IS TITAN A RADIO SOURCE?

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Abstract

Voyager 1 observations near Titan suggested that radio emissions near 60 kHz were generated via mode conversion from upper hybrid waves on the density gradient associated with Titan's ionosphere and induced magnetotail. However, simultaneous observations by Voyager 2 at a distance of 1.8 AU indicated that Saturn was actively generating radio emissions in this frequency range at the time of the Voyager 1 Titan flyby, hence, the Saturn kilometric radiation effectively masked any emissions that might have been of Titan origin. Cassini has flown past Titan five times as of the time of this writing and has observed a similar emission possibly originating at Titan during the first of those on October 26, 2004. Again, however, Saturn was actively emitting radio waves in a similar frequency range, hence, the source of the waves is, again, in question. Cassini, however, has the ability to measure direction-of-arrival and the polarization state of radio emissions, hence, it is possible to distinguish between Titan and Saturn as the source, subject to a 180° ambiguity in the direction-finding solutions. The direction-finding results suggest Saturn is just as likely a source as Titan, hence, there is no compelling, unambiguous evidence for a Titan radio source as yet. In this paper we review the reasons for suspecting the Voyager 1 emissions as Titan radio emissions and examine the Cassini observations to determine whether or not Titan is a radio source. Our conclusion is that it is still too soon to say, definitively.

1 Introduction

This paper discusses Voyager 1 and Cassini observations in the vicinity of Titan addressing the question of whether or not Titan is a source of non-thermal radio emissions. Specifically, we are interested in radio emissions arising from the interaction of Saturn's magnetosphere with Titan and we exclude discussion of lightning-related radio emissions, a subject of another study.

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It is appropriate to preface this paper with a short discussion of why the question of radio emissions from Titan is of interest and why the question would even arise. First, the question actually arose some 24 years ago based on Voyager 1 observations [Gurnett et al., 1981; Kurth et al., 1981] which will be discussed below. The evidence in favor of emissions from Titan was overwhelmed by the presence of Saturn kilometric radiation [Daigne et al., 1982], and the issue was dropped for lack of observations. The question arises again, now that Cassini is in a position to make additional observations which might resolve the issue.

The interest in the possibility of radio emissions from Titan is of course related to the possibility of finding a second solar system moon which is a source of non-thermal radio emissions. Jupiter's moon Ganymede is the first [Gurnett et al., 1996; Kurth et al., 1997]. More importantly, the interest is driven by a desire to understand just how ubiquitous planetary radio emissions may be. Titan is a possible source because Voyager 1 observed intense electrostatic noise at the upper hybrid resonance frequency in the induced magnetotail of Titan, some 2.5 Titan radii ($\mathrm{R_T}$) downstream from the moon. Furthermore, Voyager measured a draped magnetic field [Ness et al., 1982] which is almost certainly oriented more or less perpendicular to the plasma density gradient near Titan and the boundary of its induced magnetotail. These are the ingredients previously required by those who have discussed the mode conversion mechanism [Jones, 1976; Jones, 1985; see also Kurth, 1986]. It is mode conversion from electrostatic waves near the upper hybrid resonance frequency ($f_{uh}^2 = f_{pe}^2 + f_{ce}^2$ where f_{pe} is the electron plasma frequency and f_{ce} is the electron cyclotron frequency) that is the source of Ganymede's radio emissions as well as similar emissions called continuum radiation commonly found at Earth and Jupiter. On the other hand, all other known non-thermal radio sources in the solar system, including Ganymede, are magnetized and have magnetospheres (or the corona and heliosphere in the case of the Sun).

It is important to note that cyclotron maser emissions found in planetary magnetospheres are not found at Ganymede, nor is this type of emission expected at Titan. The primary reason for this is that the cyclotron maser instability requires that the ratio of the plasma frequency to cyclotron frequency $f_{pe}/f_{ce} \ll 1$. Since Titan has a dense ionosphere and the draped magnetic field is weak, this condition is almost certainly not met at Titan.

2 Voyager 1 Observations

During its flyby of Titan in November, 1980, Voyager 1 detected upper hybrid resonance emissions with intensities of $\sim 30\mu\mathrm{V/m}$ in the high-density induced magnetotail of Titan and, immediately upon exiting this region, observed strong radio emissions in the frequency range of 31 – 56 kHz. Figure 1 shows these observations in the form of a series of amplitude vs. time plots for three of the Voyager plasma wave science (PWS) fixed frequency channels [see Scarf and Gurnett 1977]. In the illustration, the height of the black area is proportional to the amplitude of the signal. Gurnett et al. [1981] identified bursty emissions near closest approach as upper hybrid resonance emissions.

