A PARTICULAR FORM OF SATURN KILOMETRIC RADIATION AT THE LOW END OF ITS SPECTRUM

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Abstract

We studied the spectral morphology of Saturn kilometric radiation (SKR) with the Cassini RPWS (Radio and Plasma Wave Science) instrument and found a particular structure at very low frequencies which we nicknamed "caterpillar" due to its shape and look in dynamic spectra. In this paper we want to present the main physical characteristics of this newly identified form of SKR at the low end of its spectrum. Caterpillars are coarse SKR structures lasting for several hours at frequencies mostly below 40 kHz and with a typical bandwidth of about 10–15 kHz. The latter feature makes them easily distinguishable from Saturn narrowband emissions. Some of the caterpillars are connected to the main SKR emission at higher frequencies and some not. Their polarization is often opposite to that of the main SKR emission, and their total polarization degree is lower. We found almost 600 caterpillar emissions throughout the Cassini mission, and they were preferentially observed from beyond a distance of 10 Saturn radii in the equatorial plane or at lower latitudes. At high time resolution caterpillars show a smooth spectral structure, and only the so-called striations were sometimes found being superimposed.

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1 Introduction

The Saturnian radio spectrum shows many different kinds of emissions in the very low frequency (VLF) range of 3–30 kHz and the low frequency (LF) range of 30–300 kHz. The LF range is mostly dominated by Saturn kilometric radiation (SKR), whose peak intensity is around 200 kHz (Lamy et al., 2008). Sometimes Saturn narrowband (NB) emissions can be seen up to frequencies of 70 kHz (Ye et al., 2010), but most of them can be found in the VLF range concentrated around frequencies of 5 kHz and 20 kHz (Wang et al., 2010). Even SKR can extend down into the VLF range, and such events have been called SKR LFEs for low frequency extensions (Jackman et al., 2009). The LFEs are thought to be caused by increases in solar wind pressure (long LFEs) or by tail reconnection (short LFEs), which both can lead to an extension of the SKR radio source to higher altitudes along the source magnetic field line (Reed et al., 2018). An LFE extending down to 10 kHz or below roughly corresponds to an SKR source region with a distance of ~ 5 R$_S$ from the center of the planet (Lamy et al., 2018). Recently a new radio component called Saturn Anomalous Myriametric (SAM) radiation was reported by Wu et al. (2022b). SAM emissions have a typical central frequency near 13 kHz, a bandwidth larger than 8 kHz, and they usually drift in frequency over time.

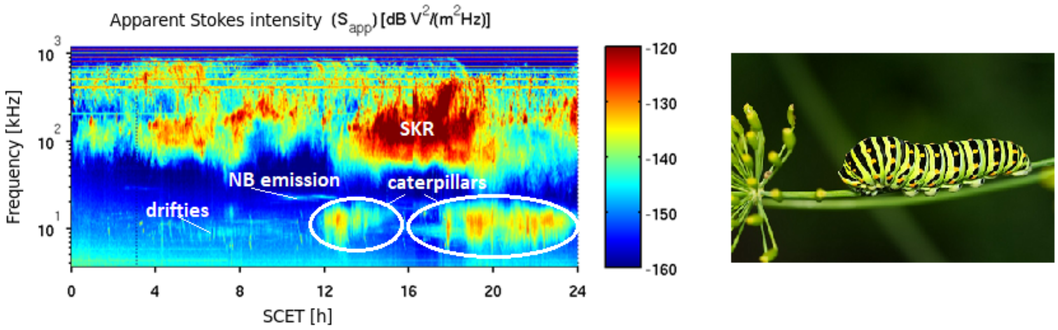

Figure 1: *Cassini RPWS dynamic spectrum from DOY 332, 2005: The apparent electric field power spectral density (apparent Stokes intensity S_{app}) in dB V^2 m^{-2} Hz^{-1} is displayed versus time (Spacecraft Event Time (SCET) in hours) and frequency from 3.6 kHz to 1200 kHz. And a real caterpillar for comparison (©Michael Reichelt, Pixabay, with permission).*

