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NEAR-SIMULTANEOUS OBSERVATIONS OF DIRECT AND RAMAN-SCATTERED LINES IN THE SYMBIOTIC STAR Z ANDROMEDAE

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ABSTRACT

Symbiotic binary stars typically consist of a hot compact star orbiting a cool giant. Overlaid on the continuum from these stars is a nebular spectrum produced by the photoionization of the cool star wind by the hot star. Most of the observed emission lines are readily identifiable with common ions; however, a pair of lines at λλ6825 and 7082 remained unidentified until relatively recently. A case has been made that these long-unidentified emission lines result from the Raman scattering of O vi λλ1032, 1038 resonance photons. We present near-simultaneous far-UV and optical observations of the symbiotic star Z Andromedae, obtained with the space-borne Hopkins Ultraviolet Telescope and the Mount Hopkins 1.5 m telescope. Our data show the presence of both the O vi λλ1032, 1038 resonance doublet and the λ6825 and λ7082 emission lines and provide strong evidence for the Raman effect in Z And. We show that the unusual line ratio of 7:1 observed for the O vi lines is due to the effects of interstellar H_2 absorption. Correction for this effect results in a line ratio of close to 2:1, consistent with optically thin emission. We derive the efficiency for the Raman-scattered O vi lines and compare them with previously reported measurements for RR Telescopii.

Subject headings: atomic processes — binaries: symbiotic — stars: individual (Z Andromedae) — ultraviolet: stars

1. INTRODUCTION

The spectra of symbiotic stars often exhibit two strong, broad (∼20 Å) emission lines at 6825 and 7082 Å (Allen 1980). These emission features are only observed in symbiotic systems that exhibit high-excitation features such as [Ne v] and [Fe vii] (Allen 1980). For years the identity of these lines was uncertain, and they became known as the "unidentified lines." Schmid (1989) proposed that the λλ6825, 7082 emission lines result from the Raman scattering of the O vi resonance doublet λλ1032, 1038. In his model, O vi photons produced near the hot component are scattered by neutral hydrogen atoms near the cool component of the binary system. The scattering also results in a broadening of the width of the doublet lines by ∼6.7 times, producing two broad, polarized lines in the red region of the spectrum.

Recently, Espey et al. (1995) used far-UV data from the Hopkins Ultraviolet Telescope (HUT) and ground-based optical data to provide the first simultaneous observations of both the O vi λλ1032, 1038 lines and the λλ6825, 7082 lines in RR Tel. In this Letter, we present similar near-simultaneous ultraviolet and optical observations of Z Andromedae.

Z And is the prototypical symbiotic star with a well-established binary orbital period of ∼759 days (Mikołajewska & Kenyon 1996; hereafter, MK). It is composed of a M3-M4 III giant and a hot component of $T_h > 10^5$ K (MK). Until recently, it was unclear whether the hot component is a white dwarf or an accreting main-sequence star, but the hot component mass derived from a study of the polarimetric orbit of Z And (Schmid & Schild 1997) favors a white dwarf. Based on this identification, the repeatedly observed 2–3 mag eruptions are most likely the result of thermonuclear runaway on the dwarf's surface. The circumbinary nebula is fairly dense compared to planetary nebulae, $n_e \sim 10^8$ cm^{-3}, and hot, with $T_e \sim 20{,}000$ K (MK).

2. THE HUT FAR-UV SPECTRUM

HUT is a 0.9 m telescope equipped with a Rowland circle spectrograph. It was flown aboard the Space Shuttle Endeavour during the Astro-2 mission between 1995 March 2 and 18. HUT obtained ultraviolet spectra in the wavelength region from 820 to 1840 Å at a spectral resolution that varies from 2 to 4 Å. The HUT calibration is described in Kruk et al. (1995).

The spectrum of Z And in quiescence was obtained on 1995 March 6 (JD 2,449,782.6) or a phase of $\phi = 0.39$ (MK, eq. [1]). A total of 1367 s of observing time was obtained on target through a 20″ aperture. An additional exposure of 100 s of blank sky data was obtained during the target acquisition procedure. These data permit us to determine the location and amount of airglow emission-line contamination during the Z And observation itself (see § 5).

The spectrum was extracted from the raw data using specialized software. Poisson statistical errors were calculated from the raw count spectra and propagated through the data reduction process. Calibration of the raw data was performed in the same manner as for the RR Tel spectrum discussed previously (Espey et al. 1995). The signal-to-noise ratio in the continuum of the calibrated data ranges from ∼4 per pixel at the ends of the spectrum to ∼10 near Lyα where the sensitivity of the instrument is highest.

