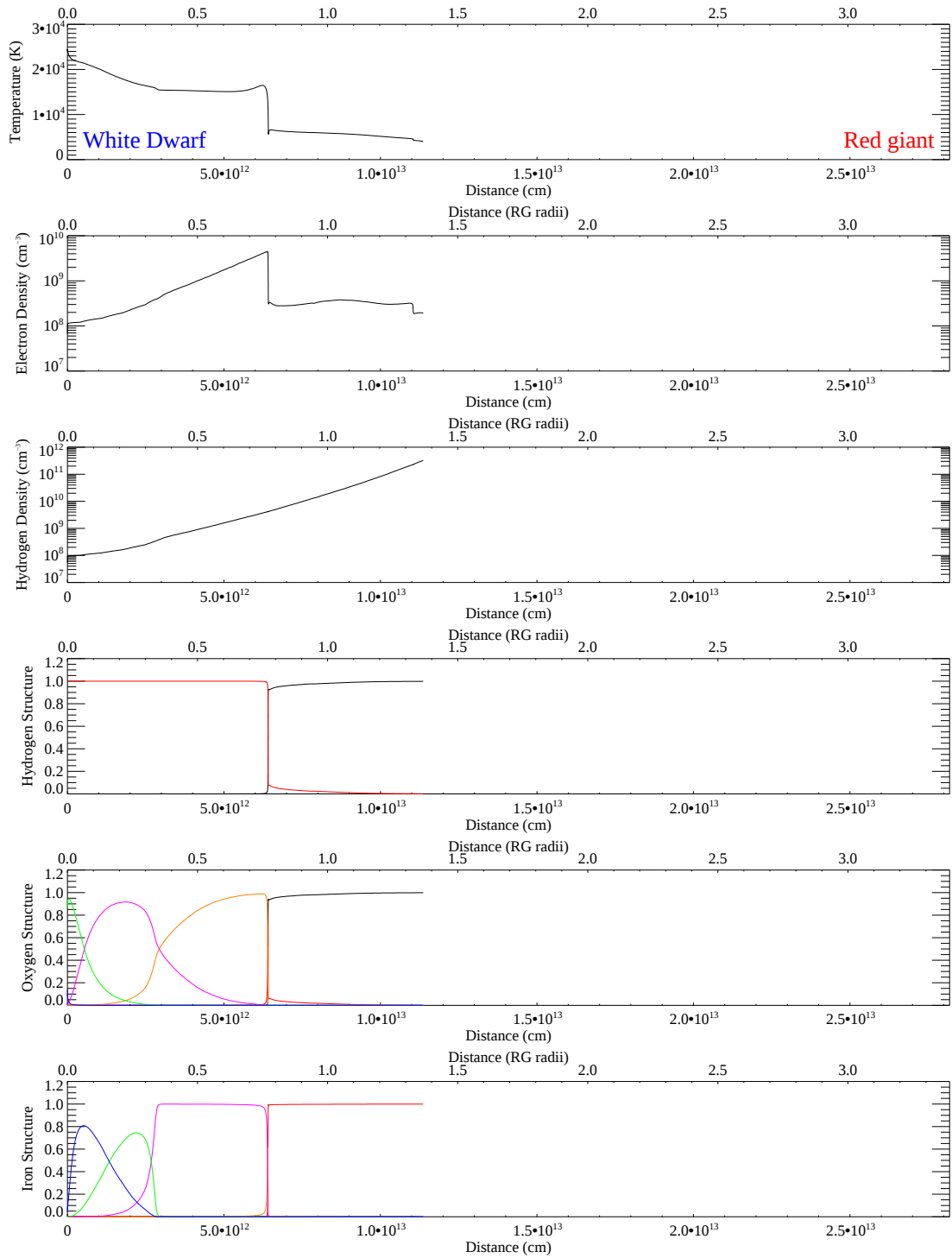
<sup>1</sup>CLOUDY is a large-scale spectral synthesis code designed to simulate fully physical conditions within an astronomical plasma and then predict the emitted spectrum (Ferland et al., 1998).

the data and, since it places the origin of most of the nebular emission lines at the regions of highest electron density which is along the binary axis, accounts for the variations in the line intensities around eclipse. The disappearance of the high-ionisation features at eclipse is also explained by the placement of this gas very close to the dwarf surface.

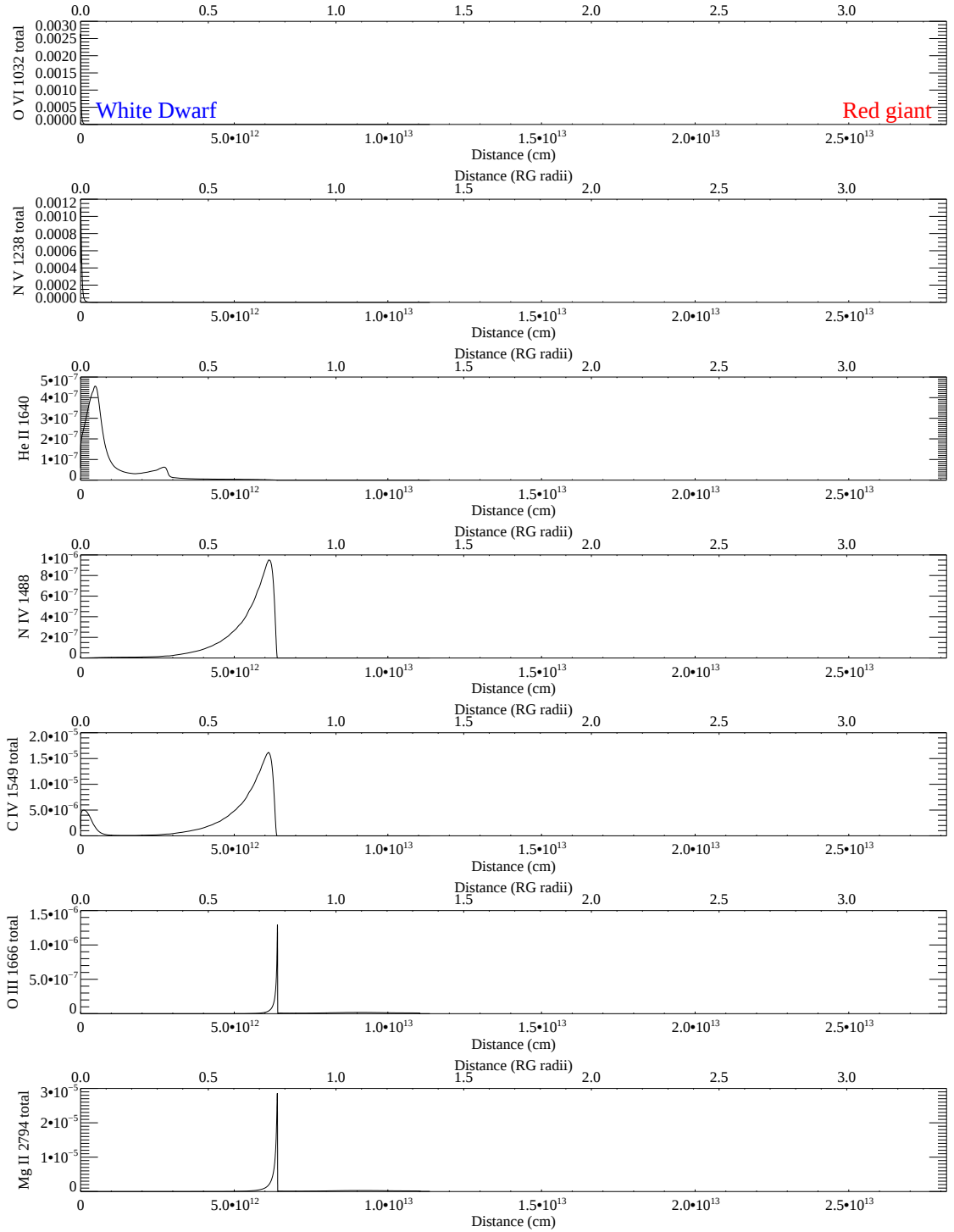
#### 4.4.2 Hydrodynamical Models

An aspect in which the cool material is definitely expected to be affected by the presence of the dwarf is through the redistribution of the wind material by the motion of the secondary. This redistribution is apparent in the asymmetry of the continuum fluxes and line strengths around eclipse, and whilst only a relatively minor effect, it must nevertheless be taken into account in any realistic wind model. Walder & Folini (2000) have published hydrodynamical models of symbiotic binary systems where the effects of the motion of the dwarf on the structure of the cool wind are examined. Plotted in Figure 4.16 is a view of the density distribution and velocity field (viewed perpendicular to the orbital plane) that the model predicts for a system with binary parameters similar to EG And. The extent of the predicted mechanical disturbance of the outflow is large, with an increase in density of the material in front of the dwarf in a type of snow-plough effect. There is a corresponding decrease in density in the wake of the dwarf and at distances further from the dwarf, the outflow is greatly disturbed. However, it must be noted that the material that is diagnosed by the phase-dependent absorption lines is located in the region at the centre of the plot, within the binary orbit, where the wind is accelerated. The fall-off in the density with distance is large and those regions in which the wind outflow is severely distorted are too tenuous to be viewed in absorption and, in any case, are beyond the point of initial wind acceleration and are of limited interest in terms of understanding the wind acceleration.

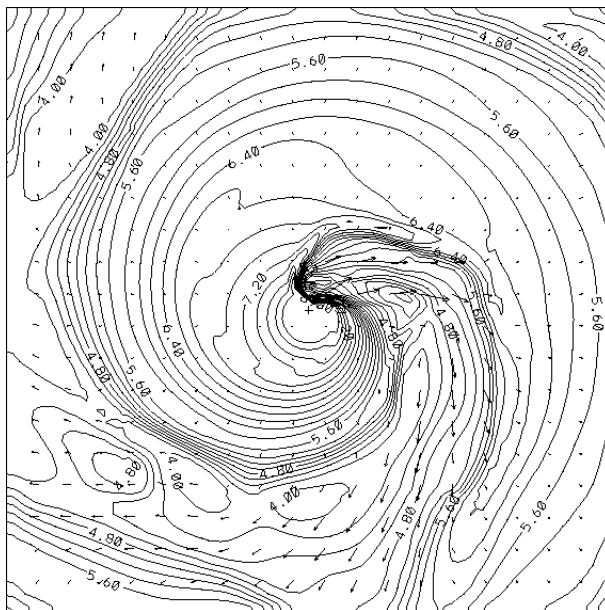
Plotted in Figure 4.17 is a close-up of the same model, but showing the locations of the dwarf (green) and the giant (red). It appears that, apart from the material directly in front of the dwarf, the wind within the binary orbit is relatively unaffected by the motion of the secondary component. This explains why the distribution of wind material in the data is not dramatically different between ingress and egress phases. Indeed, the slight asymmetry that is observed can be explained in terms of the gas being swept up in front of the dwarf. The observation of ionised material (i.e. C III 1176 Å) that is exterior to the binary orbit can be understood in light of this model as well. Since ionising photons will escape from the dwarf relatively unhindered in directions where the densities are lowest, this ionised material will be disturbed and wrapped around the giant, resulting in a circumbinary region of low-density ionised gas. This is the possible source



**Figure 4.14:** Results of a *CLOUDY* photoionisation modelling along the binary axis of both stars. The calculation is stopped when the electron temperature goes below 4,000K.



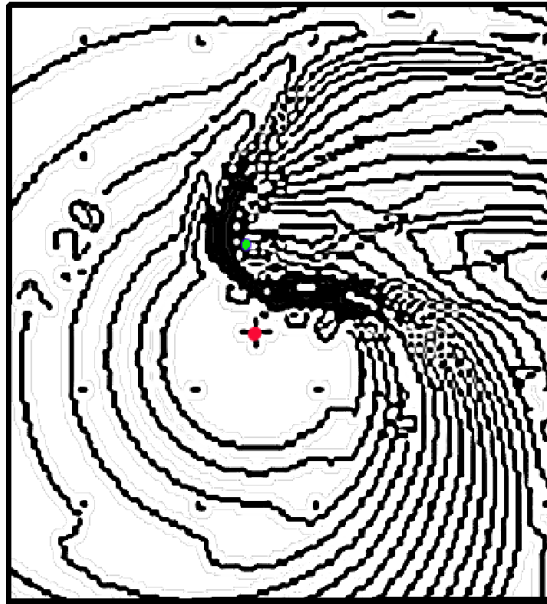
**Figure 4.15:** *Contribution functions of selected emission lines derived from the same photoionisation model as described in Figure 4.14.*



**Figure 4.16:** *Hydrodynamical model published by Walder & Folini (2000) for a binary system with similar systemic parameters to EG And. Although the outflow is severely disturbed at large distances into the wind, the density is very low and this material is not diagnosed in the absorption lines of EG And. The region of interest (within the binary separation) appears relatively undisturbed.*

of the C III 1176 absorbing component. Overall, although the wind outflow appears to be severely disrupted at large distances from the giant, the hydrodynamical models support the observational evidence that shows that the inner wind is relatively undisturbed.

I conclude this chapter by pointing out that, although it is possible to study cool winds through radio and ultraviolet observations of other binary systems, this dataset is unique in that it provides detailed thermal and dynamic information on the base of the wind where the the wind acceleration processes occur and, crucially, the material is relatively unperturbed by the hot star radiation. A detailed analysis and modelling of the wind is presented in the following chapters.



**Figure 4.17:** A close-up of the model shown in Figure 4.16, displayed are the locations of the dwarf (green) and the giant (red).

# 5

## The Red Giant Wind in Absorption

In contrast to the hot material associated with the dwarf star, the giant's chromosphere and lower wind, which is viewed in absorption, appears remarkably stable and is relatively unperturbed by the presence of its hot companion. In this chapter, an absorption analysis of this cool wind material is presented, with diagnostics obtained along different lines of sight to the hot companion as it moves behind this cool gas. By modelling the phase dependent absorption, it is possible to directly diagnose the conditions and physical structure of the material escaping from the star at different impact parameters above the photosphere. The different techniques used to model the absorption and the atomic data that is used in the analysis is described. It is then discussed how this study provides detailed information on the ionisation and excitation conditions, as well as the large and small scale structure of the outflow. As the impact parameter from the white dwarf to the stellar photosphere increases it follows that the ultraviolet radiation field will, at some point, dominate the conditions in the outflow. In an attempt to pin-point where this transition occurs, the absorption line variations are interpreted in terms of a photoionisation model for each line of sight. This provides a framework from which the line strength variations can be interpreted and from which the impact parameter at which the wind becomes significantly affected by the white dwarf can be found.

## 5.1 Analysis of the Wind Absorption

Analysis of the absorption features superimposed on the white dwarf continuum provides a direct view of the material along that line of sight. However, in order to derive accurate information on the conditions within this material, it is necessary to perform a quantitative analysis of the absorption features. In general, the quantities that are derived from absorption lines are the number of absorbers,  $N$ , along the line of sight, and  $b$ , the Doppler broadening parameter. In this study, a combination of profile fitting, apparent optical depth (AOD) and curve of growth (COG) techniques are used to determine these parameters<sup>1</sup>.

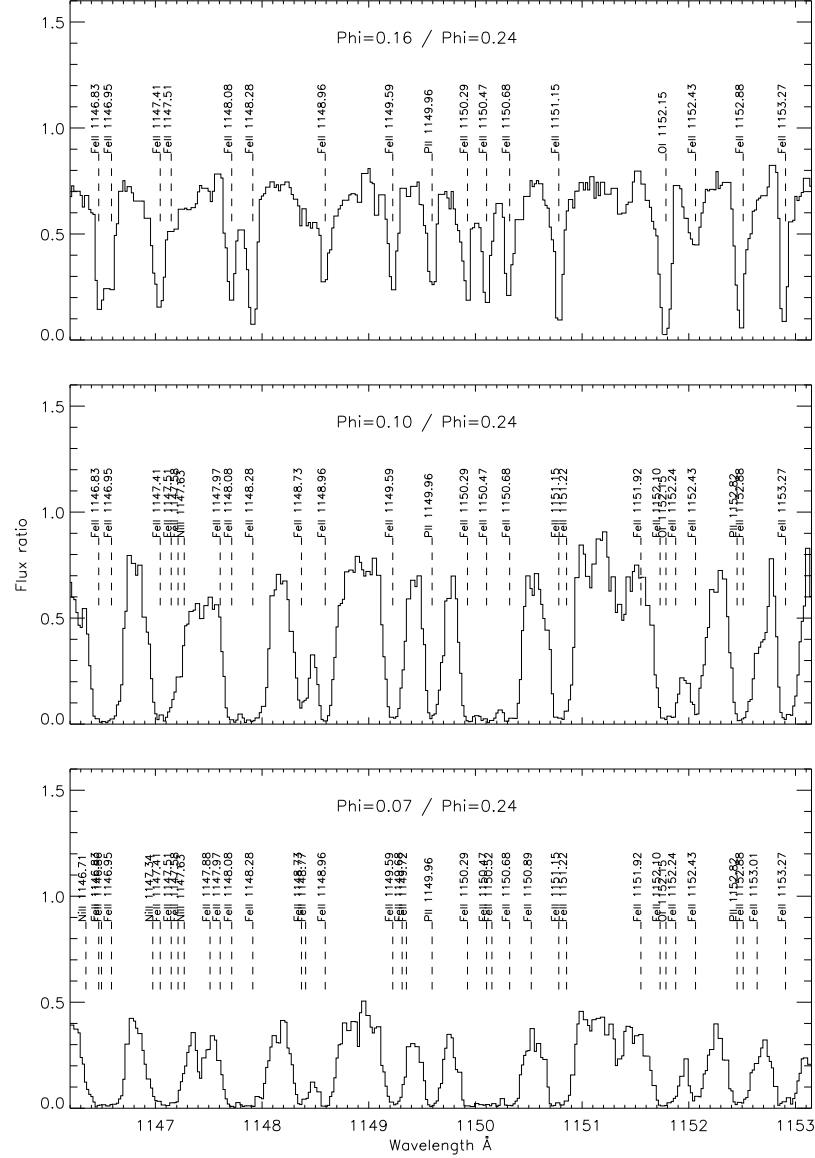
As noted in Chapter 2, the process of determining the shape of the underlying continuum is greatly aided by the presence of the uneclipsed data. Unlike most situations where the continuum must be fitted, or where a stellar model for the secondary must be assumed, the acquisition of spectra of the dwarf when it is out of eclipse makes it possible to analyse the profile of the difference between the spectra. Plotted in Figure 5.1 are examples of how the spectra can be normalised by using the ratios of eclipsed FUSE spectra to an uneclipsed FUSE spectrum. The ratios are shown over the wavelength region 1146-1153Å for 3 differing degrees of eclipse. Taking ratios of eclipsed to uneclipsed spectra makes use of the unabsorbed spectra to remove the unchanging features (such as interstellar absorption lines) and displays only the variations in emission and/or absorption.

