

# SATURN'S RADIO EMISSIONS AND THEIR RELATION TO MAGNETOSPHERIC DYNAMICS

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## Abstract

With the arrival of the Cassini spacecraft at Saturn in July 2004, there have been quasi-continuous observations of Saturn Kilometric Radiation (SKR) emissions. In this paper we review the response of these emissions to dynamics in Saturn's magnetosphere, driven by factors internal and external to the system. We begin by reviewing solar wind data upstream of Saturn and discuss the link between solar wind compressions and dynamics in Saturn's magnetosphere, evidenced by intensifications and occasional phase changes in the SKR emission. We then review the link between magnetotail reconnection and planetary radio emissions. We begin in the well-sampled magnetotail of Earth and then move to Saturn where exploration of the nightside magnetosphere has revealed evidence of plasmoid-like magnetic structures and other phenomena indicative of the kronian equivalent of terrestrial substorms. In general, there is a good correlation between the timing of reconnection events and enhancements in the SKR emission, coupled with extension of the emission to lower frequencies. We interpret this as growth of the radio source region to higher altitudes along the field lines, stimulated by increased precipitation of energetic electrons into the auroral zones following reconnection. We also comment on the observation that the majority of reconnection events occur at SKR phases where the SKR power would be expected to be rising with time, indicating that reconnection is most likely to occur at a preferred phase. We conclude with a summary of the current knowledge of the link between Saturn's magnetospheric dynamics and SKR emissions, and list a number of open questions to be addressed in the future.

## 1 Introduction

The plasma flows in the magnetosphere alter significantly as a consequence of the solar wind interaction, specifically due to steady reconnection at the magnetopause and in the tail, as first described by Dungey [1961] in the terrestrial context. These changes can be remotely sensed by studying planetary radio emissions, and a fuller picture of the global

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dynamics can be built up by combining the radio observations with upstream solar wind measurements or *in situ* magnetotail sampling. This paper is intended to provide a review of the relationship between Saturn's magnetospheric dynamics and its radio emissions. We will begin by looking at external influences on Saturn's radio emissions, namely the solar wind. Then we will proceed to discuss influences which are internal to the magnetosphere, in particular magnetotail reconnection.

## 2 Solar Wind Influence on Saturn's Magnetospheric Radio Emissions

The solar wind upstream of Saturn and its relationship to auroral radio emissions has been studied since the Voyager era in the early 1980s [e.g. Kaiser et al., 1980]. The solar wind exerts a strong influence on Saturn's magnetospheric cavity, shaping it and driving dynamics within it. Desch [1982] employed Voyager data to examine the correlation between the solar wind ram pressure and SKR intensity, and found a time delay of less than one Saturn rotation between the onset of a ram pressure increase and the beginning of an increase in SKR energy. Desch and Rucker [1983] then went on to find that solar wind momentum and kinetic energy are also significant triggers for SKR. In the Cassini era, several authors have examined aspects of this correlation in more detail [e.g. Badman et al., 2008; Rucker et al., 2008]. For example, Taubenschuss et al. [2006] found that increases in ram pressure correlated with SKR intensity increases with a 13 hour lag and 55% efficiency.

In addition to affecting the intensity of the emission, the solar wind has also been observed to alter the period of SKR [Zarka et al., 2007]. The SKR period varies systematically by  $\pm 1\%$  with a characteristic timescale of  $\approx 20$ -30 days. These variations were found to be correlated with fluctuations in the solar wind speed, with a correlation coefficient  $C > 40\%$ . While highly significant, this correlation is not perfect, one reason for this being that the solar wind might function as a trigger, efficient only when energy has previously been stored in the magnetosphere, so that SKR peaks may sometimes be "missing".