3. THE CONTINUUM

Analysis of both the continuum and emission-line properties of Z And was performed using the IRAF/SPECFIT χ^2 minimization routine developed by Kriss (1994). Below 1450 Å, the ultraviolet continuum of Z And was modeled using a blackbody; above 1450 Å, a recombination component with $T_e = 2 \times 10^4$ K was added to represent the nebular continuum. We adopt the extinction curve of Cardelli, Clayton, & Mathis (1989), with an assumed R_V equal to 3.1. For continuum fitting, we chose regions free of line features.

Our best-fit model was a blackbody of (111,000 ± 4000) K and $E(B-V) = (0.21 \pm 0.01)$ mag. These results are in good agreement with temperature estimates by Mürset et al. (1991) and extinction estimates by MK, who present an extensive discussion of extinction values derived from different methods and finally adopt 0.3 mag. The spectrum below 1130 Å is affected by the presence of interstellar H I and H_2. We fit the absorption lines by scaling a template consisting of optical depth versus wavelength. Our template is derived from recent theoretical data of H_2 rotational transitions of Abgrall et al. (1993a, 1993b) and broadened to a FWHM of 5 km s^{-1}, typical of cool interstellar gas (Morton 1975; van Dishoeck & Black 1986, and references therein). The relative scaling of the transitions comes from the mean relative column densities obtained from *ORFEUS* II observations of Galactic stars (Dixon et al. 1998).

The theoretical intensities are convolved with the instrumental resolution (Kruk et al. 1998) before fitting to spectral regions affected only by H_2; once the absorption was obtained, its contribution was fixed and absorption due to H I was determined, again by fitting regions affected by its absorption features only. Our best-fit values are log N(H I) = (21.30 ± 0.09), log $N(H_2) = (20.06 \pm 0.05)$ cm^{-2}.

TABLE 1
STRONGEST MEASURED LINES

LINE	FLUX (10^{-13} ergs cm^{-2} s^{-1}) Observed	Corrected [a]
S VI$_{tot}$ λ937	2.0	150
He II λ958	1.0	60
N III$_{tot}$ λ991	2.6	300
Ne VI] λ1000	7.9	300
O VI$_{tot}$ λ1035	300	10,000
He II λ1085	13	260
Ne V]$_{tot}$ λ1134	15	220
C IV λ1168	1.6	21
C III λ1176	5.0	63
S III/[Mg VI] λ1190	7.5	66
[S V] λ1199	3.7	43
N V$_{tot}$ λ1240	129	1300
O V λ1371	8.2	60
Si IV$_{tot}$ λ1397	40	280
O IV$_{tot}$ λ1402	55	380
N IV] λ1486	31	200
C IV$_{tot}$ λ1549	390	2300
[Ne V] λ1575	3.4	20
[Ne IV] λ1602	1.3	7.4
He II λ1640	270	1500
O III]$_{tot}$ λ1664	49	270
N III]$_{tot}$ λ1749	15	81
[Mg VI]/Si II λ1807	6.8	38

[a] We use $E(B-V) = 0.24$ and the CCM extinction law. Lines below 1130 Å were corrected for H_2 absorption (see § 5). Fluxes for strong lines are accurate to 15% or better, and weak lines are accurate to 15%–30%. The subscript "tot" indicates that the flux is the total of all lines within the multiplet.

4. THE EMISSION LINES

Emission lines were fitted as Gaussians relative to the absorbed and reddened continuum adopted in § 3, including airglow subtraction as needed. For flux measurements on closely spaced multiplet lines, such as O VI λλ1032, 1038, it was necessary to fix the wavelength ratios using the atomic data of Morton (1991) and the line widths to that of the strongest member of the blend. The fluxes of the strongest lines are presented in Table 1. Line fluxes are good to ≤15% for strong lines and to ∼15%–30% for weaker lines.

We redetermine the extinction toward Z And through use of the He II lines λλ1085, 1640, 4686 from the HUT and optical spectra. Taking the theoretical case B He II line ratios from Storey & Hummer (1995) and assuming that the emitting gas is optically thin yields $E(B-V) = (0.24 \pm 0.03)$ mag, consistent with our continuum fit. We note that MK find the line ratio of λ1640/λ4686 to be phase dependent, which sheds considerable doubt on the applicability of this line ratio as an extinction diagnostic. However, our observations were taken at a phase when the line ratio is observed to be fairly constant, and we also find that λ1640/λ1085 and λ1085/λ4686 produce the same result. As is the case with many symbiotic stars, extinction values are notoriously difficult to derive; we corrected all line fluxes assuming a value of 0.24 mag.