Figure 1 shows a Cassini RPWS dynamic spectrum displaying the electric field power spectral density of the radio emissions versus time and frequency. The time goes over 24 hours, and the frequency from 3.6 to 1200 kHz covers the A, B, C and H1 bands of the RPWS High Frequency Receiver (Gurnett et al., 2004). The strong SKR emission from about 80 to 800 kHz is clearly evident. A close inspection of Figure 1 further reveals a 20 kHz narrowband (NB) emission from $\sim 10-13$ hours SCET and so-called Saturn Drifting Bursts (SDBs) around 10 kHz mostly from $\sim 4-9$ hours SCET (Taubenschuss et al., 2011). But what are those two large emissions also centered around 10 kHz with a bandwidth of about 15 kHz occurring during the second half of the day? We put ellipses around them, and due to their peculiar shape in the spectrum we use the nickname of 'caterpillars'. This name was introduced by Fischer et al. (2022) who first classified them as a special coarse spectral structure of SKR.

In Section 2 of this paper we will show further examples of caterpillars to give the readers a better impression of their spectral morphology and wave polarization. In Section 3 we will describe their physical characteristics and show their spectral fine structure. We will discuss the lowered total polarization of caterpillars and their relation to LFEs in Section 4. The final Section 5 presents conclusions and perspectives for future research.

2 Examples of caterpillars

In Figure 2 we not only show the apparent intensity spectrum in the upper right panel, but also the apparent circular (upper left), linear (middle left), and total (middle right) polarization spectra. The so-called apparent polarization is defined in Fischer et al. (2009) for Cassini RPWS data, and it can be understood as the polarization measured in the antenna plane. From this apparent polarization one can derive the real polarization in case the incoming radio wave direction is known.

In the case of Figure 2 Cassini is located in the northern hemisphere around 20° latitude (blue line in lower left panel) beyond 27 R_S (Saturn radii, out of range in right bottom panel). From there SKR appears left–handed polarized (red color in upper left panel) after 04 hours SCET. However, the real polarization is right–handed as the angle β between the antenna plane and Saturn is negative ($\beta \approx -60°$). For a wave coming from Saturn only for $\beta > 0$ the real circular polarization sense equals the apparent one. The caterpillar emission can be seen centered at 10 kHz from $\sim 12 - 15$ hours SCET in Figure 2, surrounded by a white ellipse. Its bandwidth of ~ 10 kHz makes it easy to distinguish it from the 5 and 20 kHz NB emissions, whose typical bandwidth is just $2 - 3$ kHz (Wang et al., 2010). All emissions (SKR, caterpillar, NB emissions) have a very low degree of linear polarization close to zero. The caterpillar is oppositely polarized to the main SKR emission, and here it has the same circular polarization sense (left–handed in the real sense) as the 20 kHz NB emission. The 5 kHz NB is almost unpolarized except a small circular polarization in the same sense as the main SKR around 16 hours SCET. While the main SKR emission has a very high degree of total polarization close to one, the degrees of apparent total polarization of 20 kHz NB and caterpillar emissions are somewhat lower and roughly in the range from 0.6 to 0.8.

In Figure 3 one can see two caterpillars below 10 kHz, the first one at $\sim 12 - 18$ hours SCET, and the second one at $\sim 21 - 24$ hours SCET. In the first case, the spectra of the SKR and the caterpillar overlap, and this can also be regarded as an LFE of SKR. In the second case there is no overlap, similar to the caterpillars in Figures 1 and 2. All emissions (SKR and caterpillars) again have a low linear polarization degree. The main SKR has an apparent right-handed polarization, but its real polarization is left–handed as $\beta < 0$ and Cassini is at medium to low southern latitudes, thus it should observe left–handed SKR coming from the southern hemisphere. Towards the end of the day one can see SKR of real right–handed polarization at higher frequencies, which could be from the northern hemisphere. At lower frequencies the opposite polarization to the main SKR might indicate L–O mode (Cecconi et al., 2009). Also both caterpillars are oppositely polarized to the main SKR emission, i.e. they could be also in L–O mode. The total polarization of the caterpillars is close to zero below ~ 5 kHz, and somewhat higher