The abrupt onset of the radio emissions as Voyager left the vicinity of Titan suggested

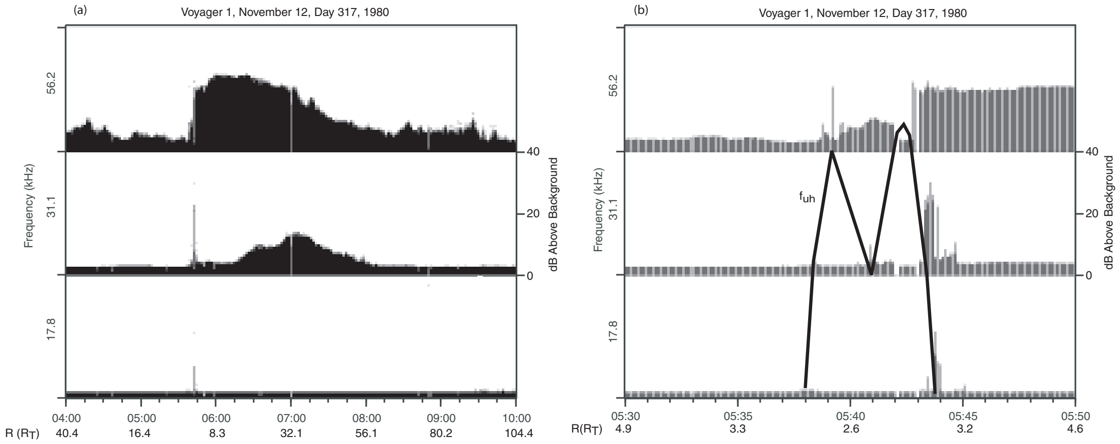

Figure 1: The Voyager 1 observations at 17.8, 31.1, and 56.2 kHz near the closest approach of Titan. (a) An abrupt increase in radio emissions is observed immediately upon leaving the high density plasma in the induced magnetotail at 56.2 kHz. Additional emissions are observed somewhat later at 31.1 kHz. (b) A detail immediately around the time of closest approach.

that Titan was the source of these emissions and the presence of the upper hybrid waves suggested that the generation mechanism was mode conversion of electrostatic waves near f_{pe} to ordinary mode radiation [Gurnett et al., 1981], similar to the source mechanism for continuum radiation in the magnetospheres of Earth and Jupiter [Kurth, 1992]. Examination of the temporal variations of these emissions as compared to Saturn kilometric radiation (SKR) observed in a similar frequency range showed that these radio emissions exhibited unusually smooth temporal variations, further suggesting a different source for them. Figure 2 shows a comparison of the peak-to-average field strength for the suspected Titan emissions illustrated in Figure 1 with SKR emissions observed over a ∼ two-week period near the Voyager 1 Saturn flyby.

However, the Voyager 2 planetary radio astronomy instrument (PRA) [Warwick et al., 1977] observed Saturn kilometric radiation at the same time (accounting for one-way light travel time) as the emissions observed by Voyager 1 [Daigne et al., 1982]. Voyager 2 was some 1.8 AU distant at the time. The detected power flux of the radio emission at Voyager 2 relative to that observed at Voyager 1 at 59 kHz was 23 to 25 dB weaker, inconsistent with the r^{-2} relation expected considering Voyager 1's distance to Titan. The detected power flux ratio, however, was more consistent with the square of the ratio of the distances of the two spacecraft from Saturn. This conclusively identifies Saturn as the actual source of the primary radio emissions in Figure 1. Even so, it seemed possible that the conditions near Titan were similar enough to the plasmapause at Earth (a source of continuum radiation) that considering Titan as a source of radio emissions was at least plausible and that, perhaps some level of emissions might, indeed, be generated as a result of Titan's interaction with the Saturn magnetosphere.