For those features that are unblended, it is possible to obtain accurate column densities as long as the atomic data is reliable and there are not heavily saturated unresolved components along the line of sight. Although the analysis did provide evidence for some saturated components at some phases, the tests that were carried out showed that the derived column densities are not altered dramatically by the moderately saturated line structure. This is supported by Jenkins (1986) who finds that the analysis of ensembles of moderately saturated blended lines is not compromised by assuming a one-component profile. In most cases, uncertainties introduced by atomic data errors and blending problems are minimised by fitting a range of lines simultaneously using the COG technique and/or profile fitting (more commonly used). Although the accuracy of the column densities vary from spectrum to spectrum, uncertainties of the narrow absorption columns are typically  $\pm 25\%$ .

In the case of the H I profiles, the absorbing column is so strong that the lines are all on the damped section of the COG. This removes the complications associated with saturation and the well-defined broad damping wings enable a very accurate determination

---

<sup>1</sup>A discussion of these techniques and their application to the data in this study is contained in Appendix A.



**Figure 5.1:** Plots of the ratios of an uneclipsed *FUSE* spectrum to eclipsed *FUSE* spectra for 3 different degrees of eclipse. This plot basically removes the unchanging features (such as interstellar absorption lines) and displays only the spectral variations. The spectra are observed at increasing degree of eclipse from top to bottom. Note how the wind absorption lines strengthen and the continuum decreases with respect to the template quadrature spectrum. Most of the absorption features at these wavelengths originate from excited states of  $\text{Fe}^+$ ,  $\text{P}^+$ ,  $\text{O}^+$  and  $\text{Ni}^+$ .

of the absorbing column. It is well-known, however, that the H I transitions in the *FUSE* wavelength region suffer from large uncertainties in atomic data. This is usually a major obstacle for measuring distributions of neutral material through H I absorption techniques.

However, this is not a significant problem in this dataset as the columns are so high that the blue wavelength wing of the Lyman  $\alpha$  profile attenuates the long wavelength range of the *FUSE* region, enabling the column to be measured with this transition.

An important factor that must be accounted for when analysing the absorption columns is that, unlike interstellar absorbing material, the gas is thermally excited to chromospheric temperatures, which leads to a large number of absorption features originating from levels well above ground. Since such a detailed absorption analysis of this type of excited gas at ultraviolet wavelengths is not a common procedure, it was necessary to develop specific software tools that incorporate the latest atomic datasets in order to model the observations.

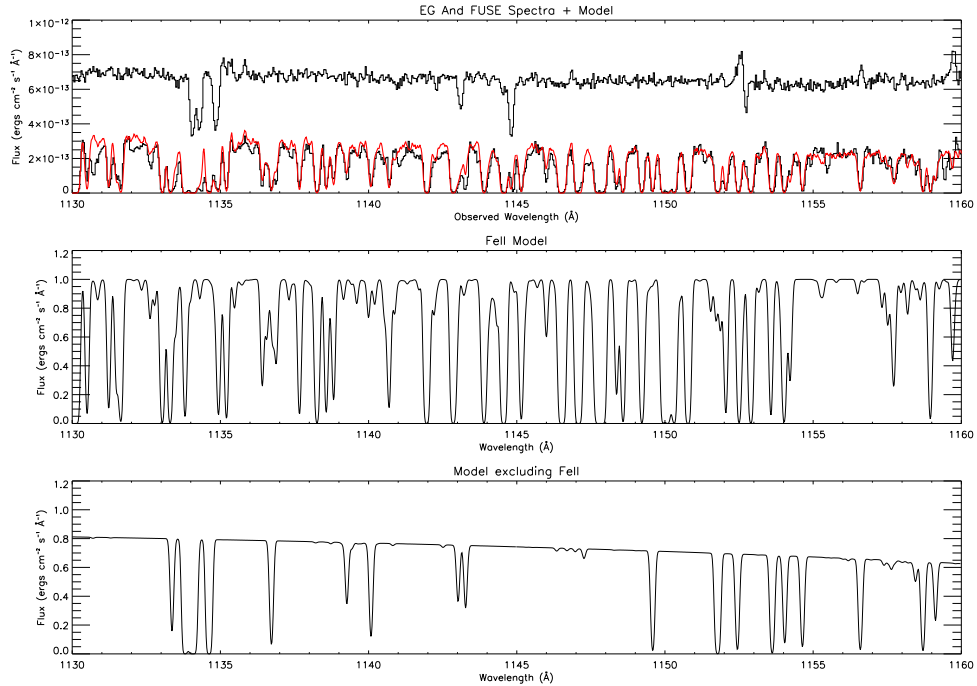
The analysis procedures treat the lower ionisation stages of 19 different elements and assume thermodynamic equilibrium (LT)<sup>2</sup>. The thermal and dynamic conditions of the gas, the instrumental broadening factors of the telescope, in addition to the well-understood physics of spectral line formation, are all taken into account in the analysis. Thousands of UV lines originating from different lower energy levels are accounted for and a variety of different fitting techniques are used to determine the physical conditions in the gas. For example over 2,700 lines of Fe<sup>+</sup>, spanning a range of lower energy levels and transition probabilities are included in the EG And analysis.

All partially eclipsed spectra were analysed in this way and the vast majority of absorption features ( $\sim 90\%$ ) were identified and well-reproduced. Reproducing the absorption in the *FUSE* data proved much more difficult than that in the STIS region (mostly due to atomic data uncertainties). However, for wavelengths greater than  $\sim 1000\text{\AA}$ , the data could still be fitted reliably. Displayed in Figure 5.2 is a fit (red) to an absorbed region of *FUSE* spectrum (black). Also plotted (but offset for clarity) is the template uneclipsed spectrum. Most of the absorption features are due to Fe II, Ni II and P II, while the Lyman  $\alpha$  profile is attenuating the continuum. Presented in Appendix B is a fit to a complete set of *FUSE* and STIS spectra for data observed close to orbital phase  $\phi=0.10$ . The complete linelist for the narrow lines that are modelled (line core below 85% of the continuum after convolution with the instrumental resolution) can be retrieved electronically from <http://www.tcd.ie/Physics/Astrophysics/data/fuse/EGAndlinelistUV.dat>.

A time-series of all of the *FUSE* and STIS spectra are presented in Figures 5.3 and 5.4. Also plotted are the derived H I fits, superimposed on a fit to the continuum of

---

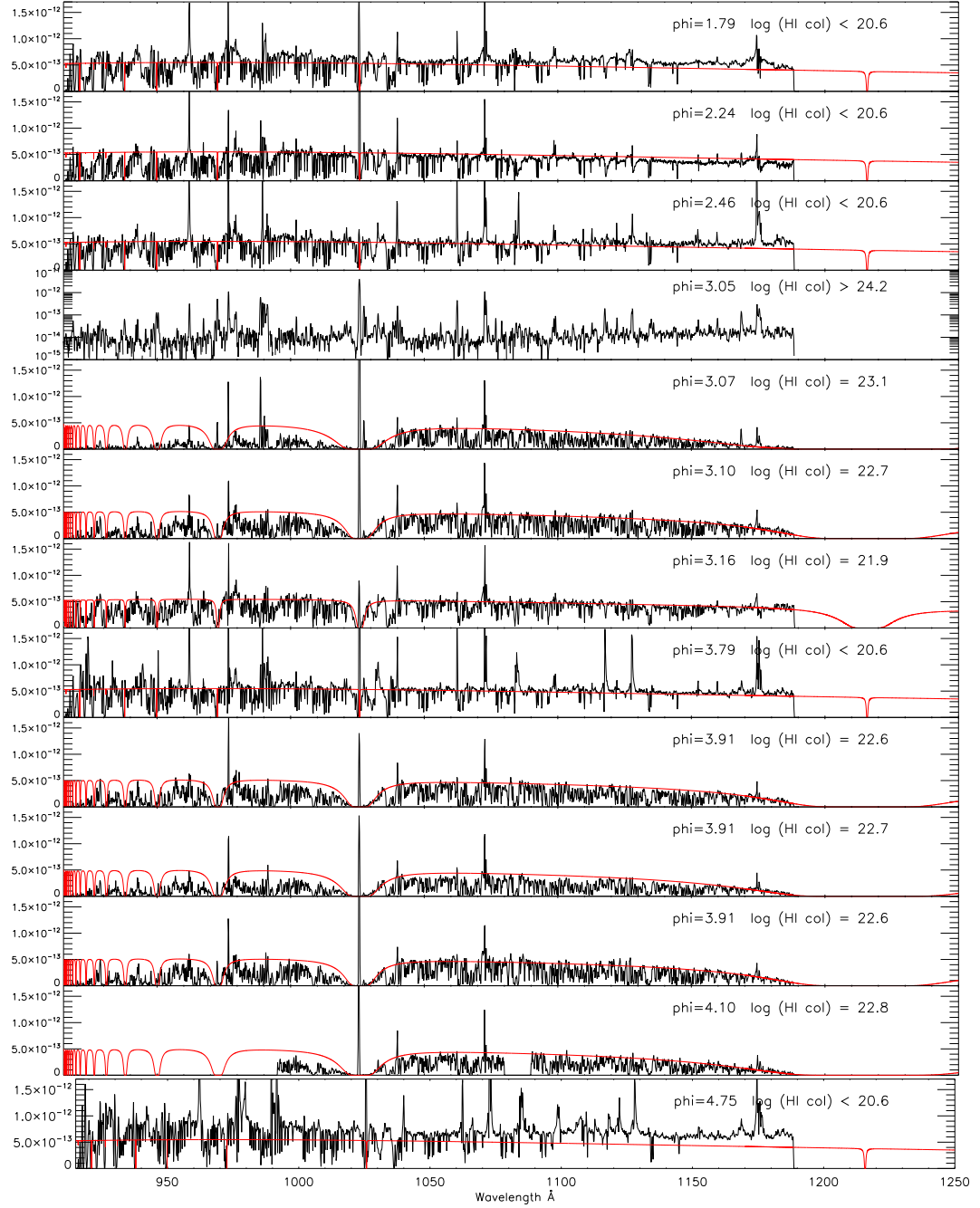
<sup>2</sup>Although this approximation is not usually valid for strong transitions in the relatively tenuous layers above the photosphere, it is found that the TE excitation model matches the data extremely well for the vast majority of the transitions. While the ionisation temperatures that are determined do not match the implied corresponding excitation temperature, it is found that the majority of level populations remain approximately Boltzmann.



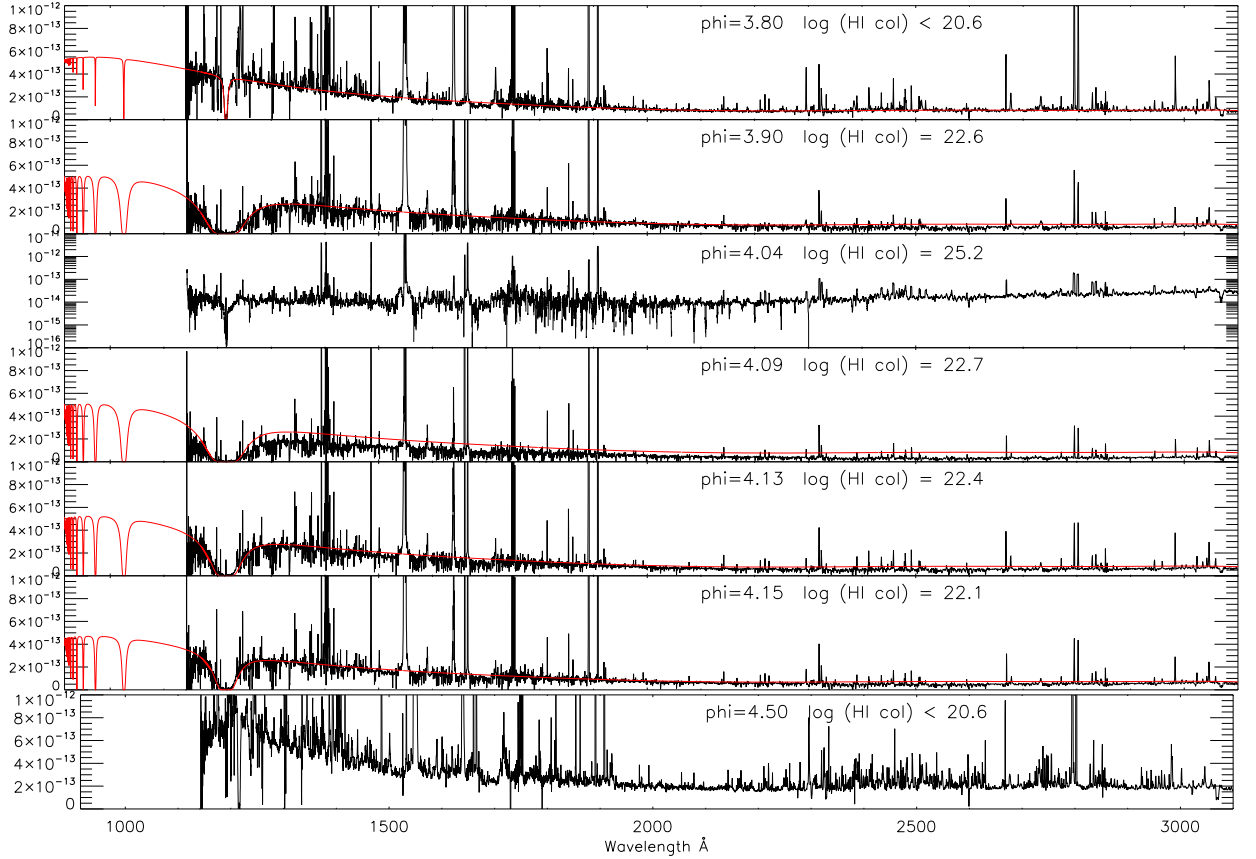
**Figure 5.2:** The top panel shows two *FUSE* spectra of EG And. The uneclipsed spectrum was taken at quadrature and is an unobscured view of the dwarf where the absorption lines are all interstellar (flux is offset by  $+3 \times 10^{13}$  for clarity). The absorbed spectrum was taken part-way during eclipse ( $\phi=0.10$ ) and a fit is overplotted (red). The fit was generated by placing absorbing material in the line of sight to the uneclipsed spectrum. The second panel shows the Fe II contribution to the fit while the bottom panel shows the H I contribution along with a number of other species (in this wavelength region mostly N I, P II and Ni II). Note that the blue wing of Lyman  $\alpha$  defines the continuum shape. The Fe II model was generated using atomic data from Raassen & Uylings

the reference quadrature continuum (red). The continuum level is observed to fluctuate and these variations are apparent in these plots as offsets in the continuum level. The fluctuations are plain to see in the unabsorbed spectra but are also observable in the eclipsed data as continuum mis-matches between the attenuated reference spectra and the data. In addition to displaying the spectral variations, these plots, therefore, show that an additional scaling of the reference continuum must be applied in order to fit the absorption profiles.

Since the atoms and ions in the wind often have significant electron populations in many excited levels, it follows that the success of the modelling process is heavily reliant on having accurate atomic data. For example, in order to determine the excitation



**Figure 5.3:** Plots of the complete FUSE dataset for EG And. Overplotted are the H I absorption models superimposed on a fit to the continuum of the template spectrum (red). The plotting of the template spectrum highlights the variations in the continuum that are unrelated to phase. The data are binned for clarity.



**Figure 5.4:** *Plots of the complete STIS ultraviolet dataset for EG And, similar to Figure 5.3.*

temperature of the gas and also in order to apply excitation corrections to derived column densities, models of the atomic (or ionic) structure of the absorbing species must be assumed. Of even more importance, is the use of accurate transition probabilities.

#### 5.1.0.1 Atomic Data

Absorption lines originating from lower levels with excited states up to  $\sim 5$  eV above ground are generally not observed in *FUSE* or STIS spectra. This lack of empirical constraint, combined with the fact that laboratory measurements of transitions in the ultraviolet are extremely difficult to carry out, mean that atomic data (particularly transition probabilities) in this region of the spectrum (especially in the *FUSE* region) can be very uncertain for many transitions. The choice of which atomic data source to use is therefore an important input into the analysis. After a literature search to determine

which dataset best describes other published spectra, combined with an iterative procedure to see which dataset best matches the EG And spectra, it was decided to use the calculations provided by Raassen et al. (1998); Raassen & Uylings (1998a,b) for the  $\text{Fe}^+$ ,  $\text{Co}^+$ ,  $\text{Cr}^+$  and  $\text{Ti}^{2+}$  ions. The data published by Kurucz & Bell (1995) was used for the remaining atoms/ions.