Clearly Saturn's radio emissions are influenced at least in part by conditions external to the magnetosphere, and by understanding the relationship between solar wind conditions and SKR emission, it has even been possible to remotely diagnose upstream conditions while a spacecraft is inside the magnetosphere. This was done by Jackman et al. [2005] who examined the correlation of IMF strength and SKR power during Cassini's approach to Saturn over five solar rotations. They found a clear pattern of Corotating Interaction Region (CIR) compressions and rarefactions in the IMF, which is what would be expected for the outer heliosphere during the declining phase of the solar cycle. Due to the regular nature of such CIR compressions, (and hence the regular pattern of SKR bursts), it was possible to predict that Cassini would observe the effects of a solar wind compression while executing its Saturn Orbit Insertion (SOI) manoeuvre. On inspection of the data from SOI, it subsequently transpired that a compression impacted on Saturn's magnetosphere during the outbound pass of SOI, and its effects are discussed below.

In Figure 1 we show the radio and magnetic field data taken by Cassini throughout the

entire SOI pass by the Radio and Plasma Wave Science (RPWS) and magnetometer (MAG) instruments [Gurnett et al., 2004; Dougherty et al., 2004]. At the beginning of the interval, the spacecraft crosses Saturn's bow shock and then magnetopause before entering the magnetosphere fully as it continues its inbound trajectory before closest approach on day 183. The radio emissions pulse regularly during this interval, with roughly consistent powers, and at a period close to the expected planetary rotation rate (marked by the white arrows in the middle panel at 10.75-hour intervals). However, on the outbound pass the behaviour is dramatically different. There is a large burst of intense SKR on day 184 (bracketed by the vertical dashed lines). Jackman et al. [2005] suggested that this burst marks the arrival of the predicted solar wind compression at Saturn's magnetosphere. This burst is accompanied by an extension of the emission to lower frequencies, a feature which we will comment on later in section 4. The timing of this burst disrupts the previous pattern of bursts, which then begins to reassert itself after several planetary rotations. This burst is coincident with a large field disturbance, which Bunce et al. [2005] interpreted as *in situ* evidence of compression-induced tail reconnection and hot plasma injection. In the next two sections we will explore this topic of magnetotail reconnection in more detail, first at Earth and then at Saturn, and examine how radio emissions can be used to tell us more about the global effects of this process.

### 3 Magnetotail Reconnection and Radio Emissions: Terrestrial Review

The topic of magnetotail reconnection has been widely studied at the Earth for many years. Magnetometers on spacecraft orbiting in the tail can detect signatures of dipolarizations or plasmoids passing spacecraft, and such field signatures are often accompanied by the detection of strong plasma flows, plasma energizations, and enhancements in the auroral electrojet indices. Over the years, many authors have explored the correlation between magnetotail reconnection at Earth and sudden intensifications in the Auroral Kilometric Radiation (AKR) [Benediktov et al., 1968; Gurnett, 1974; Voots et al., 1977; Kurth et al., 1998]. Understanding the relationship between these radio emissions and terrestrial substorms is an important first step on the path to understanding the relationship between SKR and magnetotail reconnection at Saturn.

While the average power of AKR is found to increase with substorm activity, the nature of the relationship is more complex. The AKR can also show abrupt frequency expansion at the time of substorm onset [e.g. Kaiser and Alexander, 1977; Anderson et al., 1997]. Recently, Morioka et al. [2007, 2008, 2010] have reported on what they term the "dual-component AKR spectrum". They identify two distinct sources of AKR: 1) A low-altitude source (MF-AKR) which corresponds to middle-frequency AKR and is active before and after substorm onset, and 2) A high-altitude source which corresponds to low-frequency AKR (LF-AKR). This source appears abruptly with intense power (increasing by a factor of up to 1000 times) at substorm onset.