5. O VI

We expect the ratio of O VI λ1032 to λ1038 lines to be between the optically thin and thick values of 2:1 and 1:1, respectively. The observed ratio relative to the absorbed continuum is closer to 7:1 due to selective absorption by H_2. Schmid et al. (1998) report $F(1032)/F(1038) \approx 10$ using *ORFEUS* I data, which is significantly different from the HUT observation. The discrepancy may result from differences in the fit to the continuum and/or some real variation in the line intensities, as is evident in the case of RR Tel (Schmid et al. 1998). The absorption template technique that we used for the continuum will not work for the emission lines, since the emission line profiles are relatively narrow with respect to the H_2 features and the details of the absorption are hidden through convolution with the instrumental response.

We calculate the effect of H_2 lines by observing the amount of flux absorbed from a Gaussian profile of similar characteristics to the far-UV lines. The H_2 template is generated at 0.01 Å resolution with the column density and the FWHM set to the values used for the continuum fit (§ 4). The emission lines are modeled as Gaussians with FWHM = 30 km s^{-1}, as observed for the high-ionization He II λ4686 line (Ivison, Bode, & Meaburn 1994). We set the relative velocity of the absorption and emission components to be zero, consistent with the small radial velocity of the emission lines (MK). The amount of absorption of each far-UV emission line is estimated by integrating the product of the emission- and absorption-line profiles across each emission line. By this method, we calculate that the O VI λ1032 line suffers only about 4% absorption, while the λ1038 line undergoes a 65% decrease. Correction for these values results in an estimate of $F(1032)/F(1038) = 2.56 \pm 0.38$, where the error estimate includes the effects of errors in the flux measurements and H_2 determinations. Other lines suffering considerable absorption include S VI λλ937, 944 (5% and 9% respectively), N III λλ989.8, 991.5, and 991.6 (13%, 98%, and 95%), and the Ne VI] multiplet at 1000 Å (between 3% and 67%). These factors have been incorporated into the corrected flux values shown in Table 1. Even before allowance is made for interstellar absorption, Figure 1 and Table 1 show

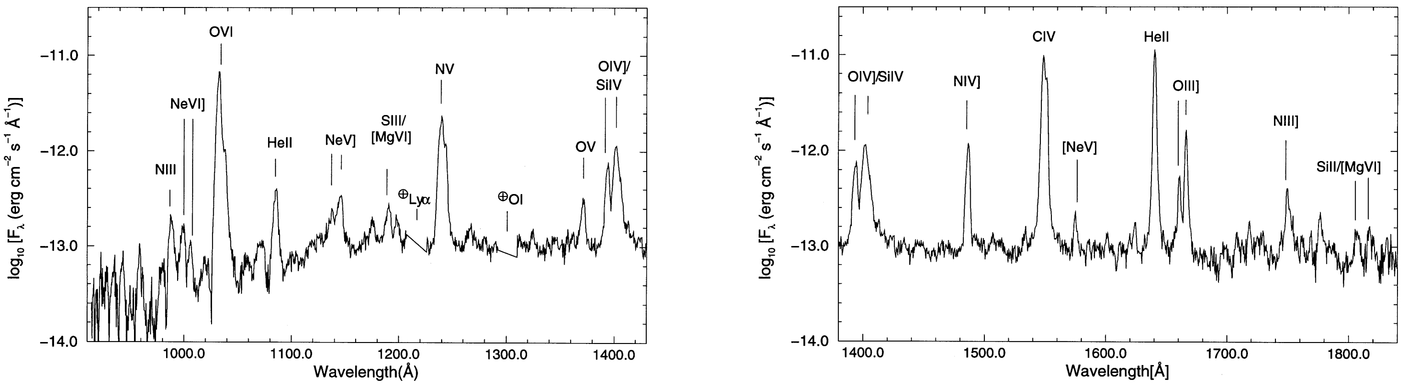

FIG. 1.—Airglow-subtracted HUT spectrum of Z And obtained during the Astro-2 mission. Positions of the Lyα λ1216 and O I λ1304 airglow lines are indicated.

quite clearly that the O VI doublet is the strongest emission feature in the far-UV.

We estimate the temperature of the O^{+5}-emitting region assuming that the O V λ1371 emission results principally from the dielectronic recombination of O VI. Using the method of Nussbaumer & Storey (1984), the fluxes of the O V λ1371 and O VI λ1032 lines, and the O VI collisional strengths of Mendoza (1983), we determine $T_e \sim 2.3 \times 10^4$ K.