Although the accuracy of the H I column densities derived from *FUSE* data is usually limited by the quality of atomic data for those transitions in this wavelength region, the results obtained in this study are not affected. This is due to the strength of the H I absorption profiles which are on the damped portion of the curve of growth where the short-wavelength damping wing of the Lyman  $\alpha$  absorption line attenuates the long-wavelength end of the *FUSE* spectra. It is thus possible to measure the H I column using Lyman  $\alpha$ , even with the *FUSE* data.

It is also worth noting that due to the high quality of the spectra and also to the fact that such highly excited, low-ionisation material is rarely observed in the ultraviolet, it is possible to test the veracity of different sets of wavelengths and theoretical atomic oscillator strengths. For example the Fe II lines in the *FUSE* data were fit using the atomic data published by both Kurucz & Bell (1995) and also from Raassen & Uylings (1998b) and it was found that the Raassen & Uylings data provided a better match to the observed spectrum.

## 5.2 Wind Ionisation and Overall Structure

In all 12 spectra where  $\phi \leq 0.16$ , the line of sight to the dwarf passes through a significant column of cool wind material, resulting in a host of narrow ( $\sim 12 \text{ km s}^{-1}$ ) absorption features superimposed on the dwarf spectrum. As the dwarf moves closer to eclipse, the absorption lines grow stronger and the dwarf continuum shape is redefined by attenuation due to the large amounts of neutral hydrogen present in the wind (Vogel, 1991). In both of the spectra with  $\phi < 0.06$ , the continuum is obliterated and what remains is a low level of flux ( $\sim 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ ) and nebular and chromospheric emission lines of reduced intensity.

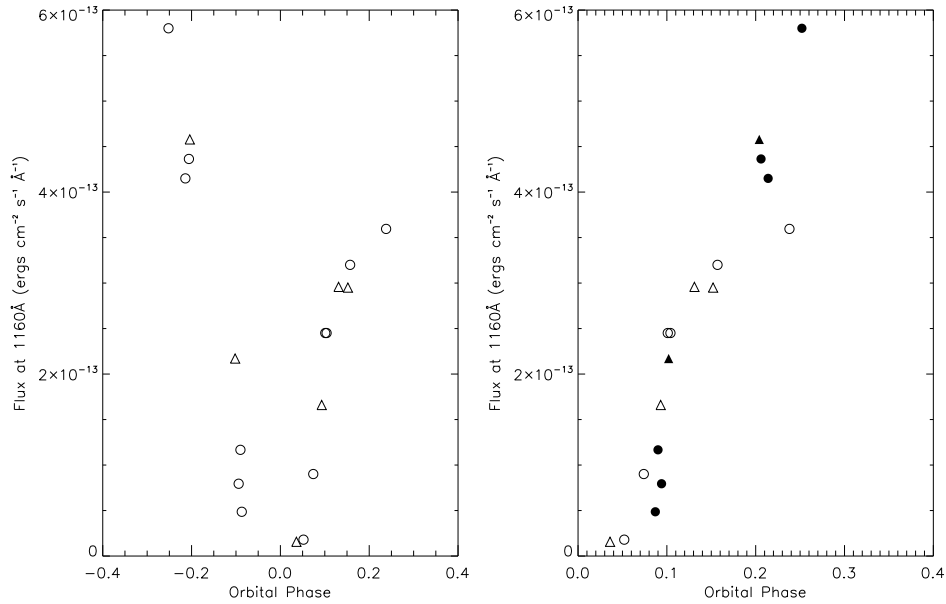
In contrast to the complex ionisation structure observed in similar eclipsing systems, such as the  $\zeta$  Aurigae binaries (e.g. Baade et al., 1996) where the line of sight to the secondary passes through a complex ionisation structure, it is found that the ionisation structure along each line of sight is relatively straight-forward. With one exception, the ionisation level remains constant for all absorbed spectra. The wind is predominantly neutral in hydrogen, carbon, oxygen and nitrogen and is mainly singly ionised in the

heavier common elements such as magnesium, silicon, sulphur, nickel and iron. Identified wind absorption features include H I, C I, C II, N I, N II, O I, Mg II, Al II, Si II, P II, Ar I, Ti II, Ti III, Mn II, Fe II and Ni II. The majority of the lines are from singly ionised states of complex iron-group elements such as  $\text{Mn}^+$ ,  $\text{Fe}^+$  and  $\text{Ni}^+$  and originate from either ground levels, or from lower levels up to  $\sim 5$  eV above ground. Most species exist in only one ionisation stage (i.e. iron is present only as  $\text{Fe}^+$ ) and the ionisation is symmetric around eclipse. The wavelength coverage provided by *FUSE* covers the transitions of many ionisation stages for many species ensuring that any changes in ionisation will be noted (i.e. covers strong transitions from lower levels of  $\text{Fe}^0$ ,  $\text{Fe}^+$  and  $\text{Fe}^{+2}$ ). The one exception where changes in ionisation are observed occurs in the *FUSE* spectrum taken at  $\phi = 0.16$ , where the Fe absorption is split between  $\text{Fe}^+$  and  $\text{Fe}^{+2}$ . In this spectrum, the linewidth also decreases significantly compared to the other absorbed spectra (from  $\sim 12 \text{ km s}^{-1}$  to  $\sim 7 \text{ km s}^{-1}$ ) and it can be deduced that a significant amount of hydrogen in the line of sight is ionised at this phase. The observation at this phase probes the line of sight through the wind which is further from the giant photosphere, at an impact parameter of  $\sim 3.7 R_{RG}$ .

In contrast to the symmetry of the ionisation structure around the primary, we observe an asymmetry in the density of material that is apparent from both the continuum level variations and also from the strengths of the narrow absorption lines. Plotted in Figure 5.5 are the variations of the continuum flux at a line-free region of the continuum at  $\sim 1160 \text{ \AA}$ . For absorbed spectra, the continuum flux at this wavelength is defined by the strength of the damped blue wing of the Lyman  $\alpha$  transition of hydrogen. The observed fluxes, therefore, diagnose an asymmetry in the column densities of neutral material around eclipse. This can be ascribed to the mechanical redistribution of the giant wind by the motion of the dwarf star and can be understood in terms of the snow-plough effect discussed in chapter 4.

### 5.2.1 Molecular Lines

The *FUSE* wavelength range contains a large number of strong molecular hydrogen transitions from a range of energy levels. Indeed, these spectra include a number of  $\text{H}_2$  lines of interstellar origin. Our observations, therefore, are extremely sensitive to the presence of  $\text{H}_2$  in the wind acceleration region at a distance of  $\sim 2.2 - 3.7 R_{RG}$ . No  $\text{H}_2$  lines (or CO or  $\text{H}_2\text{O}$  lines in the STIS data) at the rest velocity of the binary are detected at any phase, setting tight constraints on the molecular content of the wind at these distances above the limb. The upper limit of molecular hydrogen is found to be  $n(\text{H}_2)/n(\text{H}) < 10^{-8}$  throughout the wind acceleration region.

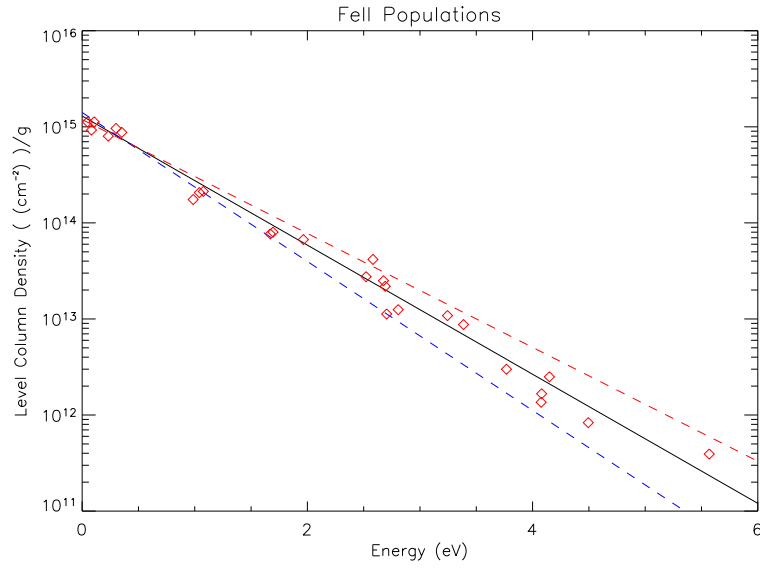


**Figure 5.5:** Plot of the continuum flux at a line free region (at  $\sim 1160 \text{ \AA}$ ) against orbital phase is displayed in the left panel. The right panel shows the same data plotted against the reduced phase. Triangular points represent STIS data and crosses represent FUSE data in both plots. Filled datapoints represent ingress data and open symbols define egress data for the panel on the right. The observed asymmetry between ingress and egress datapoints diagnoses the asymmetry in the distribution around the giant.

### 5.3 Wind Temperature and Excitation

In the case of species such as Fe II and Ni II, which have a large number of lines, it is apparent that there are absorption features arising from transitions from lower levels ranging from ground to levels  $\sim 5 \text{ eV}$  above ground. This, therefore, makes it possible to calculate the level populations and examine the excitation structure. In all of the absorbed spectra, the FeII level populations can be explained by a simple collisional excitation model. By comparing the excitation diagrams with model ions populated collisionally, it is possible to derive a temperature and total column density. We find that for the range of impact parameters observed ( $\sim 2.2 - 3.7 R_{RG}$ ), the wind temperature is consistently located within the range  $\sim 6,000 - 8,000 \text{ K}$  throughout eclipse (see Figure 5.6).

The level populations are found to be consistent with a simple local thermodynamic equilibrium (LTE) approximation. (i.e. all Fe absorption in the above mentioned impact parameter range is in the form of  $\text{Fe}^+$ , with only lines from levels  $\lesssim 5 \text{ eV}$  present. The drop-off in the populations of the statistically weighted energy levels is linear.



**Figure 5.6:** By measuring the apparent absorbing column for a range of lines coming from different lower levels, it is possible to examine the excitation structure in the gas. Here is an excitation diagram of Fe II derived from one of the STIS spectra. The solid line corresponds to a total FeII column of  $7 \times 10^{16} \text{ cm}^{-2}$  and a temperature of 7,500 K. The lower and higher dashed lines correspond to the same column but to a temperature of 6,500 K and 8,500 K respectively.

## 5.4 Modelling the Column Density Variations

In order to fully understand the variations of the column densities, in particular the brief appearance of Fe III profiles in the spectrum, and also the sharp disappearance of all narrow wind features at phases  $\phi > 0.16$ , the photoionisation model discussed in Chapter 4 was extended to model the full range of sightlines. Again, a wind following the Vogel acceleration law and spherical, constant mass-loss was assumed. A mass-loss rate of  $7.5 \times 10^{-8}$  times solar was inputted into the model (along with other binary parameters that were listed in Table 2.1), and the ionisation structure along the lines of sight for 50 orbital phases were calculated using CLOUDY, similar as to what was carried out along the binary axis and detailed in Chapter 4. This information was then used to create models of the variation of the column densities of different species with the orbital phase.

The resultant integrated columns match the observed changes well and the sharp peak in the Fe III column density is accounted for. This can be understood when one imagines the variation of the density profiles that the ultraviolet photons must ‘see’ at different orbital phases in one dimension. At relatively eclipsed phases (say  $\phi < 0.10$ ),

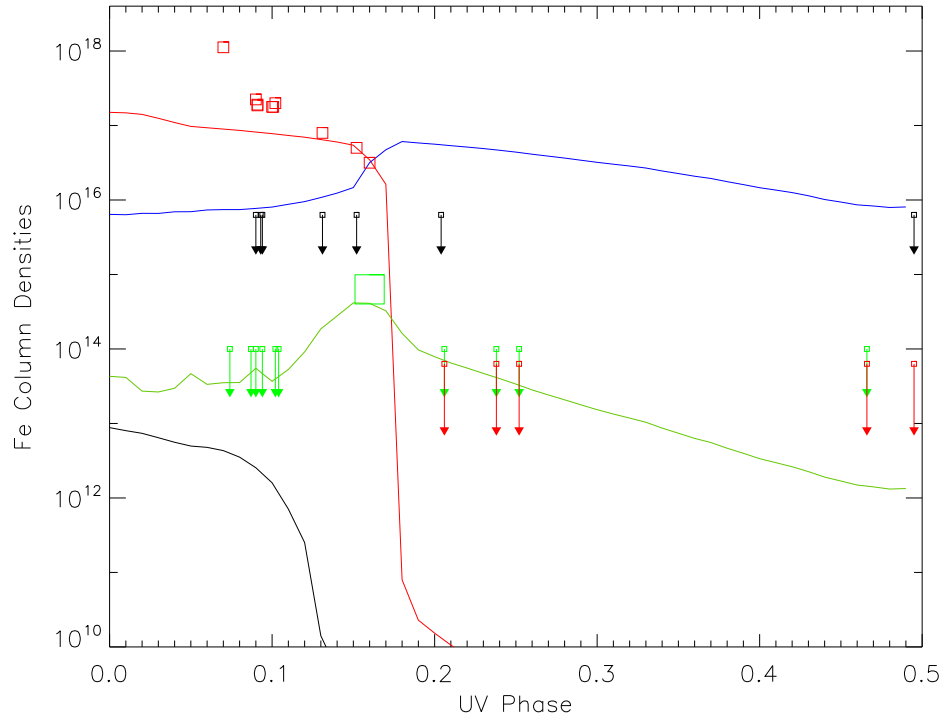
the photons ‘see’ a large amount of wind material along the sightline. The photons are rapidly exhausted and the  $\text{Fe}^{2+}$  zone is extremely narrow and lies close to the dwarf where the cool wind density is relatively low. At this phase the Fe III column densities are undetectable and the vast majority of material along the line of sight is unaffected by the ultraviolet radiation field.

At a less eclipsed phase (say  $\phi \sim 0.16$ ), the density profile along the line of sight is much shallower and the photons can propagate further and ionise further along the line of sight. The models still predict a narrow  $\text{Fe}^{2+}$  zone, however this zone is much further from the dwarf than at  $\phi \sim 0.10$  and occurs closer to the giant where the giant wind density is higher than it is for more eclipsed phases. Since the density within the  $\text{Fe}^{2+}$  region is higher, the column is now detectable. This explains the temporary appearance of Fe III lines at phase  $\phi=0.16$ .

At even less eclipsed phases (say  $\phi \sim 0.20$ ), the density of the giant material between the dwarf and the observer is much less and the ultraviolet photons propagate much further, and ionise the full sightline (at least interior to the binary orbit). The models predict that the ionisation level does not fall below  $\text{Fe}^{3+}$  (which is undetectable in the ultraviolet wavelength range) and explain the disappearance of both Fe II and Fe III features at these phases.

The results of the modelling of the iron column densities are presented in Figure 5.7. The predicted column density variations of  $\text{Fe}^0$  (black),  $\text{Fe}^{1+}$  (red),  $\text{Fe}^{2+}$  (green) and  $\text{Fe}^{3+}$  (blue) are plotted. The measured data points are overplotted in the corresponding colours, where the size of the datapoints represent the size of the uncertainties. Upper limits are also plotted. The model was calculated assuming a Vogel wind acceleration. The velocity law used did not significantly affect the results as long as the wind acceleration was delayed (i.e. either a Vogel acceleration or else a high order  $\beta$ -law wind). This is discussed further in chapter 7.

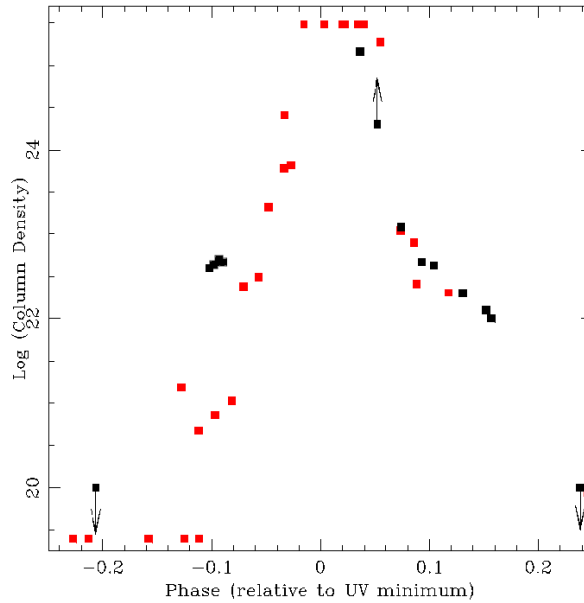
It must be noted that the photoionisation calculations are stopped once the electron temperature drops below 4,000K along each line of sight, therefore these models only treat the material in the region of the wind which is affected to some degree by the dwarf radiation. Therefore, the column densities which match the model at the less eclipsed phases, but not at more eclipsed phases, must diagnose the ‘extra’ intervening material which is not accounted for in the photoionisation model; i.e. the radiatively undisturbed parts of the wind. The Fe II columns are significantly higher than predicted by the model at more eclipsed phases so it follows that the extra material is singly ionised iron. The models show that for phases where  $\phi < 0.15$ , the majority of the material along the sightline will not be significantly radiatively affected by the dwarf.



**Figure 5.7:** Models of the column density variations of Fe I (black), Fe II (red), Fe III (green) and Fe IV (blue) assuming a Vogel wind acceleration. Overplotted are the column densities derived from the data. There are no transitions diagnosing the  $\text{Fe}^{3+}$  column densities. Note that material which is not affected by the dwarf radiation is not included in the column densities, therefore the sections of the line of sight which are unaffected by the dwarf radiation does not contribute to the columns. This accounts for the discrepancy between the model and the datapoints for more eclipsed phases. See text for further details.