An example of this is shown in Figure 2, reproduced from Morioka et al. [2007]. In this case, the Polar spacecraft was orbiting in Earth's nightside polar magnetosphere with the

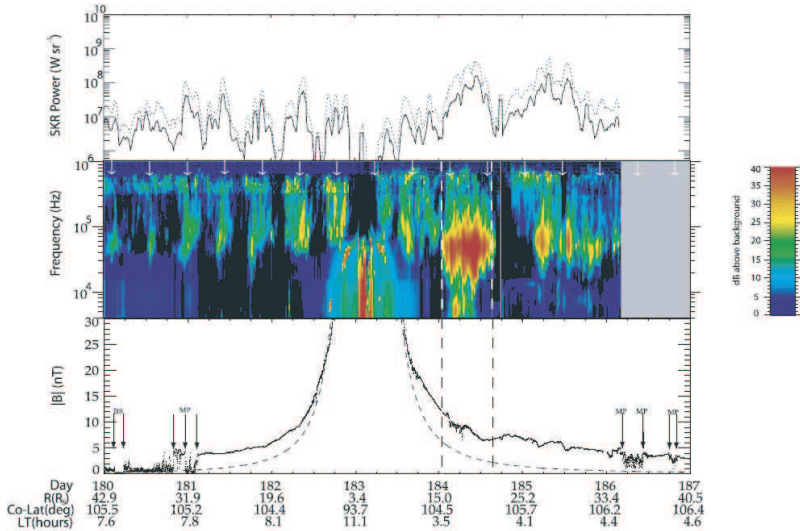


Figure 1: Cassini RPWS and MAG data for 2004 day 180-186. The top panel shows the inverse-square corrected power of the sum of LH and RH circularly polarized radio waves, where the solid line shows the power in the 100–300 kHz frequency band and the dashed line shows the power in the 4–1,000 kHz band. The middle panel shows the corresponding frequency-time spectrogram covering the whole frequency band from 4 to 1000 kHz, colour-coded according to the bar on the right-hand side. The bottom panel shows the total magnetic field strength with the dashed curve showing the strength of the internal field of the planet from the SPV model. Vertical dashed lines indicate the interval of the first major burst of SKR observed on the outbound pass, beginning on day 184. From Jackman et al. [2005].

PWI (Plasma Wave Instrumentation) measuring the AKR emissions, while the ground-based magnetometer at Kakioka station was measuring Pi 2 pulsations, another good indicator of substorm onset in the terrestrial tail. A large substorm occurred around 1200 UT on this day as evidenced by a sudden onset of Pi 2 pulsation. This is accompanied by a strong intensification of the AKR with an expansion of the emission down to 30 kHz, forming what the authors term “LF-AKR”.

The frequency of the AKR emission is related to the position of the radio source along the field lines, due to the fact that the emission is generated at or close to the local electron cyclotron frequency,  $f_{CE}$ , which in turn is proportional to the total field strength. The interpretation put forward by the Morioka papers is that electrons precipitating into the auroral zones following energetic magnetotail reconnection can cause the radio sources to move/merge/grow to higher altitudes along the field lines. In the next section we explore whether a similar behaviour is observed at Saturn whereby SKR emissions intensify and expand to lower frequencies in tandem with kronian magnetotail reconnection events.