The nebular density in the O^{+5} region can be estimated with the Ne V] and Ne VI] diganostics of Espey et al. (1996), since these lines have ionization potentials bracketing that of O VI. Assuming a temperature of $T_e \sim 2 \times 10^4$ K, the Ne V] diagnostic $F(1137)/F(1575) = 3.18 \pm 0.56$ yields $\log n_e = 9.2$–9.4 cm^{-3}. The Ne VI] diagnostics ratios are less definitive: $F(1006.1)/F(999.6) = 0.78 \pm 0.19$ yields $\log n_e \approx 5.5$ cm^{-3}, and $F(1010.6)/F(999.6) = 0.20 \pm 0.08$ gives $\log n_e \approx 6$ or ≈ 10 cm^{-3}. However, the errors on the flux ratios actually allow the entire range from $\log n_e \approx 5$ to 10 cm^{-3}. There are several problems with the Ne VI] diagnostics: (1) 1006.1 and 1010.6 are blended, (2) the 1010.6 line is extremely weak, and (3) all three of the Ne VI] lines undergo significant absorption by H_2. We adopt a density of $\log n_e > 9$ cm^{-3} for the O VI region. The derived temperature of the O^{+5}-emitting region is similar to that of RR Tel, but the density for Z And is significantly higher.

6. OPTICAL OBSERVATIONS: THE RAMAN EMISSIONS

Optical observations were provided by MK. The spectrum was obtained 1995 January 31 using the FAST spectrograph mounted on the 1.5 m telescope on Mount Hopkins, Arizona. The spectrum covers 3800–7500 Å at a resolution of ~3 Å, and the flux calibration is believed to be accurate to 10% (see MK).

The optical spectrum of Z And displays a strong red continuum and TiO absorption bands from the cool giant and nebular H I, He I, and He II emissions. Using SPECFIT, the observed M giant star continuua of Fluks et al. (1994) were fitted to the continuum of the red giant (see Fig. 2). The best-fit Fluks model was M4.1 III. The λ6825 and λ7082 lines were modeled assuming Gaussian profiles with line widths tied together, and the wavelength ratio tied to the ratio of the progenitor λ1032 and λ1038 lines, scaled by a factor of 6.7 as expected under Raman scattering. The extinction-corrected fluxes are $(7.32 \pm 0.67) \times 10^{-12}$ and $(2.23 \pm 0.50) \times 10^{-12}$ ergs cm^{-2} s^{-1}, respectively. The ratio $F(6825)/F(7082)$ is 3.3 ± 0.8, which is consistent with the ratio of 3.6 ± 0.7 found by Schmid & Schild (1997).

The scattering efficiency for the Raman process is the ratio of the output to the input photon numbers. The above fluxes for the Raman lines and the corrected O VI fluxes, $F(1032) = (7.26 \pm 0.87) \times 10^{-10}$ and $F(1038) = (2.80 \pm 0.36) \times 10^{-10}$ ergs cm^{-2} s^{-1}, yield conversion efficiencies of ~7% for λ1032 and ~5% for λ1038. These values are similar to those derived for RR Tel, ~6% and ~3%, respectively.

Raman scattering is a dipole process; hence, we expect the emission lines at 6825 and 7082 Å to be polarized. Contemporaneous polarization measurements are not available, but a recent study of Z And by Schmid & Schild (1997) indicates a polarization of 6% ± 1% for the λ6825 line at $\phi = 0.39$; the polarization in the λ7082 generally follows that of the λ6825 line.

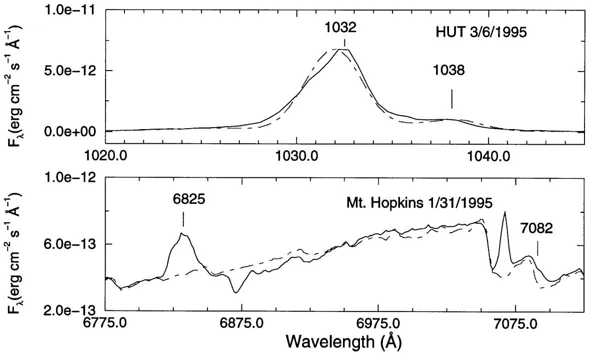

FIG. 2.—O VI $\lambda\lambda$1032, 1038 emissions and the Raman-scattered O VI lines at 6825 and 7082 Å in the visible. The dotted lines indicate the fits discussed in the text.

7. SUMMARY

Combined far-UV and optical data lead us to conclude that Raman scattering of O VI is occurring in the symbiotic star Z And. This is the second system, after RR Tel, for which a strong case can be made that the “unidentified” lines are the result of this process, and as such it lends further support to the occurrence of Raman scattering in some symbiotic stars.

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