With the arrival of Cassini at the Saturnian system and multiple close flybys of Titan, one objective of the Cassini radio and plasma wave science (RPWS) investigation [Gurnett et al., 2004] is to search for radio emissions emanating from Titan. In addition to carrying

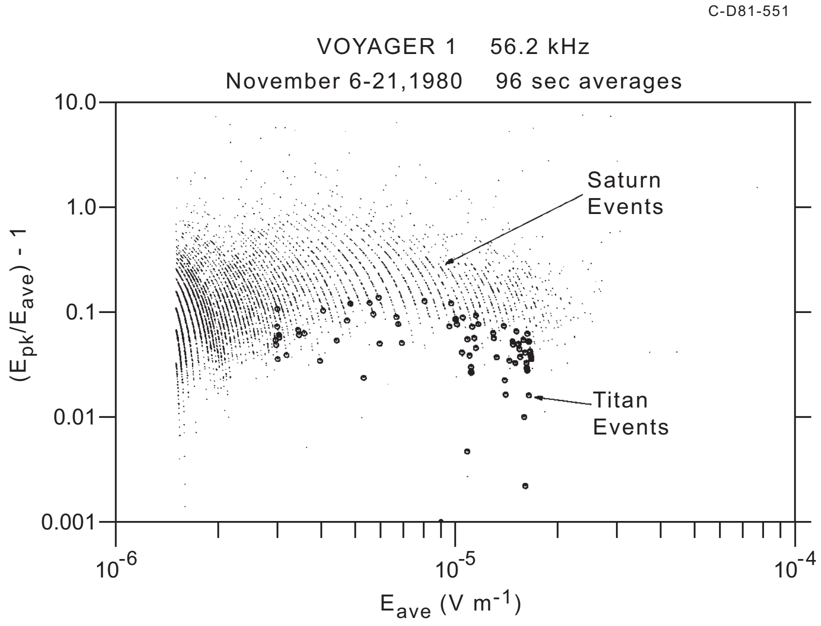

Figure 2: A study of the peak-to-average ratio of emissions seen shortly after the Voyager 1 Titan closest approach and Saturn kilometric radiation events seen in a ~ two-week period near the Saturn flyby. We have used 96-s averages and peak electric fields measured during the same interval and plot (peak/average) - 1. Note that the event observed just after the Titan closest approach has a much smaller peak-average ratio than most SKR events, suggesting a different type of radio emission.

the ability to measure the spectrum of radio waves, the Cassini instrument also includes the capability for determining the direction of arrival of radio waves and their polarization, at least under some instrument operational modes. The next section presents early observations near Titan which bear on this issue.

3 Cassini Observations

As of the writing of this paper, Cassini has executed five close flybys of Titan during which the RPWS was on. All of these flybys show extensive Saturn kilometric radiation near the time of the encounters, but with obvious occultations of Saturn's radio sources for times when Cassini is situated on the anti-Saturn side of Titan. Such occultation periods offer the most ideal times to look for radio emissions from Titan, but to date, we have observed no strong emissions which appear to be related to Titan during the occultations. It remains to be seen whether there are weak emissions in these time periods. We have examined the stronger radio emissions seen very close to Titan with the expectation that Titan-related emissions would have a narrowband structure and would drop off rather rapidly with distance from Titan (i.e. displaying approximately an r^{-2} radial dependence). Most of the radio emissions observed show no such radial variation and typically show similar frequency and time variations to Saturn kilometric radiation, hence, are very unlikely to be related to Titan.

However, following the closest approach to Titan on Orbit A (sometimes referred to as the Ta flyby) a rather narrowband emission was observed near 100 kHz which fell off rapidly in intensity as Cassini departed the vicinity of Titan. The geometry of this flyby is shown in Figure 3. This emission appears to be the best candidate for a Titanian radio emission observed so far and we selected it for further study. An overview of the radio and plasma wave spectrum for the Ta flyby is shown in Figure 4.

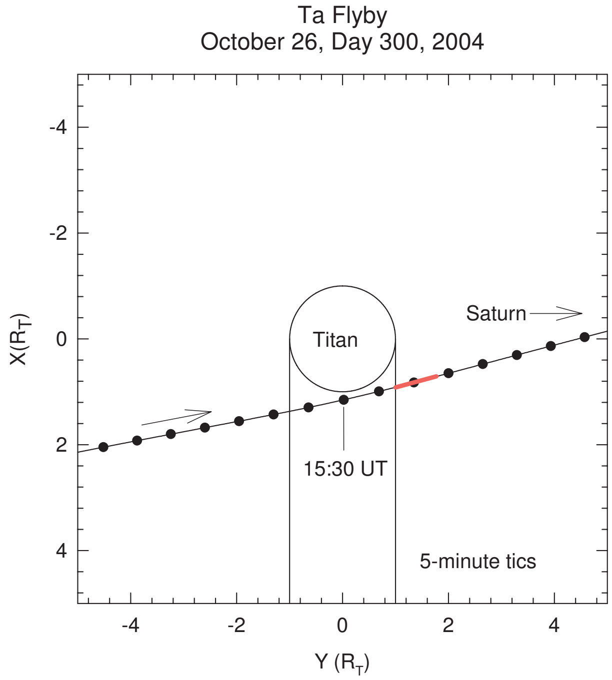

Figure 3: The geometry of the Ta flyby of Titan. This is an equatorial plane projection with corotation in the direction of +x and Saturn in the direction of +y. The interval just after closest approach highlighted in red is the time during which possible narrowband radio emissions associated with Titan were detected.