## 5.5 Large-Scale Wind Structure

The fact that the wind is directly viewed in absorption and that the change with impact parameters can be measured means that it is possible to measure the overall distribution of the circumstellar material. Once the ionisation structure is known, the distribution can be derived from the variations of any absorption features. Due to the H I profiles being so well-defined, the most reliable transition with which to study the large-scale structure is Lyman  $\alpha$ . Displayed in Figure 5.8 are the variations of the neutral hydrogen column densities with orbital phase. The datapoints in red were derived from fits to *IUE* data. While the black datapoints (with uncertainties less than the size of the points)



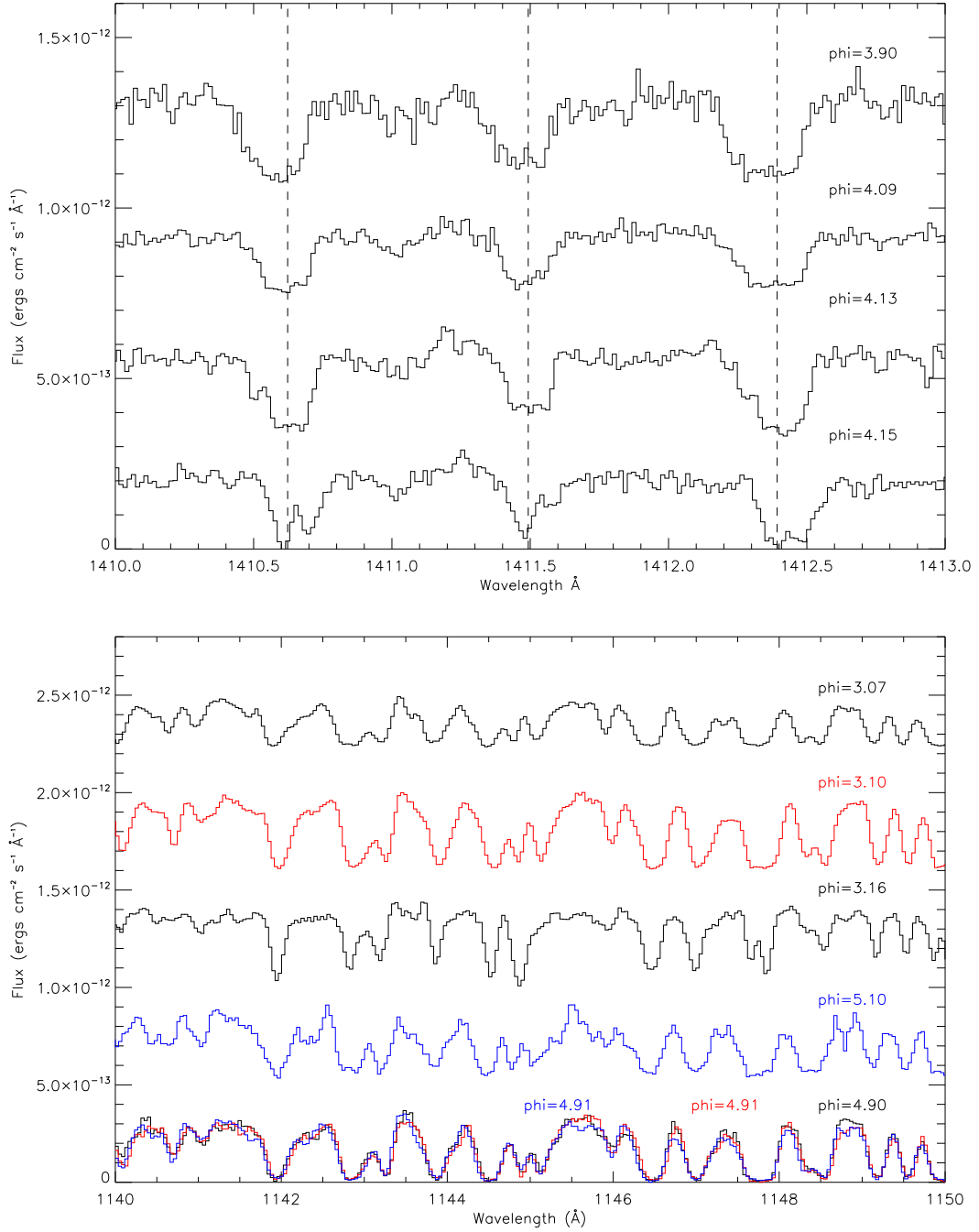
**Figure 5.8:** Column densities of neutral hydrogen as a function of orbital phase. The red datapoints are derived from fits to low resolution *IUE* data. The black datapoints are derived from *FUSE* and *STIS* data where the uncertainties are of the order of the size of the datapoints. There is evidence for an asymmetry in the material around the giant, which is most likely due to a mechanical redistribution of the material by the motion of the dwarf.

were derived from the *FUSE* and *STIS* data. This distribution provides a measure of the neutral material that is located above the limb of the giant photosphere. A method of inferring the shape of the wind acceleration profile from this data is discussed in the following chapter.

## 5.6 Small-Scale Wind Structure

In addition to providing information on the large-scale wind distribution, the shapes of the wind absorption profiles also provide clues as to the small-scale wind structure. The lower spectral resolution of *FUSE* precludes the detection of structure within the narrow far-ultraviolet profiles. However, the fact that there are no major changes observed in the line shapes over daily time-scales places an upper-limit on the short time-scale variability of the wind structure (see Figure 5.9 (lower panel); also note the variation of the continuum and absorption line profiles with phase).

An analysis of the STIS echelle data, however, unveils a definite structure to the wind absorption profiles. This is clearly evidenced by viewing Figure 5.9 (top panel). The majority of the components are located very close to the radial velocity of the system. However, some of the weaker components lie up to  $30 \text{ km s}^{-1}$  either side of the line centre in velocity space. These absorption profiles are further discussed in the following chapter.



**Figure 5.9:** Example plots of the variation of the narrow wind line profiles from STIS (top panel; where the dashed lines correspond to the line centres at the EG And rest velocity) and FUSE (lower panel) spectra. Note the structure that is resolved in the STIS profiles. This structure remains unresolved in the lower resolution FUSE spectra, however the relative constancy of the profiles observed over a 3-day-time period (lower three spectra) place upper limits on the variability and unevenness of the outflow.

# 6

## Implications for Stellar Mass-Loss

In this chapter the significance of the results that were derived from the wind analysis are discussed. Both the extent of the regions displaying chromospheric conditions and also the actual physical conditions in the lower wind itself (derived from both absorption and emission line analysis) are discussed in light of model predictions, and also of what exists in the literature. Information from the absorption lines is used to constrain the possible wind acceleration profiles and also infer information on the small scale structure of the wind. Finally, the implications that these results hold for the mass-loss theory of evolved stars are discussed.

### 6.1 Physical Conditions

The viewing of the circumstellar material in absorption provides us with a direct method of measuring the wind conditions. It is found that, within the error-bars, the excitation temperature of the wind as measured with the Fe II populations remains isothermal ( $\sim 8,000$  K). According to the PHOENIX model which was run for the EG And stellar parameters (see Chapter 3; Figure 3.6), the temperature rise above the photosphere is extremely sharp. In fact, the model displays a temperature rise from  $\sim 3,600$  K in the photosphere to  $\sim 8,000$  K over a distance of  $\sim 0.5 R_{\odot}$ . This implies that chromospheric

conditions exist directly above the photosphere and that the temperature remains approximately constant up to a distance of at least  $\sim 3.2 R_{RG}$ . It should also be noted that the temperature derived from the ionisation level within the wind does not match the excitation temperature. The ionisation level is higher than would be expected in a gas at  $\sim 8,000$  K which is in thermal equilibrium. However, this is expected for material above the photosphere, as it is apparent that the LTE approximation does not apply for these type of conditions, even though the level populations of complex ions (such as  $\text{Fe}^+$ ) appear to be Boltzmann.

It is also directly observable from the spectra that the chromosphere extends out to at least  $\sim 3.2 R_{RG}$ , and possibly beyond. Although the material viewed in absorption at the larger impact parameters ( $\phi \sim 0.16$ ) is certainly affected by the dwarf radiation, the two dimensional photoionisation modelling shows that the majority of the gas along the line of sight for  $\phi < 0.16$  is unaffected. Whilst the photons will ionise wind material along a fraction of the line of sight, they are exhausted when reaching the denser regions of the wind and the majority of the sight line remains unaffected. Therefore, it follows that the conditions that are derived are intrinsic chromospheric conditions. In addition to the information that is obtained from the absorption lines, details on the chromosphere can be obtained by examining the eclipsed ultraviolet spectra.

### 6.1.1 The Extended Chromosphere in Emission

As noted by Stencel & Sahade (1980) and in subsequent papers, the *IUE* spectrum of EG And during eclipse consists of strong narrow emission lines arising from a wide range of excitation energies, with no indication of continuum above the sensitivity limit of *IUE* ( $\sim 1 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ ). As discussed in chapter 4, the emission from the broad, high-ionisation components disappears during eclipse, and the narrow cores ( $\sim 30 - 50 \text{ kms}^{-1}$ ) of the strong emission lines are reduced, typically by a factor of  $\sim 3$ . Much of this residual emission originates in the photoionised section of the wind located between the two stars.

However, there is also a chromospheric component to the emission lines of the relatively low-ionisation and low-excitation lines. This is especially apparent for a number of low-excitation Fe II and Ni II emission lines at the near-ultraviolet red wavelength end of the STIS data. These lines have upper energy levels that can be collisionally populated at chromospheric temperatures (i.e.  $\lesssim 10,000$  K) and, in contrast to most transitions from the same species, they appear in emission at all orbital phases, including at complete

eclipse<sup>1</sup>. Those transitions that lie within the *FUSE* and STIS E140M bandpasses (corresponding to  $\lambda < 1730\text{\AA}$ ) must have upper energy levels of at least 7.2 eV, and higher if they are not resonance transitions. These energies are too high for the levels to be populated collisionally at chromospheric temperatures. This explains why the chromospheric emission lines are only observed towards red wavelengths where the upper levels can be as low as  $\sim 4$  eV above ground. The upper levels can certainly be populated in other ways. However, previous studies of red giant chromospheres have found that Fe II chromospheric emission is primarily collisionally excited (Judge & Jordan, 1991), in agreement with our observations. The collisionally excited model for the chromosphere and lower wind is also consistent with the excitation structure derived from our absorption data.

## 6.2 Large-Scale Structure

If the ionisation structure along the individual lines of sight are understood, it is then possible to derive information on the large-scale structure of the wind by analysing changes in the absorbing columns with phase. Since the column densities of neutral hydrogen are subject to least uncertainty, the variations of these profiles can be used to reconstruct the velocity profile of the wind.

### 6.2.1 Wind Acceleration

By tracking the variation of the profiles of neutral hydrogen absorption features at different phases it is possible to map the spatial extent and distribution of the wind. However, finding the run of the velocity profile using the absorption column densities is a mathematically complicated inverse problem that requires the density profile along the sightline to be reconstructed. Knill et al. (1993) discuss this particular problem of reconstructing the density profile of a stellar wind in a binary system and have developed a mathematical technique for doing so. The equation to be inverted is:

$$N_H(b) = a \int_b^\infty \frac{dr}{\sqrt{r^2 - b^2} r v(r)}, \quad (6.1)$$

where  $b$  is the impact parameter of the two components,  $a$  is a constant defined by the mass loss parameters of the system,  $r$  is the distance from the giant and  $v(r)$  is the velocity, i.e. the variable to be determined.

---

<sup>1</sup>These features are not used to obtain column densities in partially eclipsed phases. The profiles are complex, with radiative transfer calculations required to model them, which are in contrast to the lines at bluer wavelengths where a pure absorption analysis is possible.

As outlined by Knill et al. (1993), the continuity equation (6.1) is an integral equation of Fredholm's type, but it can be brought to Abel's type by means of suitable transformations. Using this method, it is then possible to invert the equation by an explicit diagonalisation of the Abel operator. The analysis assumes a neutral, spherical wind and a circular orbit. In practise, the observed column densities are parametrised by a polynomial and the velocity field is then obtained from the inverted Abel's operator. The technique is implemented by Knill et al. (1993) who fitted column densities derived from low-resolution *IUE* data of EG And, and concluded that the onset of the wind acceleration is swift, but does not occur until a distance of  $\sim 2.5 R_{RG}$  from the limb of the giant. This result is similar to that derived by Vogel (1991) using empirical methods on the same H I data. However, no information on the ionisation structure of the wind (apart from the fact that large amounts of neutral hydrogen are present) could be obtained from the *IUE* data, and the limitations of the instrument meant that there were large uncertainties in the column densities. This inversion was applied to the H I column densities derived from the *FUSE* and STIS spectra and the resultant fit and derived velocity profile are presented in Figure 6.1.

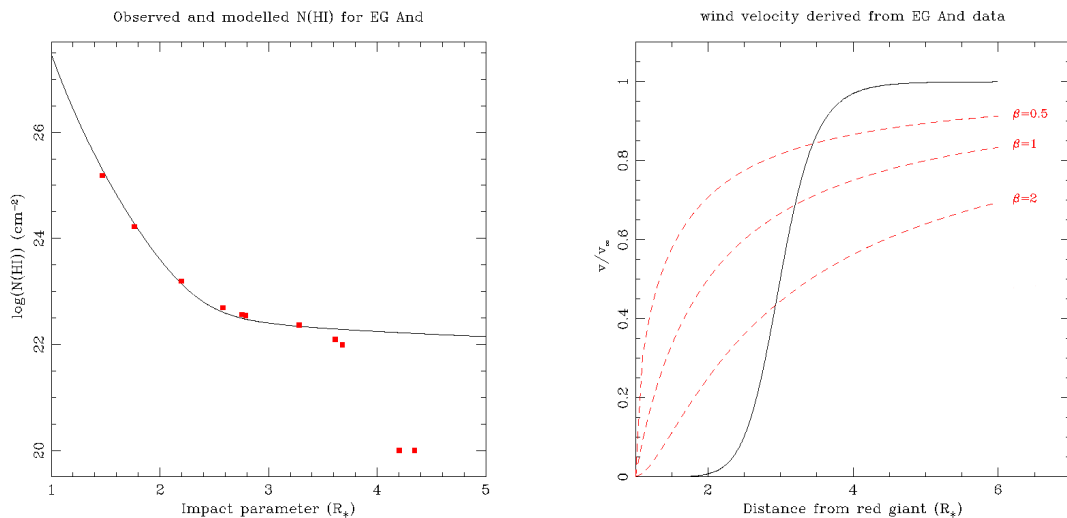
Plotted in the panel on the left of Figure 6.1 are the H I column density datapoints (which were measured on egress<sup>2</sup>) plotted against impact parameter. Overplotted is a parametrised fit. The sudden drop in H I column at  $b \sim 3.5 R_{RG}$  corresponds to the distance above the limb of the giant where its wind becomes fully ionised and the majority of hydrogen in the line of sight is no longer visible in the H I lines (see the description of the photoionisation modelling of the sightlines in chapter 5).

Although the resultant velocity profile appears to be incompatible with the overplotted  $\beta$ -laws, it is instructive to examine the robustness of the inversion to uncertainties in the H I columns at crucial impact parameters. For example, although the derived wind acceleration is extremely steep between impact parameters  $\sim 2.0$  and  $3.7 R_{RG}$ , the column density datapoints are only accurately known at impact parameters corresponding to the interval  $\sim 2.1$  and  $3.2 R_{RG}$ . The column densities of the most absorbed spectra are uncertain due to almost complete attenuation of the continua, whilst the H I columns derived from the least eclipsed spectra become uncertain due to partial ionisation of the sightline. Therefore, much of the inverted velocity profile is extrapolated and, since the inversion is unstable, it is desirable to test the stability against errors where the columns are known to possibly be unreliable.

In order to test the stability of the inversion to errors in the column densities, and also

---

<sup>2</sup>The ingress datapoints were excluded since the wind is known to be asymmetric. However, since the asymmetry is small, their inclusion does not alter the derived wind profile beyond the original error-bars.



**Figure 6.1: Left:** Model of the HI column density falloff as a function of distance from the giant primary in EG And overplotted against the H I columns derived from FUSE and STIS egress data. Note the deviation of the model from the datapoints at  $b \sim 3.5R_{RG}$  corresponding to the distance where the hydrogen is ionised by the white dwarf. **Right:** Plot of the run of the velocity profile of the giant derived from the model shown on the left using an inversion technique. Note the deviation of the velocity profile from  $\beta$  laws, commonly used to parameterise the wind profile in late giants.