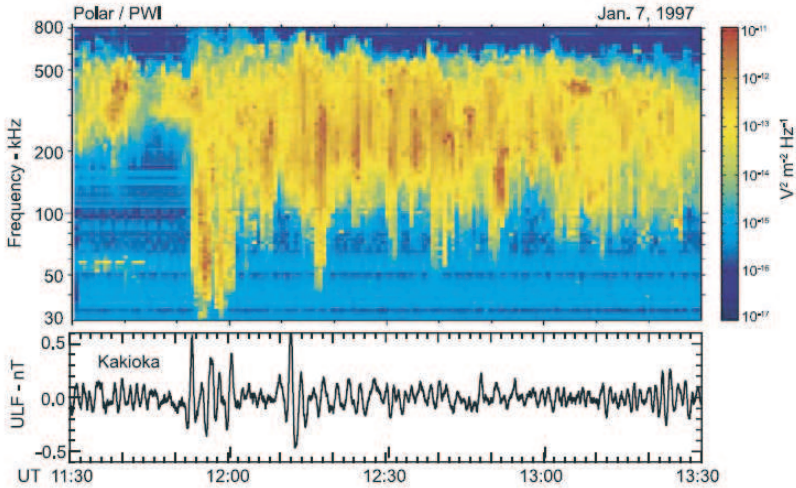


Figure 2: Radio and geomagnetic data observed on January 7th 1997. The top panel is a 2-hour dynamic spectrogram of AKR as observed by the Polar PWI in the frequency range 30–800 kHz. The spacecraft was in the region 4.8–7.0  $R_E$ , 27.9–54.9° MLAT, and 18.8–19.5 hours MLT. The bottom panel shows geomagnetic Pi 2 pulsation data observed at a low-latitude station, Kakioka. From Morioka et al. [2007].

#### 4 Magnetotail Reconnection at Saturn and Link to Radio Emissions

Since the arrival of the Cassini spacecraft at Saturn in 2004 it has been possible to investigate conditions in Saturn’s magnetotail *in situ*. Jackman et al. [2007, 2008] surveyed magnetic field data from the Cassini magnetometer to look for evidence of magnetotail reconnection. Events appear as clear field deflection signatures, particularly in the  $B_\theta$  (north-south) component. Bursts of energetic particles are also frequently observed [e.g. Mitchell et al., 2005], and thus the kronian events have strong parallels with reconnection in the Earth’s tail. The events found thus far are clustered in the midnight or post-midnight sector, at radial distances of 28–62  $R_S$  downtail.

Here we review work which has been done to explore the correlation between such reconnection events and SKR emissions. As at Earth, we might expect that energization of particles from the reconnection site may stimulate intensification of the radio emission and possibly a shift in source location (and hence frequency). Jackman et al. [2009a] showed three detailed examples of known reconnection events at Saturn and their accompanying radio signatures and we reproduce one of those examples in Figure 3 below.

Figure 3 shows the radio and magnetic field data for a four-day period during 2006 during which Cassini observed a Travelling Compression Region (TCR). A TCR is a magnetic signature observed by a spacecraft in the magnetotail lobe, and represents a localized

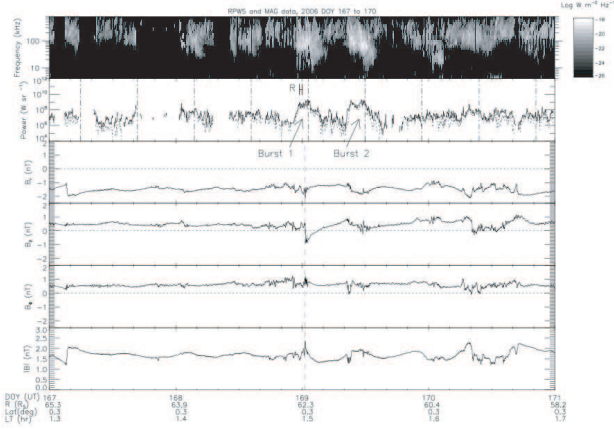


Figure 3: Cassini RPWS and MAG data for 2006 day 167-170, showing a) a frequency-time spectrogram of the radio emissions and b) the band-integrated SKR power across the 4-1000 (solid line) and 100-300 kHz (dashed line) ranges. c-f) Also shown are the magnetic field components in KRTP co-ordinates and total magnetic field strength. KRTP is a Saturn-centered co-ordinate system where the radial component  $B_R$  is positive outward from Saturn, the theta component  $B_\theta$  is positive southward, and the azimuthal component  $B_\phi$  is positive in the direction of corotation (in a prograde direction). From Jackman et al. [2009a].

bulge in the plasma sheet formed by a newly-created plasmoid moving rapidly downtail. The TCR here has two key signatures: the first is a northward turning of the field (a negative deflection of the  $B_\theta$  component). The second is a localized compression of the field, which can be clearly seen by the increase in total field strength centered on the event time (0034 on day 169), marked by the vertical dashed line.

