Auroral radiowave emissions have been detected from six of the magnetized planets in our solar system and provide a useful method of remotely sensing the planetary environments. Saturn’s radio emissions, known as Saturn kilometric radiation (SKR), were first detected by the Voyager spacecraft as they flew by Saturn in 1980 (Kaiser et al. 1980). SKR is believed to be generated by wave–particle interactions on magnetic field lines mapping into the planet’s polar auroral regions and its emission peaks in the frequency range 100–300 kHz. Voyager measurements showed that the intensity of the radio bursts was modulated at a period of 10h 39m 24s which, in the absence of any fixed surface features, scientists used as the first determination of Saturn’s rotation rate (Desch and Kaiser 1981).

Since then the story has become far more complicated: more recent measurements by the Ulysses and Cassini spacecraft have shown that the SKR period has changed significantly since the Voyager measurements, which cannot be explained by a change in the rotation rate of Saturn itself because of the planet’s large inertia. The SKR period also exhibits fluctuations on timescales of a few days and it seems likely that there may be factors other than the planet’s rotation that influence the emission of SKR (Zarka et al. 2007).

**A planet pulsar?**

The region that contains and is controlled by a planet’s magnetic field is called its magnetosphere. The magnetosphere acts as a bubble protecting the planet from the high-speed solar wind plasma flowing past it. The solar wind also carries with it the Sun’s magnetic field, forming the interplanetary magnetic field (IMF). The pressure of the solar wind flowing past the planet is positively correlated with the intensity of the emitted SKR bursts (Desch 1982). The solar wind has important effects on planetary environments, including the exchange of plasma and momentum, establishment of current systems, and changes in the configuration of the planet’s magnetic field. Planetary missions such as Cassini suffer the disadvantage of having no nearby upstream solar wind monitor, such as the ACE spacecraft which is in the solar wind upstream of the Earth. If the SKR response to different solar wind conditions can be accurately characterized, then the SKR could be used as a solar wind monitor even while Cassini is deep inside Saturn’s magnetosphere.

Understanding potential solar wind control of SKR emissions will help isolate those features controlled by the planet’s rotation. In addition, it is well known that the solar wind conditions strongly affect the brightness and morphology of Saturn’s ultraviolet auroral emissions (Crary et al. 2005) as illustrated in figure 1. Because SKR is also produced by auroral electrons, it seems likely that the solar wind will affect the radiowave emissions too. Further study of the solar wind effects on auroral emissions at different wavelengths will improve understanding of the auroral plasma properties, and the dynamics and currents that drive the aurora. Understanding SKR behaviour has broader applications too,

**ABSTRACT**

Saturn emits bursts of radio waves from its polar regions as it rotates. This study examines how the solar wind affects the intensity and periodicity of the radio bursts. The results not only show how Saturn’s magnetosphere interacts with the solar wind, but they also provide a framework for understanding radio emissions from extrasolar planets and pulsars.
for example in aiding the discovery and study of extrasolar planets and pulsars. Predictions can be made about the detection of emissions from extrasolar bodies by comparing with observations made in our own solar system. In addition, when emissions are detected from a pulsar they can be interpreted based on our understanding of planetary and interplanetary (or stellar and interstellar) interactions. In this study we have therefore examined the effects on both the intensity and the pulsing of SKR of compression regions in the solar wind as they impinge on Saturn's magnetosphere.

Features of the SKR

Since Cassini approached Saturn, many more features of SKR behaviour have been observed. For example, as well as the detection of intense SKR bursts following compressions of Saturn's magnetosphere by high-pressure solar wind, a “missed” SKR pulse was also identified (Bunce et al. 2005, Jackman et al. 2005). This was when virtually no SKR was detected at a time when its intensity should have been at a maximum. These case studies were obtained from isolated solar wind compressions in January and July 2004, but a more general picture of SKR behaviour has been gained by carrying out a survey of all compression regions in the solar wind encountered by Cassini. In each identified case the following features were examined: the timing and intensity of the SKR burst immediately following the arrival of the compression, the pulsing of any intensified emissions, any drop-out in emissions at the expected times, and the relative timing and intensity of the SKR bursts before and after the compression.

The Cassini data used in this study are from late 2003 (day 344) until Cassini encountered Saturn’s magnetosphere on day 179 of 2004, and then days 195–298 of 2004 when Cassini had left Saturn’s magnetosphere and moved back into the solar wind. Over this time, during the declining phase of the solar cycle, the solar wind generally exhibited a two-sector structure of a few days of high field and density compression regions, surrounded by longer low-field rarefaction regions. The SKR data were measured by the Cassini Radio and Plasma Wave Science (RPWS) instrument over the same time intervals. Fifteen compression events were identified when there was good data coverage during this time. One of the purposes of this study is to determine whether solar wind compressions disrupt or shift the pulsing of the SKR peaks, therefore the expected times of the pulses based on their long-term behaviour must be known for comparison with those observed. These times are found from an expression derived by Kurth et al. (2007) for the variation of the SKR phase relative to a fixed period ($T_p = 0.4497$ days) by fitting a third-order polynomial to Cassini measurements of the timing of the SKR peaks over the interval from 1 January 2004 to 28 August 2006. This expression was then solved to give a set of times when the peak SKR emissions were expected to occur, for comparison with the observations.