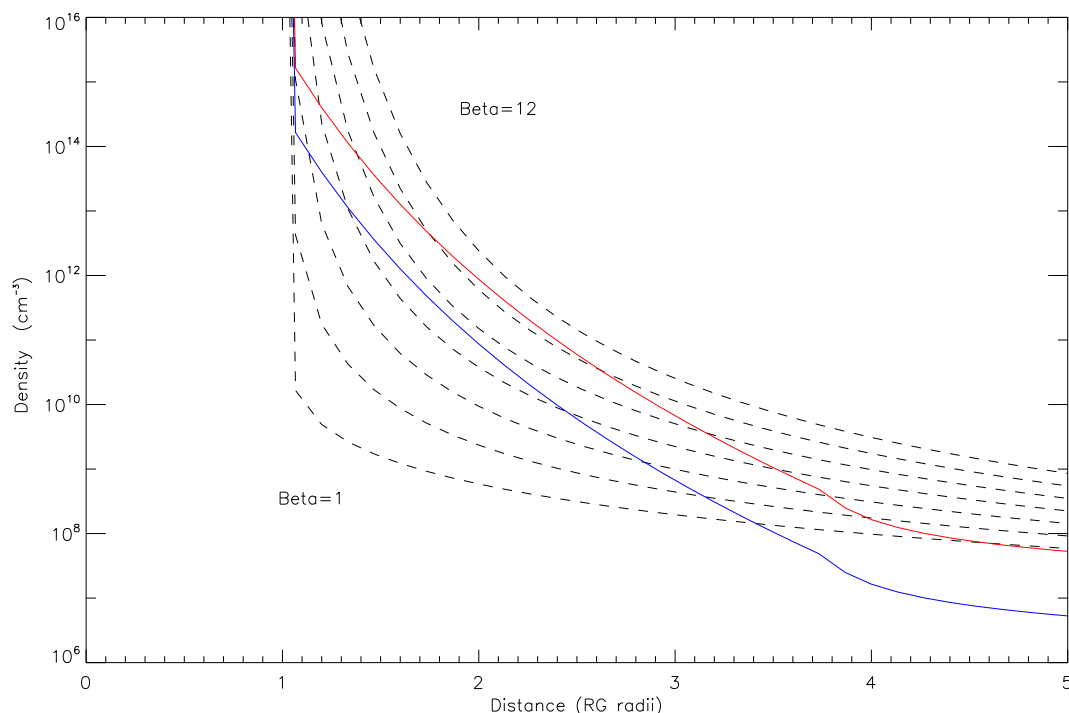
to an absence of data at crucial impact parameters, a numerical forward modelling analysis was carried out. In the analysis, a grid of points ( $100 \times 100$ ) are assigned densities based on an input velocity law and assuming constant and symmetric mass-loss and continuity of mass. The densities along the lines of sight were then integrated to derive column densities at different impact parameters which were used to reproduce the observable information derived from the ultraviolet data. Noise was added to these column densities, which were irregularly sampled, and they were inverted in order to test the robustness of the process. The results (using the EG And binary parameters) show that, *although the inversion reproduces the shape of the velocity profile within the first few stellar radii, the shape of the acceleration past  $\sim 3$  stellar radii is not well-defined if the impact parameter is poorly sampled, or if there are large errors at crucial impact parameters.* Since the H I datapoints that are derived only sample the initial wind acceleration region, it must be realised that the derivation of the Vogel law requires an extrapolation to impact parameters where no H I data can be obtained for EG And.

The fact that similar results will be obtained for winds of a high  $\beta$ -law number and wind with a Vogel type wind can be understood by examining the density profiles of the

winds with different acceleration profiles. Plotted in Figure 6.2 are the wind densities against distance above the photosphere for a range of different wind acceleration models. The dashed lines correspond to different  $\beta$ -laws whilst the red line displays the density profile of a wind with a Vogel type acceleration. The blue line also corresponds to a Vogel wind acceleration, but with a mass-loss rate an order of magnitude less than the other models. It is apparent that if the mass-loss rate is poorly constrained (typically only known to orders of magnitude), and if the densities at impact parameters less than  $\sim 2$  stellar radii and greater than  $\sim 3$  stellar radii are poorly constrained, then the data will not be able to differentiate between a high  $\beta$ -law wind and a Vogel wind. What is easily distinguishable, though, is whether or not the wind is accelerated steeply just above the photosphere (i.e. a low  $\beta$ -law model, typically used to parametrise hot, luminous stars and sometimes cool giants). The shape of the density profile (and also column density profile) is radically different from the ‘slow’ wind models.

However, despite the uncertainties that are involved in deriving the shape of the acceleration profile past  $\sim 3$  stellar radii, the knowledge of the ionisation structure of the wind, combined with the high quality of the spectra, lead us to believe that the derived steep wind acceleration at  $\sim 3$  stellar radii (the Vogel law) is probably *not an artifact of the technique*. The observation of a very similar wind in the eclipsing symbiotic star SY Mus (albeit derived using the same H I technique) would, again, argue for the existence of this wind acceleration profile in evolved giants. For the EG And case, the errors on the H I columns are sufficiently small to constrain the shape of the function to be inverted, although it would require more ultraviolet observations within the phase range ( $\sim 0.10$ - $0.15$ ) in order to definitively tell if the Vogel wind law is real.

One very likely possibility is that the Vogel law is real, but that the characteristic swift acceleration is an *artifact of the binary nature of the system* and is not present in isolated giants. It is expected that the presence of the dwarf will have an effect on the wind flow when the wind material is close enough to the dwarf so that its gravitational effect becomes appreciable. Assuming masses of  $3.5M_{\odot}$  and  $0.6M_{\odot}$  for the giant and dwarf respectively, then the mass ratio is  $\sim 5.8$  and it is apparent that the wind will not be significantly gravitationally affected by the dwarf until large impact parameters are reached. However, it is possible that the wind is gaining an extra impetus from the dwarf gravitational field at an impact parameter of  $\sim 3$  stellar radii; which is where the Vogel law places the steep acceleration. Since this technique relies on observations where the dwarf is always ‘behind’ the wind from our viewpoint, then this is a real possibility. This would also explain why no changes in the physical conditions in the wind are diagnosed through the absorption lines as the wind begins to accelerate. However, any possible binary effect



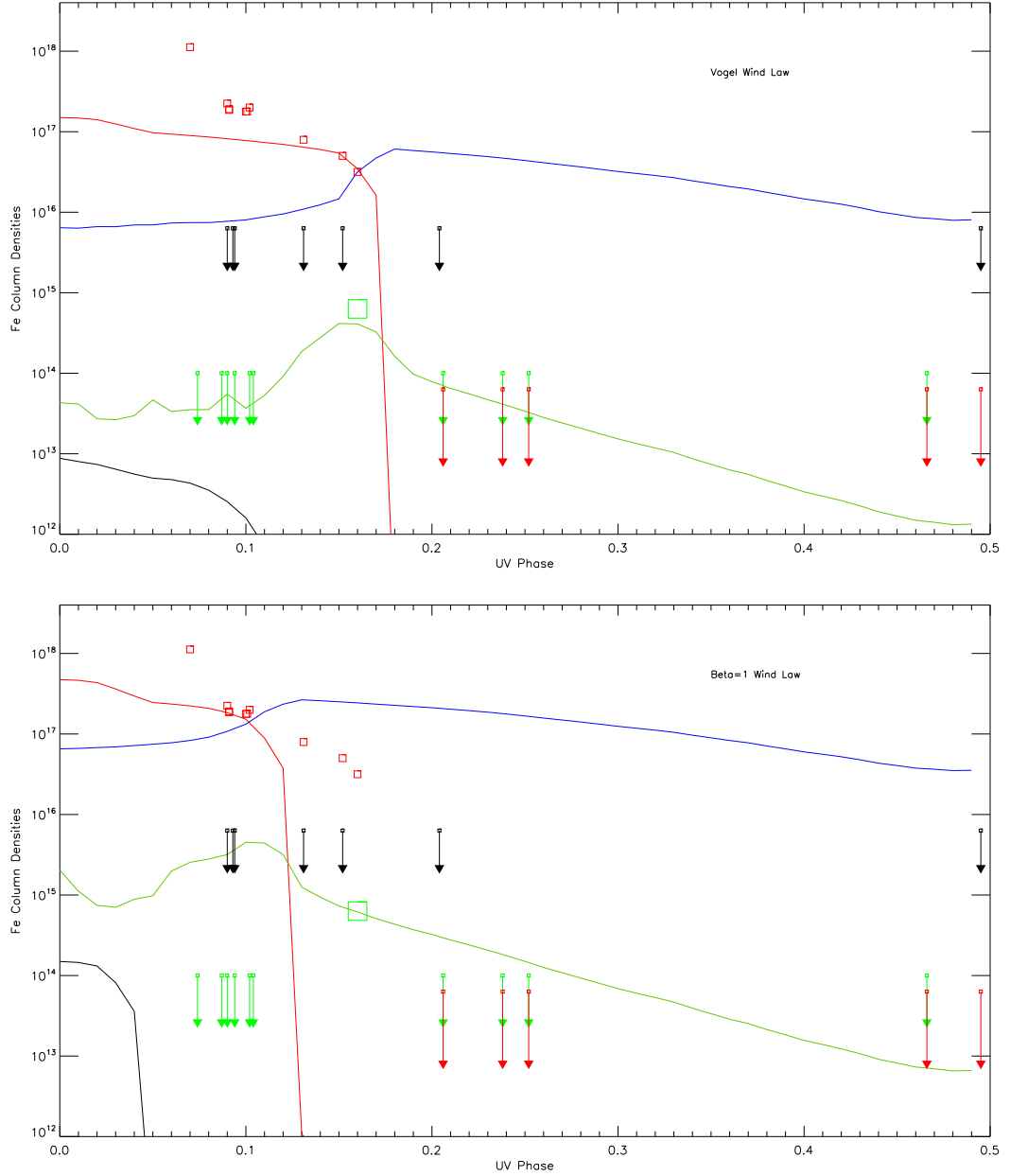
**Figure 6.2:** The predicted densities in the wind plotted against distance above the photosphere for a range of different wind acceleration models. The dashed lines correspond to different  $\beta$ -laws whilst the red line displays the density profile of a wind with a Vogel type acceleration. The blue line also corresponds to a Vogel wind acceleration, but with a mass-loss rate an order of magnitude less than the other models. The derived H I column densities are rather uncertain outside the impact parameter range  $\sim 2.1 - 3.2 R_{RG}$ .

cannot mimic a slow wind acceleration if the intrinsic acceleration was rapid (i.e. low order  $\beta$ -law). The effect of the dwarf on the wind would be to speed up the acceleration, and not to slow it down. In any case, the profiles of the narrow absorption lines preclude a rapid acceleration from the side of the giant star which is facing away from the dwarf. The structure of the narrow lines, as observed with STIS, are symmetric about the line centre, and no preference is observed for components on the red-wavelength side of the profile. If appreciable amounts of material are being deflected towards the dwarf, or if the material close to the surface of the giant is being accelerated, either on the side facing the dwarf, or on the opposite hemisphere, then this would be observable through asymmetric line profiles. In short, from the resolution of individual components that are symmetric about the line centre we infer that the wind has the same initial velocity profile both on the side facing the dwarf and also the opposing side.

## 6.2.2 Photoionisation Models

Using the same photoionisation methods as were described in section 5.4 (see this section for a full discussion of the modelling), the ionisation along the line of sight to the dwarf was calculated for a range of orbital phases, and also for a range of wind velocity laws. 50 lines of sight were modelled for 11 different wind acceleration profiles (the Vogel law and  $\beta$ -laws with  $\beta=1,2,\dots,9,10$ ) and the column density variations were calculated for each wind law. The results of the modelling for the Vogel law (top panel)  $\beta=1$  law (lower panel) are presented in Figure 6.3 for different species of iron. Models of the column density variations for both wind laws are plotted for Fe I (black), Fe II (red), Fe III (green) and Fe IV (blue). The corresponding measured column densities (and upper limits) are overplotted in the same colours for each species of iron. It can be noticed that the Vogel law model matches the data much better than the  $\beta$ -law model. As discussed in the previous chapter, the sudden, and brief appearance of Fe III lines is explained by the Vogel model, whilst the  $\beta=1$  model predicts a completely different behaviour of the Fe III lines. This is due to the necessity for large amounts of wind material to be located at distances of a few stellar radii above the photospheric surface. If the density of circumstellar material falls off too quickly, then the ionising photons will ionise all the material along the line of sight (in the region of the star) and the Fe II columns will disappear even at small phases; such as is predicted by the  $\beta=1$  model. The Vogel law results in a slower acceleration, and hence a corresponding increase in the density of material above the photosphere, thus altering the absorption column variations.

While increasing the mass-loss rate will result in the  $\beta=1$  wind having more material throughout the lower wind region, the mass-loss rate would have to be unrealistically large. For these models a mass-loss rate of  $7.5 \times 10^{-8} M_{\odot} \text{yr}^{-1}$  was used, which is an upper-limit to the EG And mass-loss parameter. Therefore, the star is most likely losing less material, thus making the  $\beta=1$  law column densities deviate further from the observed values. When  $\beta$ -laws of 5 and higher are used, then the results are very similar to those predicted by the Vogel model. Therefore, this analysis places constraints on the location of the wind acceleration, but not on its shape. It should be noted that if a lower mass-loss rate than  $7.5 \times 10^{-8} M_{\odot} \text{yr}^{-1}$  is used, then larger values of  $\beta$  are required to match the data. This is a confirmation of the slow wind acceleration that is independent of the H I column densities and, indeed, the Abel inversion.



**Figure 6.3:** Models of the column density variations of Fe I (black), Fe II (red), Fe III (green) and Fe IV (blue), similar to that presented in Figure 5.8. The upper panel assumes a Vogel wind acceleration whereas the lower panel assumes a  $\beta=1$  wind model and the same mass-loss rate ( $7.5 \times 10^{-8} M_{\odot}$ ). Note that material which is not affected by the dwarf radiation is not included in the column densities, therefore the sections of the line of sight which are unaffected by the dwarf radiation does not contribute to the columns. This accounts for discrepancies at more eclipsed phases.

### 6.2.3 $\beta$ Laws

As noted by Harper et al. (2005), the use of the  $\beta$ -law velocity model for isolated giants may well be misdirecting our interpretation of the diagnostics of the outflows from evolved stars. The use of this wind acceleration law has its origins in its proven ability to describe the radiatively driven winds of hot, luminous stars and also out of mathematical convenience. However, for evolved giants, the wind is known not to be driven by radiative processes and in these times of high computational power there is no reason to rely on this restrictive parametrisation. Indeed, it is likely that the a priori assumption of a  $\beta$ -law wind in studies of isolated giants is reinforcing the suggestion that winds from single stars behave in this way. In all studies of evolved binaries where the wind can be sampled with pseudo-spatial resolution, the wind acceleration profiles are found to behave very differently from low  $\beta$ -law models. Studies of the ultraviolet eclipses of  $\zeta$  Aurigae and VV Cepheid binaries indicate a ‘slow’ wind acceleration, where the material escapes very slowly out to distances of a few stellar radii before the acceleration steepens. This type of acceleration can be consistent with a very high  $\beta$ -law (i.e.  $\beta=8$ ), but which is in complete contrast to hot, luminous stars where the wind accelerates rapidly above the photosphere and where low order  $\beta$ -laws successfully predict the wind properties. Indeed, as described in the previous chapter, by using the Abel inversion, it is found that the wind of the giant may well be sharply accelerated at a distance far above the photosphere and completely at odds with any sort of  $\beta$ -law. While the effects of the secondary star on the wind acceleration are not well understood, the evidence from this dataset shows that the ‘slow’ acceleration is not an artifact of binarity, although the characteristic Vogel acceleration possibly is.

## 6.3 Small-Scale Structure

The profiles of the absorption features show that the wind material is not escaping in a smooth outflow, but in a rather clumpy and time-variable form. This type of structure has been observed before in the winds of supergiant stars (Bennett, private communication; Griffin, 2005), but still cannot be satisfactorily explained. Griffin (2005) found that the lower chromospheres of several  $\zeta$  Aurigae systems are composed of structures (small relative to the outflow size) whose movements in velocity space can be tracked for several days, or even weeks. The structure of individual clouds that are resolved in our STIS data, while not variable over *HST* orbital time-scales ( $\sim 90$  minutes), cannot be tracked from observation to observation (closest spacing is 8 days), which suggests that the cloud sizes are smaller than observed in the supergiants. It is apparent in the case of EG And

that new clouds of gas are viewed in absorption during each observation. Indeed, this is all consistent with calculations carried out by Freytag (1999) whose results suggest that a supergiant star such as Betelgeuse could have a few hundred cells on its photospheric surface, and that the number of cells will increase (and their sizes correspondingly decrease) as one examines stars with smaller radii.

By estimating the local pressure scale heights of the upper atmospheres of EG And and typical supergiant stars, it emerges that the characteristic scale lengths that are calculated are comparable to the inferred cloud sizes. Assuming chromospheric temperatures and a stellar mass of 1.6 times solar, the scale height in EG And is  $\sim 0.2R_{\odot}$ . If typical clouds are of these dimensions, then the line of sight to the dwarf would pass through different clouds on time-scales of a few hours; in agreement with the observations. Using the scale heights calculated for supergiants (using parameters of the stars studied by Griffin (2000)) and the orbital parameters of long period  $\zeta$  Aurigae binaries, it works out that the same cloud can be viewed on time-scales of days. Again, this is in agreement with the observations. Support for the flocculi having these dimensions comes from the observation of only two strong components in the February 16 STIS spectrum. If the clouds were very much smaller than a solar radius, then the integrated profiles would be much smoother, and no individual clouds could be resolved in the integrated profile. However, for all of the profiles observed at more eclipsed phases, the components are all blended and overlapping close to the line centre and no resolved structure is observed. This implies that enough clouds are always present in absorption to broaden the profile; thus setting an upper limit on the cloud sizes. In addition, based on a simple reconstruction of the sightline interior to the dwarf's orbit, it is possible to recreate the characteristic structure that is observed in the line profiles with flocculi with sizes of fractions of a stellar radius. Also, by assuming that the clouds retain their photospheric densities as they pass along the line of sight, analysis of the column densities shows that the sizes will be roughly consistent with those derived above (i.e. a few thousand would cover the stellar photospheric disk). It appears that the clumpy nature of cool star outflows is ubiquitous and that the characteristic cloud sizes scale with stellar radius.

## 6.4 Implications for Wind Driving Mechanisms

The analysis of these data has provided many constraints on the possible processes contributing to the driving of the wind.

EG And is a system with no intrinsic dust, yet it is still observed to be losing mass. It is therefore obvious that the wind acceleration is unrelated to dust in this object. In fact,

it is possible that dust does not contribute to the initial wind acceleration in the more evolved AGB stars either. Judge & Stencel (1991) find that the mass-loss process is most likely unrelated to the presence of dust (except for the most evolved stars; infrared carbon stars) and it probably involves a two-stage process. In this scenario, AGB stars lose mass through the same processes as all other red giant stars, however when a significant dusty circumstellar shell has formed (typically stars of type M5 and cooler) the mass-loss rate is increased due to a second, additive mass loss process. This mass-loss enhancement is due to radiation pressure on the dust that has formed in the outer shell and can explain the enhanced mass-loss. However, it follows that, even for AGB stars, the initial mass-loss from the photosphere itself cannot be explained by the presence of dust and that the wind generation cannot be explained. From analysis of energy momentum fluxes, Judge & Stencel (1991) conclude that the same mass-loss processes are probably at work in all evolved cool stars. Therefore, it seems that the same mechanism that drives the wind in EG And also drives the initial outflows in more heavily evolved stars.