Figure 4 focuses on the mid-frequency portion of the RPWS frequency range, from 4 to 700 kHz. The primary feature in this spectrogram is the upper hybrid resonance band which is highlighted with a white trace. Titan closest approach is at 15:30 UT; the peak in the ionospheric density is biased to earlier times since the inbound hemisphere of Titan was sunlit at the time of the encounter. The trajectory approached Titan from the anti-Saturn side of Titan, hence, Titan occulted most of Saturn's radio source prior to the flyby, but the sources reappeared shortly afterwards. At the highest frequencies, 400 – 500 kHz in the region highlighted with a white rectangle, the spectral and temporal variations in the radio emissions are similar to those expected for Saturn kilometric radiation. However, the band of emission highlighted by the lower white rectangle appears to be smoother and fixed at a constant frequency.

In Figure 5, we examine the variation of spectral density with distance from a source in

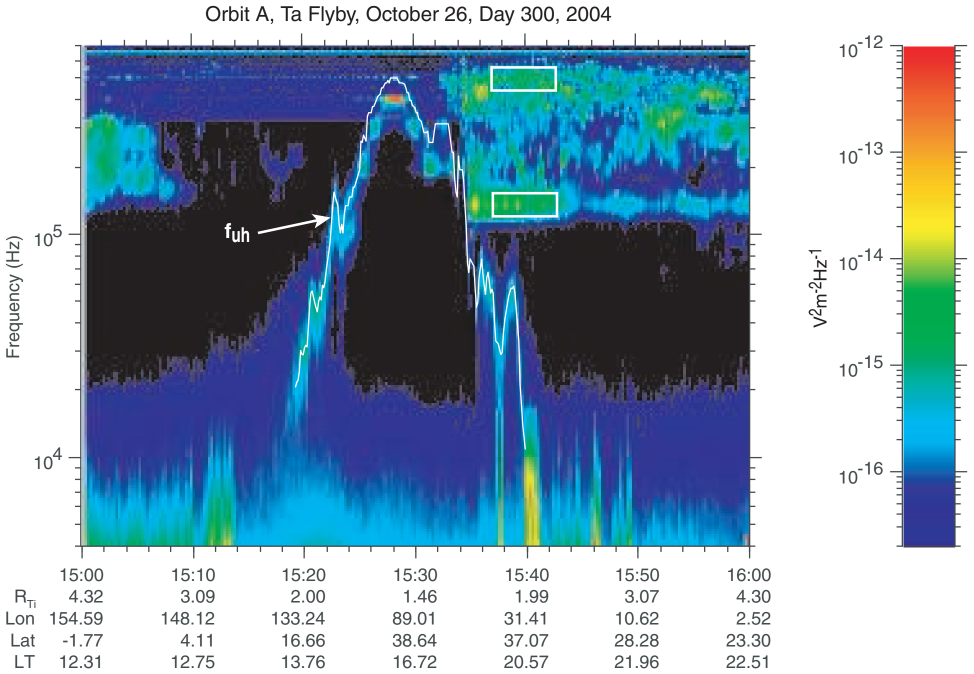

Figure 4: An overview of the radio and plasma wave spectrum observed during the Ta flyby of Titan. The relatively narrowband emission just above 100 kHz is a good candidate for an emission generated near Titan.

the vicinity of Titan. We have fit the data with a curve of the form

$$log(P_f) = log(P_0/(r - R_0)^2) \tag{1}$$

where R_0 is the radial distance of the putative source from Titan, P_0 is a constant, and r is the distance of Cassini from Titan. The fit parameters are $P_0 = 1.69 \times 10^{-14}$ W/m^{2}Hz and $R_0 = 1.64$ R$_\mathrm{T}$. The fit is rather poor and we do not believe the radial variation represents an r^{-2} trend. A three dimensional fit can also be performed, but the fit is unlikely to improve.

We conclude that the radio emission in question does not follow an r^{-2} trend, but one could argue that temporal variations in the source or beaming considerations could modify the temporal behavior; the lack of an r^{-2} dependence does not irreconcilably remove Titan as a possible source.