There are two striking features in the radio data. The first is an intensification of the emission closely coincident with the passage of the TCR. This is visible both in the spectrogram in the top panel and also in the order of magnitude increase in the total radio power displayed in the second panel. Secondly we observe an extension of the radio emission to lower frequencies. Radio emissions at Saturn have a spectrum that spreads from 3 kHz to 1.2 MHz, but the broad peak is generally located between 100 and 400 kHz [Kaiser et al., 1984]. Both at the beginning and towards the end of the interval shown in Figure 3, the SKR emission is largely in this 100-400 kHz band. However, we note the low-frequency extension (LFE) to below 10 kHz closely associated with the timing of the event.

We suggest that the character of these emissions is analogous to those reported by Morioka et al. [2007] which are linked with terrestrial substorms. For nine tail reconnection examples studied by Jackman et al. [2009a], all had some intensification of SKR power coincident with the event, and most had an extension of the emission to lower frequency.

More recently, Jackman et al. [2010] selected another event for analysis. They looked at a 10-day interval of data from 2006, combining propagated solar wind data with RPWS,

MAG and plasma data from Cassini. The interval began with a strong solar wind compression, followed by several days of magnetotail loading and suggested driving of the magnetosphere by the Dungey cycle through reconnection at the dayside. After several days of these conditions, the magnetotail became unstable and at least two plasmoids were observed passing down the tail. Coincident with the plasmoid observations were several SKR intensifications and extensions of the emission to lower frequencies. This is further confirmation of the close relationship between magnetotail reconnection at Saturn and intensified and frequency-shifted radio emissions.

#### 4.1 Phase of Radio Emission

It is worth taking a moment to consider what triggers reconnection in the first place, and whether the onset times of observed reconnection events can be categorised in some way. At Earth, various studies have explored the role of the solar wind as a trigger for magnetotail instability (through shock-compression of the magnetosphere or through flux accumulation via reconnection at the dayside magnetopause). Others have looked at the microphysics of the current sheet in order to understand why it becomes unstable. The precise drivers of terrestrial substorm activity thus remain a topic of intense debate. One study used 73 hours of auroral, radar and low-Earth orbit data to determine dayside and nightside-reconnection rates (i.e. flux addition and removal respectively) [Milan et al., 2007]. They found that approximately half the magnetotail reconnection events studied could be associated with an obvious trigger (such as solar wind compression or sudden change in IMF direction), whereas the other half appeared spontaneous.

At Saturn, the number of events observed to date is of course much smaller than the catalogue available in the terrestrial tail, and we do not have an upstream solar wind monitor. However, near-continuous RPWS data is available as a proxy for solar wind conditions. Indeed, Jackman et al. [2009a] found that all reconnection events studied at Saturn were associated with a distinct intensification in SKR power, and often an extension of the spectrum to lower frequencies. SKR is known to pulse at or near to the planetary rotation rate, and Kurth et al. [2008] devised a longitude system to organise the SKR emissions. Jackman et al. [2009a] applied an adaptation of this phase calculation to the timing of the reconnection events at Saturn and found that 8 out of 9 events occurred in the phase range 195-360°, where power is expected to be rising with time on average (0° and 360° correspond to SKR maximum). Thus, there is a strong indication at Saturn that reconnection is triggered at a preferential point in phase. The reasons for this currently remain unknown and merit future investigation. We note however, that although reconnection appears to be statistically favoured in a particular phase sector, this does not necessarily mean that reconnection events occur every time in that phase sector (i.e. once per planetary rotation). Indeed, this point was clarified by Jackman et al. [2009b] who used magnetic field and plasma data to show that regular (on the timescale of the planetary period) oscillations in the north-south component of the field should not be interpreted as regular small-scale plasmoids but rather as signatures of a wavy current sheet.