Molecular opacity is suggested as a primary contributor to the wind acceleration by many authors including van Buren et al. (1994, and references within). *FUSE* is extremely sensitive to the presence of molecular hydrogen throughout the wind acceleration region and it is found that there is no contribution of any molecular opacity to the wind generation. Photoionisation models show that the white dwarf radiation will not propagate far into the giant wind and that the derived wind conditions are representative of normal red giants. Therefore, it emerges that no molecules exist between the photosphere and the very outer region of the wind where the material is slowed by the ambient medium, and where dust and molecules can form. Indeed, the study of molecular emission features in AGB stars most likely diagnose this circumstellar shell and not the inner wind region. It should be noted that many properties of evolved star winds (such as the terminal velocity) are derived from molecular emission features and care should be taken when applying these results to stellar *winds* when they in fact diagnose a circumstellar shell.

Polarisation measurements have been carried out on EG And to determine whether a magnetic field is present. The results, however, are inconclusive, and the small observed polarisation ( $\sim 0.2\%$ - $0.4\%$ ; Schulte-Ladbeck et al., 1990) could be due to either scattering, a magnetic field or some other effect. Although high mass-loss rates and a large magnetic field are required for Alfvén waves to be an effective wind driver, the observations do not rule this out and it is possible that magnetic fields do play a role.

Judge & Stencel (1991) conclude that small-scale pulsations probably play a role in mass-loss. All stars from spectral type K0 onwards are known to pulsate, with the amplitudes increasing as one examines more evolved stars (Percy & Parkes, 1998). There is

evidence in this data that photospheric pulsations are probably related to the mass-loss. It appears that the pulsations can mechanically expel clumps of material from the surface but the underlying mechanism still remains unknown. The evidence that the mass-loss is related to pulsations comes from an analysis of the photometric variations in combination with the ultraviolet spectra. Variations in the photometric and ultraviolet spectra which are unrelated to phase most likely diagnose variations in the mass-loss. These variations manifest themselves as increases in the ultraviolet continuum flux (up to a factor of  $\sim 2$ ) and large increases (up to a factor of  $\sim 5$ ) in emission line fluxes of low- and medium-ionisation species. The variations can be explained by periodic increases in the amount of mass lost from the giant, resulting in increased nebular gas densities and enhanced accretion onto the dwarf. These changes were occasionally present in the *IUE* data and appear once in our dataset (the final STIS spectrum which was observed at phase  $\phi=0.50$ ). In addition to this, variations are also observed in the far-ultraviolet continuum fluxes which are unrelated to orbital phase. These variations were also observed with *IUE*, and are most notable in our final STIS spectrum. These ultraviolet continuum variations and also the peaks displayed in the U-band photometry diagnose increased periods of accretion onto the dwarf surface. From analysis of the nebular emission lines, it emerges that the nebular densities close to the dwarf during these periods are enhanced. This is most likely due to periodic increases in the mass-loss of the giant, which can be related to pulsational activity through the behaviour of the BVR-band photometry. It is possible that we are seeing evidence of spasmodic ejections of material from the lower chromosphere and that these are related to atmospheric pulsations, although much work remains to be done in order to understand these complex processes.

# 7

## Conclusions and Future Work

Based on a wealth of multiwavelength data, this thesis has presented the most in-depth analysis of any symbiotic binary system to date. The high resolution dataset is both spectrally and temporally extensive. A wavelength range, stretching from the far-ultraviolet to the near-infrared, is covered at high-resolution and, in temporal terms, covers a number of orbital phases over different orbital epochs. The spectral dataset is complimented by regular UBVR photometric monitoring. The observations provide information over a wide range of timescales.

Multi-wavelength data cover timescales on the order of the orbital period. This permits the stability of the system to be assessed and a model of the binary to be developed. The timing of the ultraviolet observations make it possible to study changes over timescales of months to weeks, while the photometric coverage (and also some ultraviolet spectra) provide information on the behaviour of the system over nightly timescales. By examining the individual exposures of the *FUSE* and STIS data it was even possible to monitor the behaviour of the wind, ultraviolet continuum, and hot gas over the orbital timescales of the satellites ( $\sim 90$  minutes). Using all of this information, a model for the binary system has been developed. It is found that due to the low luminosity of the dwarf star, its influence on the giant wind is minimal. Based on the optical spectral analysis and the observed repeatability of the ultraviolet observations it was confirmed that EG And is an

ideal testbed for studying the wind acceleration region of a red giant star.

The spectral and photometric data were used to construct a model of the system within which the observed data and variations could be understood. Analysis of the data, within the framework of this model, allowed the spectral features that diagnose the different material within the system to be disentangled. Interpretation of the spectra in the context of this model reveals high-velocity ( $\sim 1,000 \text{ km s}^{-1}$ ) and highly ionised material ( $\text{O}^{5+}$ ) in close proximity ( $\sim 1 R_{\odot}$ ) to the white dwarf star. The spectral features diagnosing this material are variable on the timescale of the *FUSE* orbital period and are observed to switch between P-Cygni and inverse P-Cygni wind profiles on longer timescales. As one moves away from the dwarf, the effects of the dwarf radiation diminish and the ionisation level drops, although the ultraviolet radiation field still dominates the conditions. It is this ionised portion of the red giant wind from which the narrow, nebular emission lines (i.e. C III, N III, O III) originate. Photoionisation modelling and a radial velocity analysis confirm that these nebular features do indeed originate in the outer portion of the wind and not in circumbinary gas.

As one views the red giant wind closer to the surface of the cool star, the effect of the dwarf photons rapidly becomes less important as evidenced by the diagnostics derived from the wind absorption lines and corroborated by the photoionisation models. The majority of the wind material can then be regarded as being unperturbed by the binary companion, and any information on this material that is derived can be thought of as being representative of the intrinsic properties of the wind. As one moves further away from the dwarf and eventually reaches the photosphere of the giant, it becomes apparent that the vast majority of ultraviolet photons have been exhausted and that the structure and conditions at this level in the star are very similar to isolated, cool objects. This statement is based on both the results of photoionisation modelling, as well as on the analysis of the optical spectra and on the results of a sophisticated modelling of the photosphere using the PHOENIX stellar atmosphere code. A further advantage of the photospheric modelling lies in the derivation of the inner boundary conditions of the wind. The modelling also facilitates the placement of the giant in the context of other, isolated giant stars, and to gain an understanding of whether any information obtained in this study can be extrapolated to other objects and, if so, to what extent.

The most valuable insights, however, have been gained from the analysis and modelling of the variable wind absorption lines in the ultraviolet *FUSE* and STIS spectra. Due to the small size of the secondary star, its ultraviolet radiation acts as a pencil-beam with which to view the giant wind material in absorption as the dwarf moves behind the primary star around time of eclipse. Using this phenomenon to analyse the wind provides spatially

resolved information on the thermal and dynamic conditions in the wind at a number of heights above the photosphere, right through the upper chromosphere and the base of the wind acceleration region. These are regions where much still remains unknown for evolved stars in general.

Although similar studies have been performed on other binary objects, these results are a vast improvement on what has been achieved with observations of those other systems. Many of those systems have very long periods and show evidence for a very complex ionisation structure where the secondary component is most likely having a major effect on the cool wind conditions along the line of sight. For EG And, the low luminosity of the dwarf, the high quality multi-wavelength data, and an orbital period that is conducive to space-based observational monitoring mean that the effects of the white dwarf can be quantified. In addition, this analysis represents a vast improvement on previous ultraviolet studies of this object. There are a number of areas of improvement, but the most important one is that the high sensitivities of the *FUSE* and STIS detectors combined with the high spectral resolution of the ultraviolet data allows the profiles of the narrow wind lines to be observed (and in some cases resolved). This was not possible with previous ultraviolet observatories such as *IUE*.

An analysis of these absorption lines has led to a determination of the thermodynamic conditions and physical structure of the base of the wind. Using an LTE absorption line code (in combination with other absorption line techniques) upwards of 90% of the absorption features have been identified and included in the model. The analysis has determined that the majority of the wind is neutral in hydrogen, carbon, nitrogen and oxygen, and is singly ionised for heavier common elements such as magnesium, silicon and iron. Indeed, lines from excited levels of  $\text{Fe}^+$  make up  $\sim 51\%$  of the absorption features in the combined *FUSE* and STIS ultraviolet wavelength region. By mapping the populations of the excited levels of the  $\text{Fe}^+$  ion it was determined that the wind remains relatively isothermal through the region probed in absorption, an excitation temperature of  $\sim 7,000\text{--}8,000$  K.

In addition to the information on the excitation and ionisation level of the outflowing material throughout the base of the wind, the absorption features also provide us with information on both the small and large scale structure of the outflow. While it is possible to study the structure of the very outer limits of the winds of extremely evolved giants (for example using maser emission lines), very little is known about the structure at the wind base and at distances at which the outflow is accelerated. The observation and analysis of this region is crucial to the understanding of the mass-loss problem as it is at these distances where energy is imparted into the material that allows it to escape from

the star. The analysis of material that is many tens of giant radii away from the surface (only observable in heavily evolved AGB stars in any case) deals with matter that has already escaped from the star and is being affected by physical processes that are different to those that occur at the initial wind acceleration region. i.e. the material at the outer limits of the wind is being slowed by the ambient medium, but also gaining momentum from radiation pressure on the newly formed dust grains. These processes are entirely different to those taking place at the regions where the material is being expelled from the star and this should not be confused. This should especially be borne in mind in AGB wind studies which use molecular emission lines and observable dust features to diagnose the ‘wind’. This circumstellar material is actually a shell far away from the initial wind region. Indeed, this can explain the discrepancies between many derived evolved star wind properties in the literature. For example, M-giant terminal wind velocities are often measured from molecular emission lines and are typically thought to be in the range 5-10 km s<sup>-1</sup>. However, wind velocities derived from ultraviolet resonance profiles are typically much higher (75 km s<sup>-1</sup> from this study). These observations are sampling different physical regions and care should be taken.

From an analysis of the absorption profiles, it is found that the small-scale structure of the wind is clumpy, with the flocculi having scale dimensions of a fraction of a solar radius. Indeed, variable outflows displaying internal structure have also been observed from supergiant stars and the dimensions of the clouds seem to scale with stellar radius, and to be consistent with predicted pressure scale-heights. The observed clumpy nature of the outflow seems to be a general feature of evolved stellar winds.

The damped wings of the hydrogen transitions define the ultraviolet continuum shape at absorbed phases and this allows an accurate mapping of the distribution of material around the giant. This information is used to derive a wind velocity profile contradicting simple analytical models and implies a delayed onset of acceleration. This result is confirmed by a photoionisation analysis of each sightline where an explanation of the column density variations of species such as iron require a slow wind acceleration. A further analysis shows that the wind acceleration is unrelated to the presence of dust or molecular/atomic opacity. The question is open as to whether the object possesses a significant magnetic field, and the possibility of magnetic processes contributing to the wind acceleration cannot be ruled out. A study of the ultraviolet spectral variations in connection with the photometric results, however, suggest that it is likely that the expulsion of material from the star is related to photospheric pulsations.

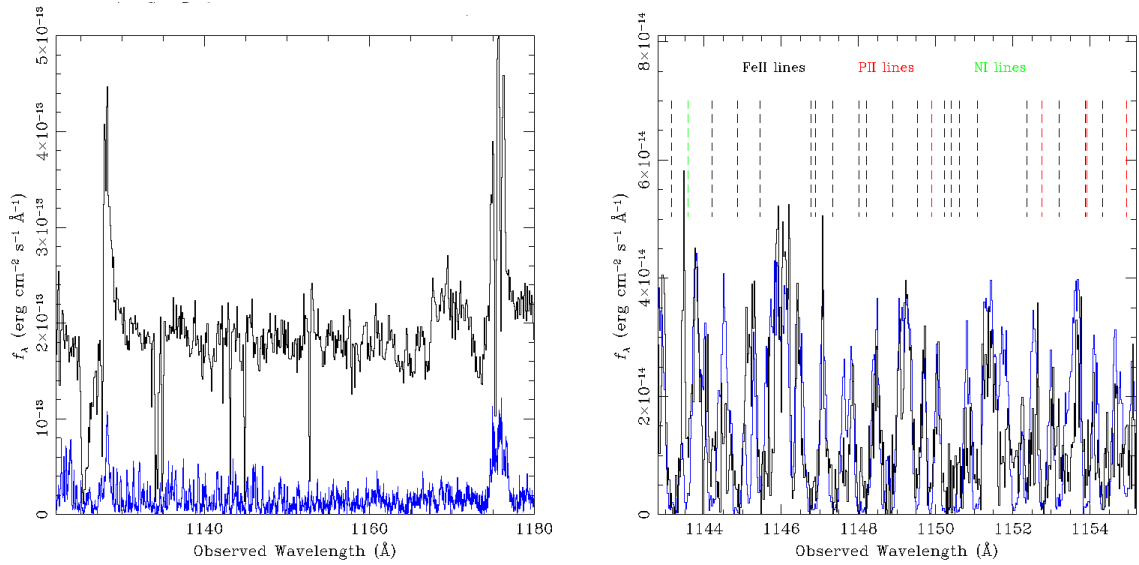
## 7.1 Future Work

An important result of this study is that it shows how suitable symbiotic binary systems are for obtaining spatially resolved information on the inner regions of red giant winds. An obvious next step in the study of these winds therefore lies in extending the ultraviolet analysis to symbiotic systems similar to EG And. This is a project I am currently engaged in with the same collaborators with whom I worked with on this thesis. Although STIS is no longer operational, it is still possible to access ultraviolet spectra of high enough resolution to detect the narrow wind absorption features through *FUSE*. We have been awarded a substantial amount of *FUSE* observing time to study the far-ultraviolet eclipses of the symbiotic systems BF Cyg and SY Mus. An ultraviolet analysis of these objects will, in theory, extend the study to a wider range of stellar parameters, which in turn will allow the effects of the different stellar parameters and chromospheric conditions to be tested. BF Cyg is of spectral type M5 and has a higher mass loss, so absorption is much stronger for a similar impact parameter. Although BF Cyg has a wider orbit, due to the larger radius of the primary it is possible to probe a similar range of impact parameters that were examined with EG And. Initial analysis shows wind conditions that are remarkably similar to EG And. SY Mus is of similar spectral type to BF Cyg, however the white dwarf luminosity is much higher and is comparable to the luminosity of the primary. A differential analysis of these systems will allow the determination of the importance of the spectral type on the wind characteristics and also the effect of the luminosity of the dwarf on the phase-dependent absorption. However, extending the ultraviolet analysis is not straightforward.

Due to pointing problems with *FUSE* (see <http://fuse.pha.jhu.edu/facts/misstat.html>) it is now difficult to observe targets at low declinations and also to schedule the repeat observations which are required for this type of study. Another problem lies in finding eclipsing binaries that are suitable for eclipse-mapping in the ultraviolet. As outlined in Chapter 2, EG And is the ideal target for ultraviolet eclipse mapping, and it follows that the other targets are less well suited. Most other systems are known to undergo outburst, some have less far-ultraviolet photons, and others present observing problems for *FUSE* in its restricted visibility mode. It is therefore not possible to study these systems in such detail as EG And. Nevertheless, it is possible to use the knowledge derived from the EG And study to maximise the amount of information that can be obtained from observations of objects that we have already obtained, and also for datasets where the orbital coverage is limited. For example, some of the partially eclipsed *FUSE* spectra of BF Cyg contain very low levels of flux from which it is difficult to differentiate between a heavily absorbed continuum and a residual continuum with weak emission features. See Figure 7.1 (left)

for a section of the uneclipsed spectrum and a section of the heavily absorbed spectrum. It would certainly be extremely difficult to gain quantitative diagnostic information on any possible absorbing material from these spectra. However, a comparison to a similarly absorbed EG And spectrum which has already been modelled immediately clarifies the situation. Correcting for radial velocity differences, and performing a simple scaling of the BF Cyg spectrum, it is apparent that the conditions and composition of the material above the photosphere are similar to those observed in EG And (see Figure 7.1 (right)). So, even though the giant is cooler and more evolved (giant spectral type M5) the ionisation conditions are similar (predominantly neutral in H,C,N,O and singly ionised in heavier common elements such as Fe. Most significantly there are no molecular hydrogen features in the lower wind. So although other symbiotic binaries are not as ideally suited as EG And for this type of study, it is possible to make use of our understanding of EG And to extend this analysis to systems with both different binary and different red giant parameters. At present we have obtained  $\sim 75\%$  of the *FUSE* data, although problems with the satellite are delaying the acquisition of some spectra. All observations are expected to be completed before the completion of *FUSE* observing cycle 7 (before April 2007) and the far ultraviolet data will be used in conjunction with archival *IUE* data, *HST* data and PHOENIX modelling of optical data to test for similarities and differences in the conditions and behaviour of the chromosphere and wind from those observed in EG And.