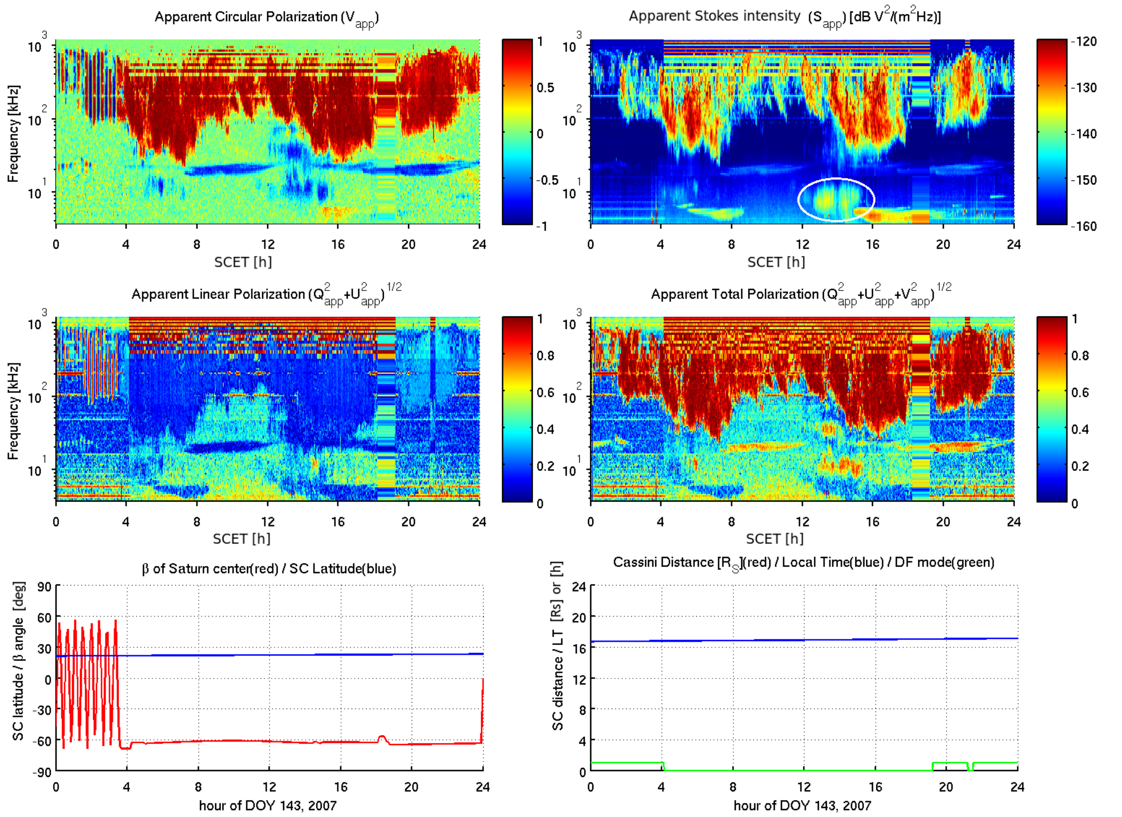

Figure 2: *Cassini RPWS dynamic spectra of apparent polarization and electric field power spectral density from DOY 143, 2007, showing SKR, narrowband emissions, and one caterpillar (within the white ellipse). The upper left panel shows the normalized apparent circular polarization ranging from -1 (fully right–handed) to +1 (fully left–handed). The upper right panel shows the apparent electric field power spectral density as in Figure 1. The two middle panels show the normalized apparent linear polarization and total polarization ranging from 0 to 1, respectively. The two lower panels show ephemeris and attitude of Cassini, and the RPWS instrument mode. The blue line in the lower left panel displays the spacecraft latitude, and the red line shows the angle β, which is the angle between the dipole–monopole antenna plane and the center of Saturn. The blue line in the lower right panel displays the local time of Cassini and the red line shows its distance to Saturn's center, but only ranging from 0 to 24 R_S (Saturn radii; no line here as Cassini is around 30–27 R_S). The green line shows a value of 1 when RPWS is in 3–antenna direction–finding mode, and a value of 0 when it is in the 2–antenna polarimeter mode.*

($\sim$ 0.6) above $\sim$ 5 kHz. During the second half of the day all SKR below $\sim$ 50 kHz seems to consist of patches of medium to low total polarization.