## 5 Conclusion

In this paper we have reviewed some of the pertinent work on Saturn's magnetospheric dynamics and their relation to radio emissions. There is a clear correlation between the solar wind dynamic pressure and the SKR intensity, but more work is required to fully understand the precise relationship, particularly if radio emissions are to be used reliably as a remote diagnostic of upstream conditions while a spacecraft is orbiting inside the magnetosphere.

At Earth, observations have shown that substorm activity is linked with both enhancements in AKR intensity and changes in the emission frequency. Physically this may represent the displacement of the source location to higher altitude along the field line in response to precipitating energetic electrons following reconnection.

Evidence of an analogous situation has been presented at Saturn. Most kronian magnetotail reconnection events lead to enhanced SKR power and an expansion of the spectrum to lower frequencies. The kronian events also display the curious property of being organised by the phase of planetary rotation, and this is a topic which merits further investigation.

For the future, there are a number of outstanding questions, some of which are overarching longer-term goals, and some of which can be tackled immediately with the data already available:

- What is the precise role of the solar wind in driving Saturn's radio emissions? How can this be more quantitatively explored in order to more fully understand the relationship so that SKR can be used as a remote proxy in the absence of an upstream monitor?
- What is the timescale over which the auroral region can respond to reconfiguration of the tail? Does reconnection lead to an intensification immediately, or is it possible even for the SKR to have a precursor-like role as has been seen with AKR at Earth [e.g. Morioka et al., 2007]?
- Farrell et al. [2005] noted that SKR can originate from nightside sources. What is the distribution of these sources and how are they affected by precipitation from the magnetotail?
- What is the recurrence rate of magnetotail reconnection events at Saturn? Within this topic lie a number of more subtle questions: What is the timescale for flux accumulation in Saturn's tail before a critical threshold is reached? How much of a role do processes internal to the magnetosphere play in driving reconnection? For example, Russell et al. [2008] suggested the idea that the moon Titan may play a role in triggering instability of the magnetotail through local mass loading.
- What is the timescale of reconnection events themselves? What is their average duration relative to the inter-event time? An adaptation of the Minimal Substorm Model from Earth [Freeman and Morley, 2004] is currently in preparation to address these questions for Saturn [Freeman et al., in preparation, 2011].
- What is the nature of and physical reason behind other radio signatures? Louarn et al. [2007] reported sudden intensifications of the SKR followed by periodic narrowband

emission associated with plasma evacuation from Saturn's disk. In addition, Wang et al. [2010] found that Saturn narrowband emissions are strongly correlated with magnetic field compressions in the magnetotail. Unlike the main SKR emission which is produced by the cyclotron maser instability, narrowband emissions have a separate driver, and thus perhaps their relationship to magnetotail reconnection is of a different nature.

- How can we separate out the roles of the solar wind and of magnetotail reconnection in stimulating SKR emission? Certainly there is strong evidence that SKR emissions can intensify very rapidly following the arrival of a solar wind compression at Saturn's magnetosphere. There is also evidence that radio emissions can intensify (and change frequency) coincident with reconnection events. It appears that sometimes a reconnection event is triggered virtually instantaneously when a compression hits (perhaps if the tail was already unstable), and sometimes it takes several days of tail loading for reconnection to be triggered (and then we see intensified SKR and LFEs). How often do solar wind compressions and magnetotail reconnection events occur in isolation/together? What are the relevant timescales over which SKR is then triggered?

One of the key advantages of the Cassini mission is the breadth of instruments on board which allow us to study all aspects of Saturn's magnetospheric dynamics in a holistic manner. The observations which have been made thus far of reconnection in Saturn's magnetotail are just the beginning: they represent a platform from which to launch many more detailed studies of this fascinating process.

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