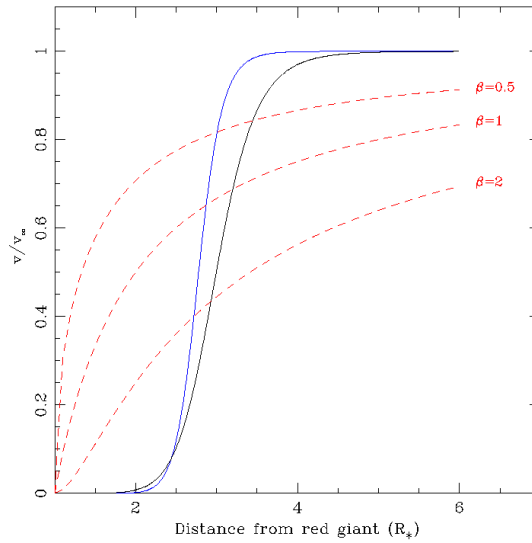
Due to the success in building a working model of the binary and in modelling the absorbing columns in EG And, it would be worthwhile to use this system as a template to compare with previously observed systems, such as the  $\zeta$  Aurigae binaries. Although these systems have long periods and the radiation from the secondary appears to complicate the ionisation structure of the cool wind, it would be worthwhile to similarly analyse the ultraviolet absorbing columns that are obtained from the complete range of eclipsing binary studies. Similar to what can be achieved by using EG And as a template from which to understand otherwise complicated spectra of symbiotics, it would be useful to compare the spectral variations of all eclipsing systems in the light of the EG And model. Using this type of differential analysis, it may be possible to test for trends in the wind conditions with spectral type and to make headway in assessing the effects of binary on the derived diagnostics. This type of study may also play a role in shedding light on the wind acceleration problem. Eclipse studies of binaries with evolved giants (where it is possible to *directly* examine the wind structure) all point to a ‘slow’ wind acceleration, i.e. where the bulk of the material only becomes appreciably accelerated at distances of a few stellar radii from the photosphere. In the case of symbiotic stars, the Abel inversion



**Figure 7.1:** **Left:** Sections of *FUSE* spectra of BF Cyg. (Black: uneclipsed, Blue: partially eclipsed) **Right:** *FUSE* spectrum of BF Cyg (black) plotted against an eclipsed spectrum of EG And (blue). Even though the orbital phases are different, it is apparent that the ionisation structure and composition of both winds are very similar.

technique implies a very steep acceleration at a height above the photosphere of a few stellar radii. In addition to the results presented in this thesis, Vogel (1991) and Dumm et al. (1999) both find evidence for this type of wind acceleration in both EG And and the eclipsing symbiotic SY Mus (see Figure 7.2). However, as I have pointed out in the previous chapter, the shape of the velocity profile at the onset of the steep acceleration is subject to uncertainties, and even if it is real, it is very possibly an artifact of binarity. However, by using an estimate of the mass-loss rate and by modelling the ionisation conditions along the line of sight, it is possible to confirm the initial shape of the wind profile. Initial analysis of the sightlines viewed using our *FUSE* data of BF Cyg shows that a slow wind profile is most likely present in this star also. If the spectral resolution is sufficiently high then this technique is unlikely to be affected by the presence of the companion star and if an estimate of the mass-loss rate and binary parameters are known, then other giants in binary systems can be studied in the same way.

Although the study of binary winds provides information that is otherwise impossible to ascertain, it is also desirable to study isolated stars in order to test the generality of the derived results. Using the improved understanding gained by the study of the binaries, it may be possible to analyse normal red giants from a new angle. For example, photometric monitoring of isolated stars in combination with a spectral monitoring of wind diagnostic



**Figure 7.2:** Plot of derived wind laws for the giants in EG And (black) and SY Mus (blue) using the Abel inversion technique. Overplotted in red are some low-order  $\beta$ -laws. Note the similarity of the profiles for both symbiotic giants. Although the delayed onset of the wind acceleration profile seems to be a real effect, it remains to be seen whether the sharpness of the velocity increase is an artifact of binarity.

wavelength regions (i.e. the Ca II optical resonance lines) over long timelines (months) can test for a link between photospheric pulsational activity and mass-loss that this study suggests is present. In addition, if more information can be derived from isolated giants then it is possible to extend the parameter space of observable objects to the full range of spectral types, from K0 giants, right through to the highly-evolved, heavily mass-losing AGB stars.

The computational power now exists to carry out a full 3-dimensional modelling of red giant atmospheres. Previously, what these models lacked were reliable observational constraints, such as those that have been derived in this study. Indeed we are presently working, in collaboration with the PHOENIX group, to model the atmosphere and wind of EG And using the photospheric parameters (discussed in Chapter 3) and the derived wind conditions as constraints. In addition to providing a deeper understanding of the EG And wind, the process will also provide critical tests for the modelling. The modelling of the inner region of the wind is presently at an advanced stage. Upon reaching the ultimate aim of having the capability to model giant atmospheres, including their pulsations and winds, we will have a much more satisfactory insight into the wind problem. To conclude, it is anticipated that the in-depth analysis of this relatively uncomplicated system will provide the opportunity to further understand other observations of evolved giants, both

isolated and those in binaries, and provide the spatially-resolved constraints that are necessary to develop reliable atmospheric models which can fully predict and describe stellar mass-loss.

# Bibliography

- Antiochos, S. K., Haisch, B. M., & Stern, R. A. 1986, *ApJ*, 307, L55
- Ayres, T. R., Linsky, J. L., Vaiana, G. S., Golub, L., & Rosner, R. 1981, *ApJ*, 250, 293
- Baade, R. 1990, in *Evolution in Astrophysics: IUE Astronomy in the Era of New Space Missions*, 65–72
- Baade, R. 1998, in *ESA SP-413: Ultraviolet Astrophysics Beyond the IUE Final Archive*, 325
- Baade, R., Kirsch, T., Reimers, D., Toussaint, F., Bennett, P. D., Brown, A., & Harper, G. M. 1996, *ApJ*, 466, 979
- Belczyński, K., Mikołajewska, J., Munari, U., Ivison, R. J., & Friedjung, M. 2000, *A&AS*, 146, 407
- Brott, I., & Hauschildt, P. H. 2005, in *ESA SP-576: The Three-Dimensional Universe with Gaia*, 565
- Carpenter, K. G. 1986, in *ESA SP-263: New Insights in Astrophysics. Eight Years of UV Astronomy with IUE*, 99–102
- Carpenter, K. G. 1992, in *IAU Symp. 151: Evolutionary Processes in Interacting Binary Stars*, 51
- Carpenter, K. G. 1998, in *ASP Conf. Ser. 143: The Scientific Impact of the Goddard High Resolution Spectrograph*, 67
- Carpenter, K. G., Brown, A., & Stencel, R. E. 1985, *ApJ*, 289, 676
- Czyzak, S. J., Keyes, C. D., & Aller, L. H. 1986, *ApJS*, 61, 159
- Deutsch, A. J. 1956, *ApJ*, 123, 210

- Deutsch, A. J. 1960, in *Stellar Atmospheres*, 543
- Diamond, P. J. 2002, in *IAU Symposium*, 253
- Dixon, W. V., & Sahnou, D. J. 2003, in *ASP Conf. Ser. 295: Astronomical Data Analysis Software and Systems XII*, 241
- Drake, S. A. 1986, *LNP Vol. 254: Cool Stars, Stellar Systems and the Sun*, 254, 369
- Dumm, T., & Schild, H. 1998, *New Astronomy*, 3, 137
- Dumm, T., Schmutz, W., Schild, H., & Nussbaumer, H. 1999, *A&A*, 349, 169
- Dupree, A. K., & Reimers, D. 1987, *Mass loss from cool stars (ASSL Vol. 129: Exploring the Universe with the IUE Satellite)*, 321–353
- Feibelman, W. A., & Aller, L. H. 1987, *ApJ*, 319, 407
- Fekel, F. C., Joyce, R. R., Hinkle, K. H., & Skrutskie, M. F. 2000, *AJ*, 119, 1375
- Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, *PASP*, 110, 761
- Fluks, M. A., Plez, B., The, P. S., de Winter, D., Westerlund, B. E., & Steenman, H. C. 1994, *A&AS*, 105, 311
- Freytag, B. 1999, in *Astronomische Gesellschaft Meeting Abstracts*, 24
- Goldberg, L. 1979, *QJRAS*, 20, 361
- Gray, D. F. 1976, *The observation and analysis of stellar photospheres (Research supported by the National Research Council of Canada. New York, Wiley-Interscience, 1976. 484 p.)*
- Griffin, E. 2005, *Proc. 13th Cool Stars Workshop*, 560, 169
- Guinan, E. F. 1990, in *Evolution in Astrophysics: IUE Astronomy in the Era of New Space Missions*, 73–86
- Harper, G. 1996, in *ASP Conf. Ser. 109: Cool Stars, Stellar Systems, and the Sun*, 481
- Harper, G. M., Brown, A., Bennett, P. D., Baade, R., Walder, R., & Hummel, C. A. 2005, *AJ*, 129, 1018
- Hartmann, L., Dupree, A. K., & Raymond, J. C. 1980, *ApJ*, 236, L143

- Hayes, D. S., & Latham, D. W. 1975, *ApJ*, 197, 593
- Hempe, K. 1982, *A&A*, 115, 133
- Iben, I., & Renzini, A. 1983, *ARA&A*, 21, 271
- Jenkins, E. B. 1986, *ApJ*, 304, 739
- Judge, P. G., & Jordan, C. 1991, *ApJS*, 77, 75
- Judge, P. G., & Stencel, R. E. 1991, *ApJ*, 371, 357
- Keenan, F. P., Ahmed, S., Brage, T., Doyle, J. G., Espey, B. R., Exter, K. M., Hibbert, A., Keenan, M. T. C., Madjarska, M. S., Mathioudakis, M., & Pollacco, D. L. 2002, *MNRAS*, 337, 901
- Kenyon, S. J. 1986, *The symbiotic stars* (Cambridge and New York, Cambridge University Press, 1986, 295 p.)
- Kenyon, S. J., & Fernandez-Castro, T. 1987, *AJ*, 93, 938
- Kenyon, S. J., Fernandez-Castro, T., & Stencel, R. E. 1986, *AJ*, 92, 1118
- Keyes, C. D., & Preblich, B. 2004, *AJ*, 128, 2981
- Knill, O., Dgani, R., & Vogel, M. 1993, *A&A*, 274, 1002
- Koen, C., & Laney, D. 2000, in *ASP Conf. Ser. 203: IAU Colloq. 176: The Impact of Large-Scale Surveys on Pulsating Star Research*, 101–104
- Kurucz, R., & Bell, B. 1995, *Atomic Line Data* (R.L. Kurucz and B. Bell) Kurucz CD-ROM No. 23. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1995, 23
- Kurucz, R. L. 1993, *VizieR Online Data Catalog*, 6039, 0
- Lamers, H. J. G. L. M. 1997, *LNP Vol. 497: Stellar Atmospheres: Theory and Observations*, 497, 69
- Lamers, H. J. G. L. M., & Cassinelli, J. P. 1999, *Introduction to Stellar Winds* (Introduction to Stellar Winds, by Henny J. G. L. M. Lamers and Joseph P. Cassinelli, pp. 452. ISBN 0521593980. Cambridge, UK: Cambridge University Press, June 1999.)
- Lattanzio, J. C. 1991, *ApJS*, 76, 215
- Linsky, J. L., & Haisch, B. M. 1979, *ApJ*, 229, L27

- Linsky, J. L., Harper, G. M., Valenti, J., Bennett, P. D., & Brown, A. 2000, in IAU Symposium, 303
- Luttermoser, D. G., Johnson, H. R., & Eaton, J. 1994, *ApJ*, 422, 351
- Mennessier, M. O., Mowlavi, N., Alvarez, R., & Luri, X. 2001, *A&A*, 374, 968
- Mikolajewska, J., Friedjung, M., Kenyon, S. J., & Viotti, R. 1988, The symbiotic phenomenon (ASSL Vol. 145: IAU Colloq. 103: The Symbiotic Phenomenon)
- Moos, H. W., Cash, W. C., Cowie, L. L., Davidsen, A. F., Dupree, A. K., Feldman, P. D., Friedman, S. D., Green, J. C., Green, R. F., Gry, C., Hutchings, J. B., Jenkins, E. B., Linsky, J. L., Malina, R. F., Michalitsianos, A. G., Savage, B. D., Shull, J. M., Siegmund, O. H. W., Snow, T. P., Sonneborn, G., Vidal-Madjar, A., Willis, A. J., Woodgate, B. E., York, D. G., Ake, T. B., Andersson, B.-G., Andrews, J. P., Barkhouser, R. H., Bianchi, L., Blair, W. P., Brownsberger, K. R., Cha, A. N., Chayer, P., Conard, S. J., Fullerton, A. W., Gaines, G. A., Grange, R., Gummin, M. A., Hebrard, G., Kriss, G. A., Kruk, J. W., Mark, D., McCarthy, D. K., Morbey, C. L., Murowinski, R., Murphy, E. M., Oegerle, W. R., Ohl, R. G., Oliveira, C., Osterman, S. N., Sahnou, D. J., Saisse, M., Sembach, K. R., Weaver, H. A., Welsh, B. Y., Wilkinson, E., & Zheng, W. 2000, *ApJ*, 538, L1
- Muerset, U., Nussbaumer, H., Schmid, H. M., & Vogel, M. 1991, *A&A*, 248, 458
- Munari, U. 1993, *A&A*, 273, 425
- Munari, U., & Tomasella, L. 1999, *A&AS*, 137, 521
- Nussbaumer, H., Schmid, H. M., Vogel, M., & Schild, H. 1988, *A&A*, 198, 179
- Nussbaumer, H., Schmutz, W., & Vogel, M. 1995, *A&A*, 293, L13+
- Oliversen, N. A., Anderson, C. M., Slovak, M. H., & Stencel, R. E. 1985, *ApJ*, 295, 620
- Owocki, S. P. 1994, in IAU Symp. 162: Pulsation; Rotation; and Mass Loss in Early-Type Stars, 475
- Percy, J. R., Nyssa, Z., & Henry, G. W. 2001, *Informational Bulletin on Variable Stars*, 5209, 1
- Percy, J. R., & Parkes, M. 1998, *PASP*, 110, 1431
- Petersson, S.-G. 1982, *Phys. Scr*, 26, 296

- Proga, D., Kenyon, S. J., & Raymond, J. C. 1998, *ApJ*, 501, 339
- Raassen, A. J. J., Pickering, J. C., & Uylings, P. H. M. 1998, *A&AS*, 130, 541
- Raassen, A. J. J., & Uylings, P. H. M. 1998a, *Journal of Physics B Atomic Molecular Physics*, 31, 3137
- . 1998b, *VizieR Online Data Catalog*, 334, 300
- Reimers, D. 1975, *Circumstellar envelopes and mass loss of red giant stars (Problems in stellar atmospheres and envelopes.)*, 229–256
- Reimers, D. 1977, in *IAU Colloq. 42: The Interaction of Variable Stars with their Environment*, 559
- Reimers, D. 1987, in *IAU Symp. 122: Circumstellar Matter*, 307–318
- Reimers, D., Huensch, M., Schmitt, J. H. M. M., & Toussaint, F. 1996, *A&A*, 310, 813
- Sahnow, D. J., Moos, H. W., Ake, T. B., Andersen, J., Andersson, B.-G., Andre, M., Artis, D., Berman, A. F., Blair, W. P., Brownsberger, K. R., Calvani, H. M., Chayer, P., Conard, S. J., Feldman, P. D., Friedman, S. D., Fullerton, A. W., Gaines, G. A., Gawne, W. C., Green, J. C., Gummin, M. A., Jennings, T. B., Joyce, J. B., Kaiser, M. E., Kruk, J. W., Lindler, D. J., Massa, D., Murphy, E. M., Oegerle, W. R., Ohl, R. G., Roberts, B. A., Romelfanger, M. L., Roth, K. C., Sankrit, R., Sembach, K. R., Shelton, R. L., Siegmund, O. H. W., Silva, C. J., Sonneborn, G., Vaclavik, S. R., Weaver, H. A., & Wilkinson, E. 2000, *ApJ*, 538, L7
- Savage, B. D., & Sembach, K. R. 1991, *ApJ*, 379, 245
- Scalo, J. M. 1976, *ApJ*, 206, 474
- Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, *A&AS*, 96, 269
- Schmid, H. M. 2003, in *Astronomical Society of the Pacific Conference Series*, ‘Symbiotic Stars Probing Stellar Evolution’, 343
- Schulte-Ladbeck, R. E., Aspin, C., Magalhaes, A. M., & Schwarz, H. E. 1990, *A&AS*, 86, 227
- Seaquist, E. R., & Taylor, A. R. 1990, *ApJ*, 349, 313
- Sion, E. M., & Ready, C. J. 1992, *PASP*, 104, 87

- Skopal, A., Chochol, D., Vittone, A. A., Blanco, C., & Mammano, A. 1991, *A&A*, 245, 531
- Skopal, A., Pribulla, T., Vaňko, M., Velič, Z., Semkov, E., Wolf, M., & Jones, A. 2004, *Contributions of the Astronomical Observatory Skalnaté Pleso*, 34, 45
- Smith, S. E. 1980, *ApJ*, 237, 831
- Snedden, C. A. 1973, Ph.D. Thesis, The University of Texas in Austin
- Stencel, R. E. 1981, in *Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, 137–145
- Stencel, R. E. 1984, *ApJ*, 281, L75
- Stencel, R. E., & Sahade, J. 1980, *ApJ*, 238, 929
- Stickland, D. J., & Sanner, F. 1981, *MNRAS*, 197, 791
- Tomov, N. A. 1995, *MNRAS*, 272, 189
- van Buren, D., Dgani, R., & Noriega-Crespo, A. 1994, *AJ*, 108, 1112
- Vogel, M. 1991, *A&A*, 249, 173
- . 1993, *A&A*, 274, L21+
- Vogel, M., Nussbaumer, H., & Monier, R. 1992, *A&A*, 260, 156
- Walder, R., & Folini, D. 2000, in *ASP Conf. Ser. 204: Thermal and Ionization Aspects of Flows from Hot Stars*, 331
- Wallerstein, G. 1981, *The Observatory*, 101, 172
- Wilson, R. E., & Vaccaro, T. R. 1997, *MNRAS*, 291, 54
- Woodgate, B. E., Kimble, R. A., Bowers, C. W., Kraemer, S., Kaiser, M. E., Danks, A. C., Grady, J. F., Loiacono, J. J., Brumfield, M., Feinberg, L., Gull, T. R., Heap, S. R., Maran, S. P., Lindler, D., Hood, D., Meyer, W., Vanhouten, C., Argabright, V., Franka, S., Bybee, R., Dorn, D., Bottema, M., Woodruff, R., Michika, D., Sullivan, J., Hetlinger, J., Ludtke, C., Stocker, R., Delamere, A., Rose, D., Becker, I., Garner, H., Timothy, J. G., Blouke, M., Joseph, C. L., Hartig, G., Green, R. F., Jenkins, E. B., Linsky, J. L., Hutchings, J. B., Moos, H. W., Boggess, A., Roesler, F., & Weistrop, D. 1998, *PASP*, 110, 1183

York, D. G. 1995, *Bulletin of the American Astronomical Society*, 27, 874

Yungelson, L., Livio, M., Tutukov, A., & Kenyon, S. J. 1995, *ApJ*, 447, 656



# Absorption Line Spectroscopy

The most important results obtained from this work are derived from an analysis of the wind absorption features. In this Appendix, an overview of some of the techniques involved in gaining information on the material which produces these features is presented.