An example interval is shown in figures 2 and 3, which we now describe to highlight some of the common features observed during this study. This was a 14-day interval beginning on day 206 (24 July) of 2004. To examine the variation in intensity of the SKR emissions, the data are presented in two formats. The centre panel shows the electric field power spectrogram measured by RPWS over the frequency range 4 kHz – 2 MHz, incorporating the peak frequency range of 100–300 kHz. The total emitted power integrated over this peak frequency range, and normalized to a distance of 1 AU is plotted in the top panel of the figure. Both these formats clearly reveal the pulsed nature of the SKR emissions. The crosses in the upper part of both of these panels show the expected timings of the SKR peaks from the Kurth et al. (2007) algorithm. The bottom panel shows the IMF magnitude |B| in nanoTeslas, which was used as a proxy for the solar wind dynamic pressure in the absence of the pressure data. The time axis is labelled at intervals of days, with Cassini’s radial distance from Saturn also labelled in units of Saturn radii (here 1 $R_S = 60268$ km). The time taken for the solar wind to propagate from the spacecraft to the planet, assuming purely radial motion and using a nominal solar wind speed of 500 km s$^{-1}$, is given at the top of the figure. The IMF data plotted in the bottom panel is lagged by the radial propagation delay (<0.1 h in this case) to indicate how they may correspond to the detected SKR emissions.

Squashing the magnetosphere

The start of a solar wind compression region is evident in the IMF data in figure 2 as a sharp
increase in field magnitude $|B|$ at ~18 UT on day 207. The vertical dashed line indicates that this was coincident with the start of an intense burst of SKR, which peaked at a power of $-6 \times 10^8 \text{W sr}^{-1}$. The peak powers of the bursts over the next few days were variable: some were intensified (e.g. 16 UT on day 209 shown), while others were reduced (e.g. ~18 UT on day 208). The occurrence of an initial intense SKR burst following the arrival of a compression at Saturn was ubiquitous in the events studied. In one case, all the bursts during the compression region were intensified relative to those preceding the compression, while during another event all were reduced. Much more commonly observed was a combination of both intensified and reduced peak powers. Overall, out of the 15 few-day events studied, similar proportions of intensified and reduced bursts were observed.

Regardless of the relative powers of the bursts, peaks in the emitted power were generally detected close to all the expected times (i.e. the times marked by the crosses). There were a couple of obvious exceptions to this. The first is that there were also several “extra” peaks of comparable powers observed at other times e.g. 14 UT on day 208. The second exception to the periodic nature of the SKR peak emissions is illustrated by the second vertical dashed line on figure 2 which marks the time on day 211 when a peak in SKR power was expected but virtually no emission was detected. A more extreme example of this behaviour was seen later in the interval on days 214–215 (see figure 3) when very low levels of emission are detected over approximately four Saturn rotations. When the intense SKR emissions return on day 216 there is no obvious trigger in the IMF data.

There is as yet no complete theory on how SKR is generated and controlled, but we can relate our findings to those presented in other studies. The intensified SKR bursts could be related to field reconfiguration events in the magnetospheric tail, which explosively release energy and accelerate plasma towards the planet (Cowley et al. 2005, Mitchell et al. 2005). This is the proposed explanation for the intense UV auroral emissions also seen during solar wind compressions.

For the very low power bursts, the latter example shown in figure 3 was coincident with a reverse shock in the solar wind, i.e. a sudden decrease in IMF magnitude. When a similar dropout in SKR emission was detected by Cassini in January 2004, SKR was still detected by the Ulysses spacecraft. This suggests that Cassini did not detect the SKR due to a beaming effect related to the relative positions of the SKR source and Cassini, rather than the source not emitting. It remains an open question whether all extremely low power detections of SKR can be attributed to a beaming effect from the source to the spacecraft, or whether dramatic changes in solar wind conditions can affect the emission of SKR from its source. Although the times of the SKR peaks exhibited small departures from the Kurth et al. (2007) fit, overall they did not undergo any major changes during solar wind compressions.

**Summary**

In conclusion, Saturn’s auroral radio emissions (SKR) are pulsed at a slowly varying period close to that of the planet’s rotation. Compression of the magnetosphere produces an intense burst of SKR but does not otherwise disrupt the pulsing of the emission. Other intense bursts with no obvious IMF trigger, and “extra” bursts not at the expected times are also identified. More detailed investigation of the spectral, temporal and intensity variations of the SKR bursts is required before they can be used as a diagnostic of solar wind conditions. Further study of internal and solar wind control of SKR, and comparison with radio emissions from Earth and Jupiter, will enable models of emission from extrasolar planets to be developed, and can be applied to understand emissions from other objects such as pulsars.

Sarah V Badman (svb4@ion.le.ac.uk), Stan W H Cowley, Department of Physics & Astronomy, University of Leicester, Leicester LE1 7RH, UK. Laurent Lamy, Baptiste Cecconi, Philippe Zarka, LESIA, Observatoire de Paris, Bâtiment 16, 5 Place Jules Janssen, 92195 Meudon, France.

**References**