The final example in Figure 4 shows SKR that seems to be organized in three 'rows': The first row is intense SKR above $\sim$ 100 kHz having a mixed circular polarization as Cassini is in the equatorial plane from where both SKR sources at north and south can be observed. The second row consists of SKR in the $\sim 30 - 100$ kHz frequency range. It is dominantly left–handed polarized in the real sense ($\beta < 0$) with some patches of right–handed polarization. The total polarization of the first row of SKR is practically one, and it is still very high and mostly close to one for the second row. The third row of SKR goes from 5 to 20 kHz and its total polarization is clearly smaller and is mostly going up to only 0.4 to 0.6. Due to the spectral morphology we identify two caterpillars

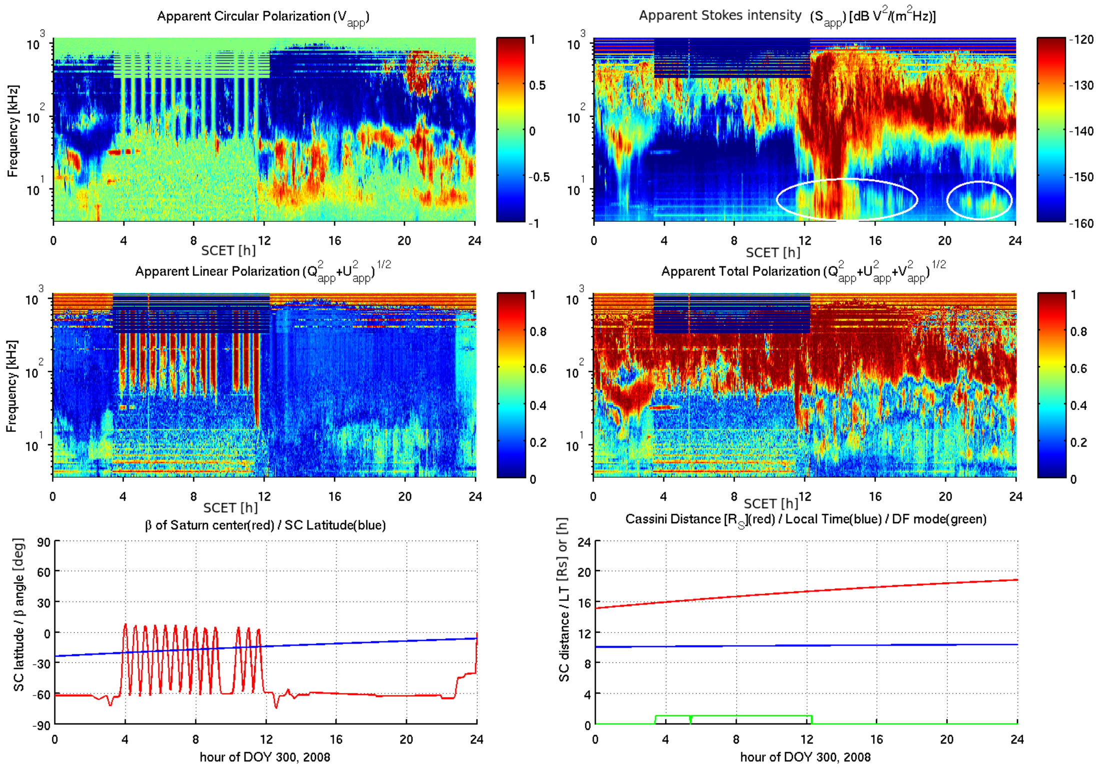

Figure 3: *Cassini RPWS dynamic spectra of apparent polarization and electric field power spectral density from DOY 300, 2008, showing two caterpillars (surrounded by white ellipses) connected and disconnected to the main SKR emission. For a detailed explanation of all panels see the caption of Figure 2.*

in the third row with a central frequency of $\sim$ 12 kHz, the first one from $\sim$ 00 to 07 hours SCET, and the second one from $\sim$ 14 to 17 hours SCET, and both are marked with white ellipses in Figure 4. The first caterpillar shows a mixed circular polarization, whereas the second shows a circular polarization opposite to the main SKR emission. The second row of SKR in the 30–100 kHz range also looks somewhat caterpillar–like, but the spectral morphology is not that clear. Since the total polarization is also still very high, we do not identify the features encircled by the dashed white ellipses in Figure 4 as caterpillars.