The Cassini radio and plasma wave instrument has the capability to determine the direction of arrival and polarization of radio sources [Cecconi and Zarka, 2005; Cecconi et al., 2005]. In the configuration used for this Titan flyby, using the three monopole antennas configured as a dipole and a monopole, we cannot simultaneously solve for all of the Stokes parameters plus the direction-of-arrival. But, we can assume the radio emissions are circularly polarized and determine the degree and handedness as well as the direction

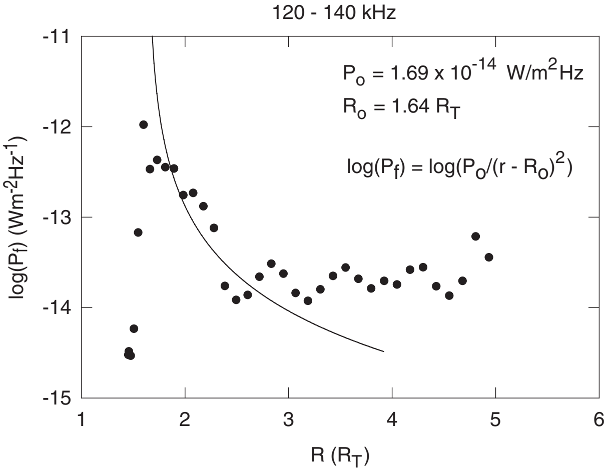

Figure 5: A fit of the spectral density of radio waves in the frequency range 120 – 140 kHz to an r^{-2} functional form which might be expected for a source near Titan. The fit is a poor one, however.

of arrival. However, there is a 180° ambiguity in the radio direction finding measurement and, as can be seen in Figure 3, during this time Cassini is between Titan and Saturn.

Figure 6 shows two sets of direction-finding results. In panel (a), the source postions relative to Titan are determined, assuming Titan is the source. The black symbols representing the 100 – 150 kHz emissions in question lie at a reasonable location for a Titan radio emission, centered on the moon in the north-south direction and biased toward the wake hemisphere. The red symbols represent the location of the 400 – 500 kHz emission under the assumption of a Titan source; these points do not fall in a logical location with respect to Titan, but we are quite certain that these higher frequency emissions are from Saturn, so this would be a consistent result.

In panel (b) of Figure 6, we have assumed that Saturn is the source and have located both the low and high frequency emission sources relative to the planet. Both sets of emissions appear to be coming from Saturn's northern hemisphere with the lower frequencies coming from further from Saturn than the higher ones, just as would be expected. There seems to be excessive spread of the low-frequency emissions to very great distances from Saturn, though. We will discuss a possible reason for this, below.

If both frequency ranges of the radio emission are SKR generated in Saturn's northern hemisphere, they should both be right-hand circularly polarized as seen by Cassini. This, indeed, is the case, although the degree of circular polarization for both frequencies is quite low and not consistent with the degree of circular polarization of SKR observed at later times, quite distant from Titan. We suggest that this result and the large spread in the low-frequency source directions might be the result of propagation effects near Titan, for example, due to some reflection from the high-density ionosphere of the moon. Figure 3 shows how close Cassini is to Titan and its ionosphere and induced magnetotail when the radio emissions were observed.

Given that both the low and high frequency radio emissions show reasonable source loca-