The chief aim of analysing absorption lines is to determine the column density, which is the number of absorbers,  $N$ , of a particular species along the line of sight. From  $N$ , ionisation conditions, abundances, wind parameters and temperatures can all be calculated. One method of calculating  $N$  is the Curve of Growth (COG) method which depends on the measured equivalent width of a particular transition.

## A.1 Equivalent Widths and the Curve of Growth

The equivalent width (EW) of a line,  $W_\lambda$ , is simply a measure of the relative depression of the absorption line below the continuum. The integrated area of the absorption line is the equivalent width.

The EW of a line can be written:

$$EW = \int (1 - e^{-\tau}) d\lambda$$

where  $\tau$  is the optical depth which involves the column density and the absorption cross-section. Since the optical depth is proportional to the number of absorbers along the line of sight times the  $f$ -value ( $f$  is the oscillator strength of the transition), then the EW is some function of  $Nf$  (i.e. the product of the column density,  $N$ , and the oscillator strength for a particular transition).

For the optically thin case where  $\tau \ll 1$ , then:

$$EW = \int \tau_{\lambda} d\lambda = \frac{e^2}{4\epsilon_0 m_e c} N f$$

i.e. for a given oscillator strength the EW increases linearly with the column density. The breakdown of the linear relationship corresponds to the point where no more radiation can be absorbed at the line centre, i.e. it is not optically thin anymore, it is saturated. Increasing  $N$  only causes a small increase in EW, but as  $N$  increases further, the line becomes so strong that the wings of the Lorentzian profile (due to the natural broadening of the line) become important. This corresponds to the damping section. For lines in this regime, the column density can be calculated using:

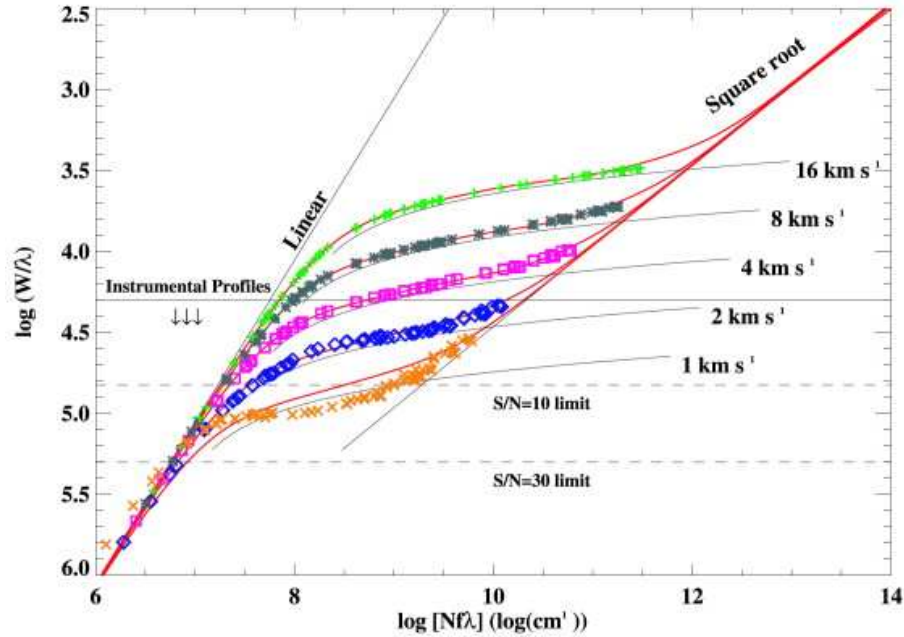
$$N(cm^{-2}) = \frac{m_e c^3 EW_{\lambda}^2}{e^2 \lambda^4 f \gamma}$$

where  $\gamma$  is the radiation damping constant.

Since both approximations above lead to equations that are dependent only on  $N$ , then the Doppler broadening parameter,  $b$ , cannot be found using simple EW relations. In practise one typically measures EW's for lines of different strengths from the same species (i.e., Fe II has many hundreds of transitions in the UV). Often, the lines have strengths such that the profiles fall between the two cases above so that they provide little information when used alone. In addition, a method that uses the information from all lines simultaneously, is less likely to suffer from systematic effects.

One method of determining  $N$ , the COG technique, makes use of the equivalent widths of a number of lines, of varying transition strengths, of a particular atom or ion.

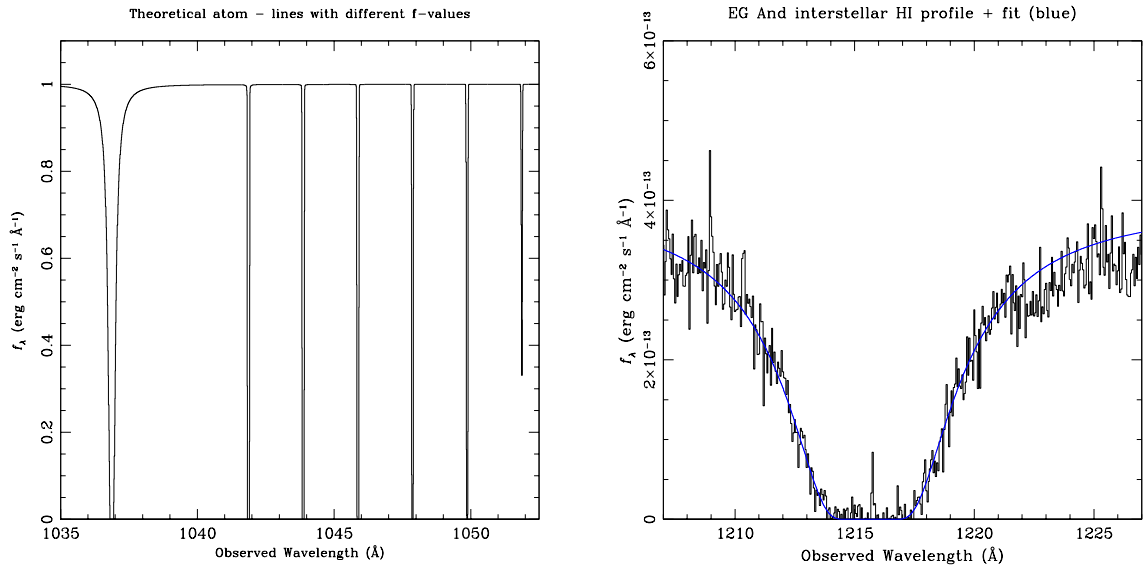
The COG describes the behaviour of a line's equivalent width as the number of absorbing atoms in the line of sight,  $N$ , is increased, or, another way of putting it, is that it is basically a plot of equivalent width versus abundance. For weak lines, the equivalent width is always proportional to the number of absorbing atoms, this corresponds to the linear region. However, as the number of atoms along the line of sight (or the strength of a particular transition) increases, saturation takes hold and the EW does not increase linearly with abundance, this corresponds to the flat region. This occurs because



**Figure A.1:** Curve-of-growth diagram illustrating the regions of validity for each of the equivalent-width approximation formulae. The numeric solution is in red, and the approximations are in black. Overplotted are the equivalent widths derived from direct numerical integration of model molecular hydrogen lines for  $b = 1, 2, 4, 8,$  and  $16 \text{ km s}^{-1}$ . The solid grey horizontal line at the middle of the graph indicates roughly the boundary between resolved and unresolved (instrumentally broadened) line profiles for FUSE data, assuming that the FUSE resolution is  $R=20,000$ .

the Doppler core of the Voigt profile (used to describe the line shape) is exhausting the available photons. If  $N$  is increased further though (or if the transition probability is sufficiently high), the damping wings become important. This then adds appreciably to the equivalent width of the line and so the EW will grow again as  $N^{\frac{1}{2}}$ . The total effect is summarised in the COG in Figure A.1. Note how the number of absorbers cannot be determined for lines situated on the saturated section of the COG without knowledge of  $b$ , the Doppler broadening parameter.

In the COG analysis the measured EW's of multiple lines are fit with a single component Gaussian curve of growth (Spitzer 1978). The Doppler value,  $b$ , and column density,  $N$ , are varied so as to minimise  $\chi^2$  between the measured EWs and a model curve of growth. Plotted in Figure A.2 (left panel) are a range of lines generated, using the approximation equations described above, for a theoretical atom. A fake atom is chosen so that lines from the same species, covering a range of transition strengths, can be conveniently plotted in order to illustrate the different profiles found on different sections of



**Figure A.2: Left.** Absorption lines generated for a theoretical atom to illustrate the profiles obtained for different sections of the COG - ie. unsaturated, saturated and again saturated but where the Lorentzian wings dominate. **Right.** Interstellar HI Lyman  $\alpha$  absorption towards the line of sight to EG And. The line is obviously situated on the square root region of the COG. Overplotted is a model with  $N_{HI}=2.5 \times 10^{20} \text{ cm}^{-2}$ .

the COG. The line at  $\sim 1052 \text{ \AA}$  is weak, unsaturated and is situated on the linear portion of the COG. Looking at the longer wavelength lines, the  $f$ -values of the transitions are increased and the lines become saturated. Its obvious that, even though the transitions are getting stronger, the EW is only increasing very slowly. However, the  $f$ -value of the line  $\sim 1035 \text{ \AA}$  has increased so much (or, analogously  $N$  has increased sufficiently) that damping wings have become important and significantly affect the value of the EW. Figure A.2 (right panel) shows the interstellar H I Lyman  $\alpha$  absorption towards the line of sight to EG And. The line is obviously situated on the square root region of the COG. Overplotted is a model with  $N_{HI}=2.5 \times 10^{20} \text{ cm}^{-2}$  (blue).

For COG fitting for this study, I use specially written IDL procedures to choose unblended lines from a particular species, fit the continuum with a straight line and numerically integrate on the flux deficit beneath the assumed continuum to obtain the EW. A grid of theoretical COGs are then generated using a range of  $b$  and  $N$  and are fitted to the COG generated from the data.

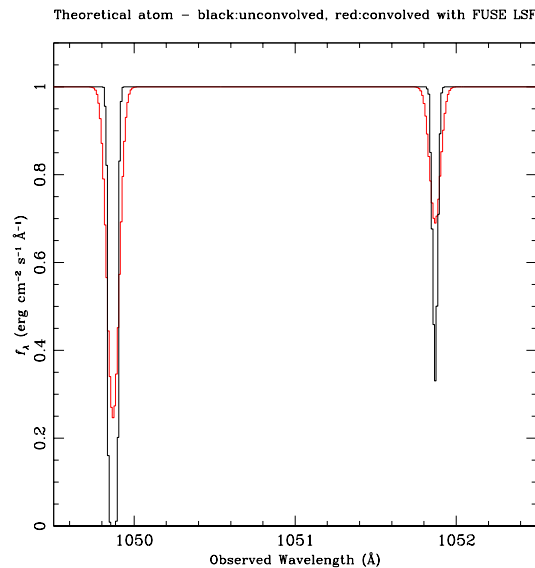
One of the problems with this approach is that in many cases an absorption feature is composed of many unresolved profiles (it is possible to test this using the apparent optical depth technique; see Section A.3). In this case the single Gaussian component

approximation breaks down, especially if the components have very different physical conditions. There are cases, however, where small corrections can be applied to correct for errors in the COG (Jenkins ,1986). However we chose to use a separate method of determining N to complement the COG method and to reduce uncertainties.

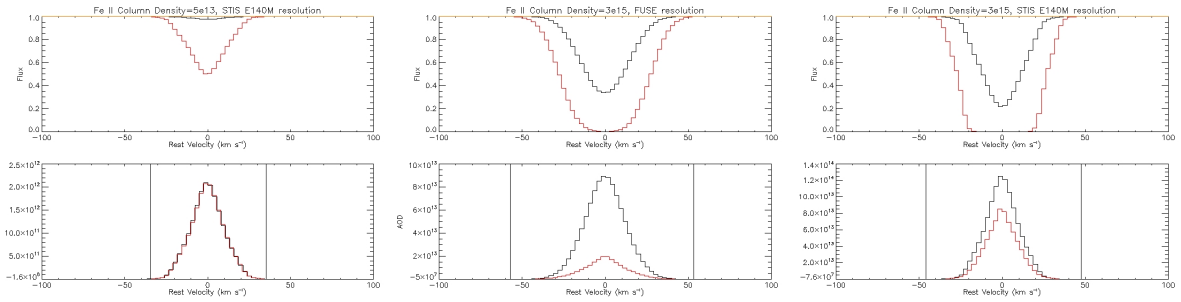
## A.2 Profile Fitting

In the profile fitting approach, each absorption line is represented by the convolution of a theoretical Voigt absorption profile with the instrumental line spread function (LSF), usually taken to be a single Gaussian. Figure A.3 shows two theoretical profiles plotted in black. The profiles are assumed to have been measured with an instrument with infinite resolution - overplotted (in red) are the same profiles, but after convolution with a Gaussian corresponding roughly to the LSF of the *FUSE* instrument ( $R \sim 15,000$  (the *FUSE* LSF is not uniquely determined and varies with wavelength)). It is apparent from the figure that although a line may not look saturated by eye, it could still lie in the flat part of the COG, and an analysis could derive erroneous results.

Profile fitting is especially useful when trying to fit blended lines, which are difficult to analyse using other techniques. The majority of the absorption features were analysed



**Figure A.3:** In black are theoretical profiles obtained with an instrument with infinite resolution; overplotted in red are the same profiles after convolution with a Gaussian corresponding roughly to the LSF of the *FUSE* instrument. The convolution with the instrumental profile can mask line saturation.



**Figure A.4:** The top three panels show theoretical absorption line profiles (black line traces a transition stronger than the red lines), whilst the lower panels show the corresponding AOD profiles. The lines shown on the left display no sign of saturation, while the differing AOD profiles for the AOD data at middle and on the right do show saturation. This is diagnosed by the differing strengths of the AOD profiles.

using this technique in this thesis.

### A.3 Apparent Optical Depth Technique

If the continuum is well-defined and if the  $S/N$  is sufficiently high, and also if the instrumental resolution is high in relation to the linewidth, then it is possible to analyse the apparent optical depth (AOD) along the profile in velocity space. When two lines of different transition strengths are compared (typically  $\lambda f$  differing by factor of  $\sim 2$ ) along the profile in velocity space it is possible to test for saturation, and possibly unresolved saturated structure in the profile. See Savage & Sembach (1991) for a full discussion.

In profile comparisons where the AOD strengths are different, then there are saturation effects to be accounted for. See Figure A.4 for an example of theoretical profile comparisons which show saturation and non-saturation.

For all methods of determining  $N$ , uncertainties in the oscillator strengths are the largest source of error. This is especially true for transitions in the UV where experimental measurements are often impractical. For instance in the *FUSE* wavelength region  $f$ -values are sometimes uncertain by orders of magnitude and there are still many lines, particularly in the more eclipsed *FUSE* spectra, that remain unidentified.

# B

## Wind Absorption Fits

This appendix contains example fits to the red giant wind absorption lines. The data are rebinned for clarity and the wind models were calculated assuming the LTE approximation and displayed here assuming a one component profile.

The *FUSE* data displayed consist of five different observations. The quadrature spectrum (black) is unaffected by wind absorption (all narrow absorption is interstellar) and was observed at phase  $\phi = 0.79$ . This was the reference spectrum from which to measure the wind absorption features. The data displayed in red, blue and orange (phases  $\phi=0.16, 0.10, 0.07$  respectively) were obtained at phases corresponding to increasing degrees of eclipse by the giant wind. The absorption features which are present in these data, but missing from the reference spectrum, are due to red giant wind material. The spectrum in green was obtained at phase  $\phi=0.05$  (close to total eclipse) where the continuum is almost completely extinguished by the damped H I features. The panel below the data shows a fit to the  $\phi=0.10$  spectrum (blue).

The STIS data follows a similar format. The data is black was obtained at phase  $\phi=0.50$ , however this is not used as a reference spectrum due to the increase in continuum and emission line fluxes which are unrelated to phase (discussed in chapters 3, 4 and 6). The quadrature spectrum (red;  $\phi=0.80$ ) was obtained 5 days after the *FUSE* reference spectrum and is used as the reference for the STIS data. The blue and orange spectra were

obtained at two differing degrees of eclipse ( $\phi=0.15$  and  $0.09$  respectively) and, analogous to the partially eclipsed *FUSE* data, diagnose the red giant wind through the multitude of absorption features. The data displayed in green was obtained at phase  $\phi=0.04$ , close to total eclipse of the dwarf. The panel below the data shows a fit to the  $\phi=0.09$  spectrum (orange).

The full linelist can be retrieved electronically from  
<http://www.tcd.ie/Physics/Astrophysics/data/fuse/EGAndlinelistUV.dat>.