3 Physical characteristics and fine structure

As the examples in the previous section have shown, caterpillars are coarse SKR spectral structures typically lasting for several hours with a relatively constant central frequency below $\sim$ 35 kHz and a bandwidth of $\sim 10 - 15$ kHz. Furthermore we require that their duration be at least 1 hour and that their total polarization be smaller than 0.9 to be identified as caterpillars. This means that caterpillar–like structures with full polarization are considered as normal SKR. The larger bandwidth of caterpillars makes them easily distinguishable from Saturn narrowband emissions. Using these criteria we looked through all intensity and polarization spectra of the Cassini RPWS HFR data by eye throughout

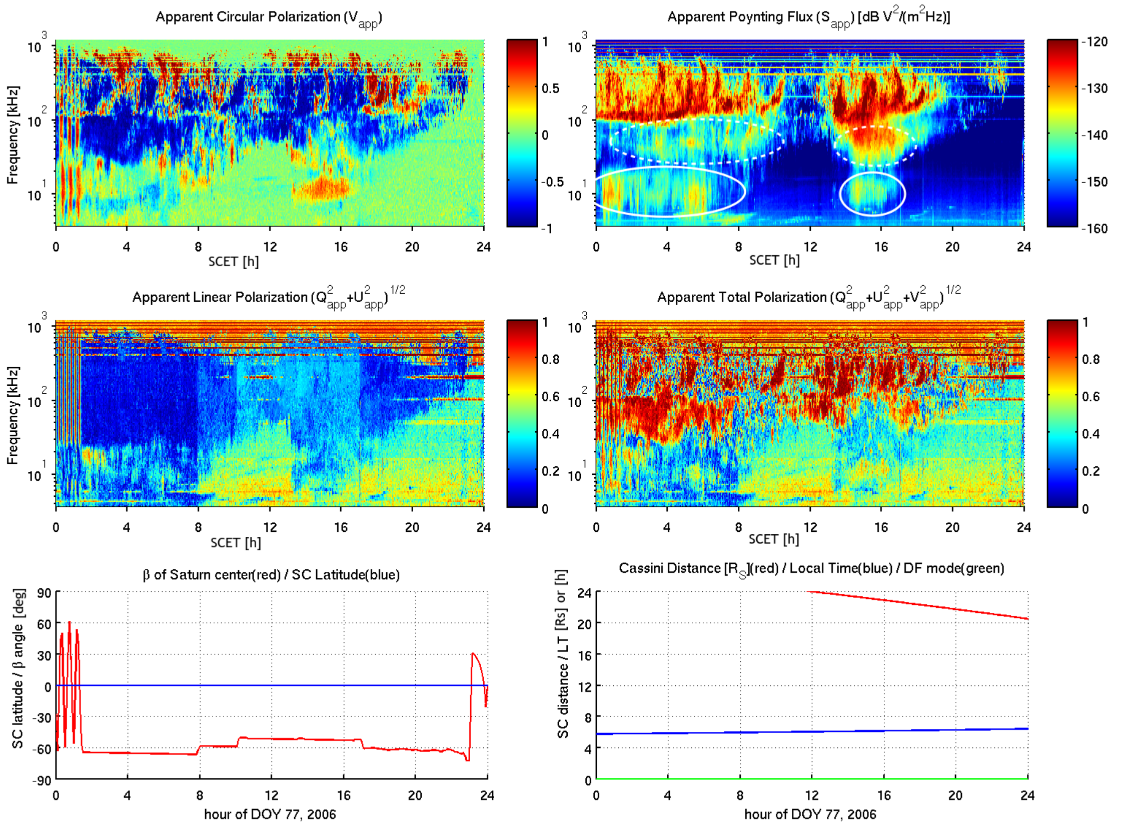

Figure 4: *Cassini RPWS dynamic spectra of apparent polarization and electric field power spectral density from DOY 077, 2006, showing SKR with caterpillar–like features in two rows. For a detailed explanation of all panels see the caption of Figure 2.*

the Saturn tour of the spacecraft.

We found 584 caterpillar events and calculated the following physical characteristics (averages with standard deviations): Their central frequencies are in the range from 4 kHz to 34 kHz with an average of (10 ± 4) kHz. Their bandwidths are in the range of 4 kHz to 46 kHz with an average of (12 ± 6) kHz. Their durations range from the defined minimum of 1 hour to 17.5 hours (with one outlier at 26 hours), and the average duration of a caterpillar is 3.8 ± 2.6 hours. Note that events with a duration of less than 1 hour are excluded. An example for such a short event can be seen from ∼01:30 to 02:00 hours SCET on DOY 300, 2008, in Figure 3 around 8 kHz. Caterpillars can be connected ($\sim$ 42%) or disconnected ($\sim$ 58%) to the main SKR emission at higher frequencies. The fact that a significant fraction of them are connected to SKR is an argument that they are not an emission of their own kind, but simply a particular kind of SKR at low frequencies. Furthermore, the spectral morphology of SKR in the LF range occasionally also looks caterpillar–like. However, the total polarization of SKR above $\sim$ 40 kHz is usually close to one, and then we do not count such structures as caterpillars. Usually the total polarization of caterpillars is moderate, typically in the range of 0.6 to 0.8. Caterpillars show mostly no linear polarization, and their circular polarization sense can be left–handed, right–handed or even mixed. Very often their polarization sense is opposite to the one