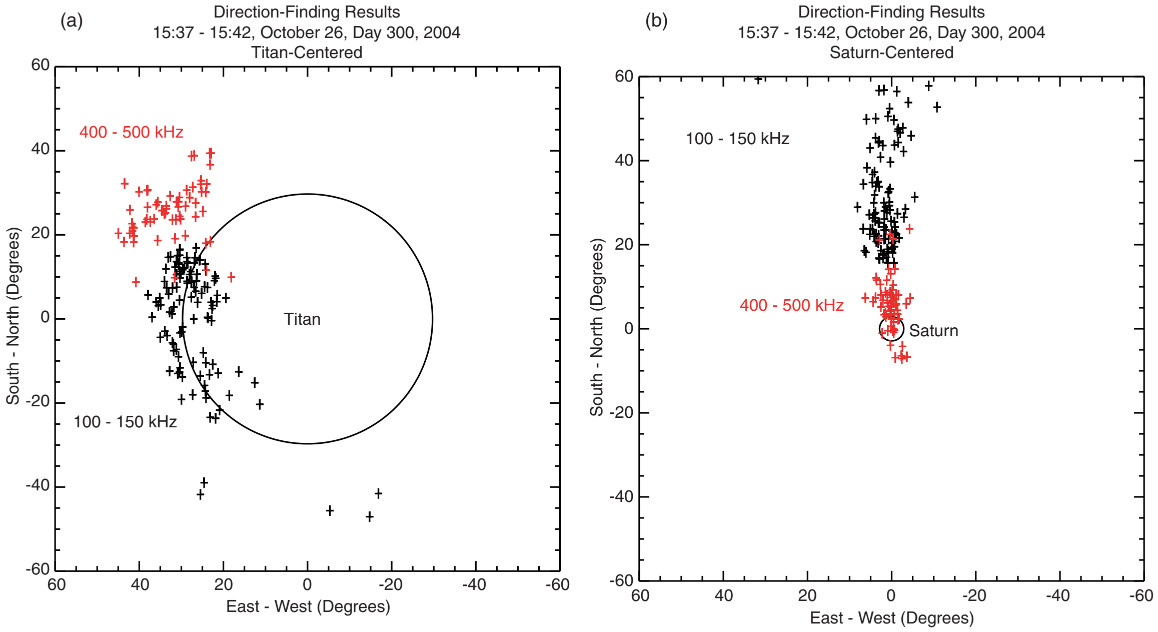

Figure 6: Direction-finding results. (a) Sources of 100 – 150 and 400 – 500 kHz radio emissions assuming that Titan is the source. The low-frequency emissions fall in a location consistent with where one might expect a Titan source to lie. The higher frequency emissions do not, but these are almost certainly Saturn kilometric radiation. (b) Source locations for the two frequencies assuming that Saturn is the source. Note that the relative positions of the high and low-frequency emissions is as would be expected for both emissions coming from the SKR source region. The spread at lower frequencies might be a result of propagation effects due to the vicinity to high plasma densities at Titan.

tions and a consistent polarization for Saturn kilometric radiation, there is no compelling reason to argue that the also-consistent Titan source location is strong evidence for a source at Titan.

4 Discussion and Conclusions

The observations presented above, while tantalizing, do not prove that Titan is a non-thermal radio source. The evidence certainly does not prove the converse, either. Cassini has nearly 40 more close flybys of Titan, so it is entirely possible proof of a Titan radio source will be found. However, after Voyager 1's encounter and five Cassini encounters, one must conclude that if there are Titan radio emissions, they are weaker than we have been looking for or they are not commonly present. And, it is possible that there simply is no source at Titan.

We consider reasons why the conditions at Titan may not favor the generation of radio waves. First, the upper hybrid resonance band at Titan measured by Cassini is rather weak. The maximum electric field strength measured on the density gradient is of order 3 μV/m whereas the electrostatic waves on Earth's plasmapause, one of the primary sources of continuum radiation at Earth, is typically 100 μV/m and sometimes larger. Further down Titan's induced magnetotail, Voyager 1 observed electrostatic waves with amplitudes of $\sim$ 30 μV/m, so perhaps emissions may be more likely from the induced magnetotail. This could be because the anisotropic distributions associated with pickup processes required to drive the electron cyclotron harmonic instability are more likely to develop downstream from the ionosphere. Second, deep in the plasmasphere and in Earth's ionosphere thermal emissions near f_{uh} are commonly observed, but these are not seen to generate radio emissions. The upper hybrid waves responsible for continuum radiation are not thermal emissions but are instabilities which grow with large convective growth rates from large temperature anisotropies in the electron distribution or a distribution with a positive slope in the direction perpendicular to the magnetic field. Rönnmark [1985] has also suggested that the source of the emissions are the F_q resonances. These are frequencies where the group velocity goes to zero. Io is another example of a moon which does not locally generate radio emissions but has thermal emissions at f_{uh} [Gurnett et al., 1996]. In this context, we ignore other upper hybrid emissions elsewhere in the Io torus which may be more intense, such as near Jupiter's magnetic equator [Birmingham et al., 1981].

If we are to find radio emissions coming from Titan, there are two likely possibilities. First, we will have to look for much lower intensities than have been examined, to date. This suggests that we concentrate on the anti-Saturn hemisphere where SKR is largely occulted. The second possibility is that there are conditions downstream from Titan, on the boundary of the induced magnetotail, where instabilities such as those observed by Voyager 1 exist, at least temporarily. Cassini has one opportunity to explore this region downstream of Titan currently planned for the T9 flyby during the 19^th orbit in December 2005.

Acknowledgements

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