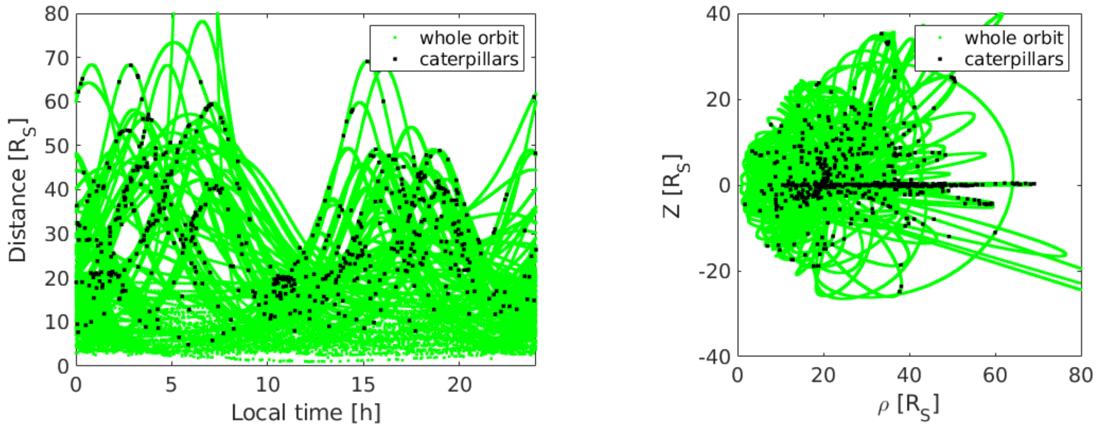

Figure 5: *Cassini orbital parameters during caterpillar emissions. The left panel shows the distance and local time of Cassini during caterpillars marked as black dots. In the right panel the black dots of caterpillars are shown in the meridian plane with height Z above the equatorial plane versus radius ρ (both in Saturn radii R_S). In both panels the green dots show the whole orbit of Cassini throughout its Saturnian tour.*

of the main SKR emissions, which in this case would mean that they are emitted in the L–O mode and not in the R–X mode as the majority of SKR.

Figure 5 shows Cassini's orbital parameters during caterpillar emissions as black dots, whereas green dots show the whole orbit of the Saturnian tour of the spacecraft. In the distance vs. local time plot in the left panel one can see no clear preference for local time, but almost all caterpillars have been recorded from distances beyond ~ 10 R_S. The meridian plot in the right panel shows the occurrence of caterpillars from all latitudes, but with a clear preference for low latitudes below $\sim 30°$ and the equatorial plane.

Figure 6 shows two Cassini RPWS Wideband Receiver (WBR) dynamic spectra with caterpillar emissions near the bottom of each. The left panel shows a smooth, not very strong caterpillar emission at $\sim 10 - 20$ kHz with a bandwidth of ~ 10 kHz compared to a strong narrowband emission at ~ 7 kHz, which has bandwidth of only ~ 1 kHz. The panel goes over ~ 80 s of time, and in this high temporal and frequency resolution it is even easier to distinguish narrowband emissions from caterpillars than in the daily plots of Figures 1 to 4. The right panel shows a comparison of SKR fine structures with linear and other discrete features above 50 kHz compared to the smooth caterpillar below 20 kHz. However, the intensity of the caterpillar might be modulated by so-called striations (Menietti & Kurth, 2006), which are discrete, narrowbanded, and negatively sloped lines lasting for a few seconds. One can also see some striations at the bottom of the SKR emission, mainly in the frequency range of $\sim 40 - 50$ kHz. In general the caterpillars are very smooth spectral structures as shown in the left panel of Figure 6. We found no other discrete fine structures of caterpillars except some rare superposed striations as shown in the right panel.

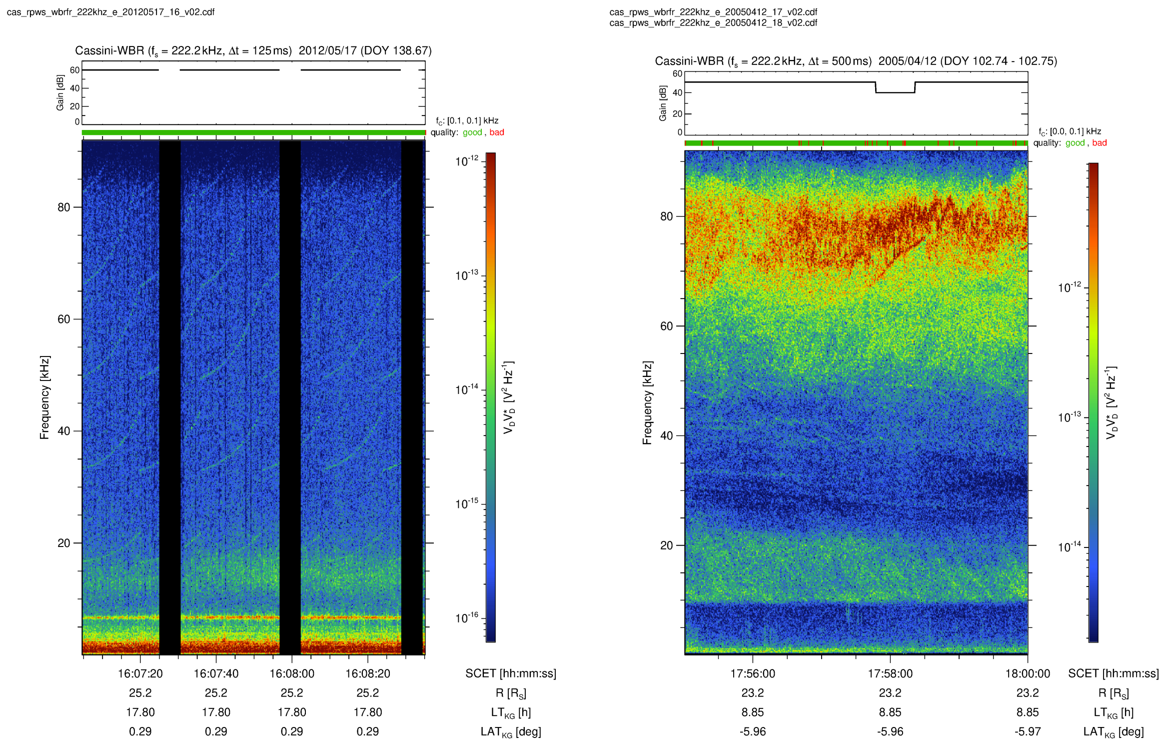

Figure 6: *Cassini WBR (WideBand Receiver) dynamic spectra showing the fine spectral structure of SKR and caterpillars. The color–coded auto–power spectral density (color bar on the right in V^2 Hz^{-1}) of the radio waves received by the electric dipole antenna is shown as a function of time (SCET) and frequency (kHz). For the left panel the spectral density goes from 6×10^{-17} to 10^{-12} V^2 Hz^{-1}, and for the right panel it goes from 2×10^{-15} to 9×10^{-12} V^2 Hz^{-1}. The x–axes also display some orbital parameters of Cassini (distance in R_S, local time in hours, latitude in degrees). The frequency goes from 0 to 90 kHz, but the intensity is weakened above 80 kHz by the frequency response of the bandpass filter. At the top, the sampling frequency f_S, the time resolution Δt, the date of the measurement, and the day of year (DOY) are shown. There is also a panel indicating the gain state of the WBR in steps of 10 dB and a green (or partly red) bar indicating the quality of the data.*

4 Discussion

We especially want to note that we compared the event lists of caterpillars and the newly detected Saturn Anomalous Myriametric (SAM) radiation: We found no overlapping events, and so they are two distinctly different phenomena that occur in the same very low frequency range below 40 kHz. SAM events usually drift in frequency over time (with a rate of a few kHz per day), and they have a mean duration of ~ 11.6 hours. They preferentially occur at high spacecraft latitudes. They are L–O mode emissions, and often they are accompanied by a first harmonic in R–X mode (Wu et al., 2022b). Caterpillar events are shorter (3.8 hours on average), they rarely show a drift in frequency, they preferentially occur at lower latitudes, and we did not find a single caterpillar event with a first harmonic. Colloquially spoken, SAM emissions and caterpillars are 'two different animals'. While SAM emissions might be a special form of Saturn narrowband emissions, we believe that caterpillars are a particular kind of SKR at the low end of its spectrum.

The extension of SKR to low frequencies is known as an LFE, and we make a first comparison between the occurrence of LFEs and caterpillars. Figure 7 of Reed et al. (2018) shows the occurrence of 264 short LFEs and 18 long LFEs during the year 2006 until DOY 350. Our event list of caterpillars shows 55 events during the same time interval. Out of these, 33 (60%) occurred during long LFEs, 16 (29%) during short LFEs, and only 6 events (11%) were not related to an LFE. This suggests that caterpillars are a subset of LFEs, which preferentially occur during increases in solar wind ram pressure (long LFEs).

Finally, we want to discuss the fact that caterpillars are not totally polarized and show a lower degree of total polarization. We consider the following four reasons for the partial polarization: First, an incoherent superposition of oppositely polarized SKR emitted from the northern and southern hemispheres leads to partial polarization for the superposed signal. This loss of polarization depends on the ratio of northern and southern SKR intensities (see e.g. Equations (14) to (16) in Fischer et al. (2007)). For example, one can see in the total polarization panel of Figure 4 that the SKR from both hemispheres above ~ 100 kHz (note that Cassini is in the equatorial plane in this case) is not totally polarized and also shows spectral regions of low total polarization, despite the fact that strong SKR is present there. However, we also have some caterpillars observed from high latitudes, where only one hemispherical SKR source should be observed, so that this explanation would not work here. Furthermore, it is unlikely that emissions from two sources superposed above each other can always lead to such a particular spectral structure as a caterpillar. Therefore, we rather favor a second explanation: The partial polarization of a caterpillar is caused by a reflection (or refraction) of the radio wave either by the magnetosheath or by the Enceladus plasma torus. The reflection off the magnetosheath is in line with the fact that many caterpillars occur during long LFEs, when the solar wind is strong and consequently the magnetosheath has a higher electron density. Only recently Wu et al. (2022a) found that 5 kHz Saturn narrowband emissions can be reflected by the magnetosheath. The same mechanism could be at work for caterpillars. Also note that ordinary SKR at very low frequencies sometimes also has a lower total polarization degree, even if its spectral structure is not a caterpillar. A third option to be considered for the partial polarization of SKR or caterpillars is the incoherent superposition of O and X–mode SKR from two adjacent sources in the same hemisphere. However, in general the flux density of the SKR O–mode is almost four orders of magnitude smaller than the flux density of the X–mode (Cecconi et al., 2009), and in such a case the polarization of the strong X–mode would prevail with only a marginal loss in total polarization degree. Only for a strong O–mode the superposition with X–mode would lead to a recognizable loss in total polarization for the superposed signal. For example, an O–mode having 10% of the flux density of the X–mode (and both fully circularly polarized) would lead to a total polarization degree of ~ 0.82 for the superposed signal. The forth and final option would be that caterpillars and SKR at VLF are produced with reduced polarization. However, most SKR is totally polarized, and we do not know if a coherent mechanism like the Cyclotron Maser Instability (CMI) is capable of producing partially polarized emissions.

5 Conclusions and perspectives

We identified a new kind of radio emission, that probably is a very low frequency component of Saturn kilometric radiation (SKR) at the low end of its spectrum (or simply a different emission). We nicknamed it 'caterpillar', and we showed several examples of this emission with its unique shape in a dynamic spectrum. Caterpillars are coarse SKR structures which on average last (3.8 ± 2.6) hours, have a relatively constant central frequency of (10 ± 4) kHz, and a bandwidth of (12 ± 6) kHz. We detected 584 caterpillars throughout Cassini's Saturn tour that were mostly observed beyond 10 Saturn radii and at low latitudes. Future research about this peculiar new phenomenon might comprise a more thorough statistical analysis of caterpillars than presented here, a comprehensive comparison of all caterpillars with SKR low frequency extensions (LFEs), and direction–finding studies of caterpillars and LF SKR to find its sources and to clarify if the partial polarization is due to reflections of the radio waves at the magnetosheath or due to superposition of X–mode and O–mode SKR.

Acknowledgments

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