We show that the source region for Saturnian kilometric radiation (SKR) which originates in the high latitude near-noon dayside ionosphere can be mapped via the Saturn magnetic field to the outer edge of the dayside equatorial plasmasheet. In contrast, at higher latitudes the waves are primarily field-aligned in propagation direction near the equator in the plasmasheet. The field-aligned MHD waves may be mapped into the high latitude ionosphere using the Saturnian magnetic field $Z_3$ model of Connerney et al. [1983, 1984a, b]. This model has shown itself to possess a high degree of accuracy and has even proved useful in diagnosing systematic instrumental errors on other spacecraft that have encountered the Saturn system [Connerney et al. 1984a, b]. Using the $Z_3$ model, along field lines to the planetary surface, we can map the noon meridian outer edge of the plasmasheet to approximately 76°N latitude, very near the most probable SKR source location as deduced from Voyager observations by Kaiser and Desch [1984]. The ionospheric source location deduced by Kaiser and Desch [1982] is thus consistent with a free energy source located on closed field lines which contain the outer plasmasheet boundary. The overall mapping of the high latitude radio emission source region to the equatorial plasmasheet boundary is shown in Figure 1. Another interesting aspect of the Voyager radio emission observations at Saturn was the strong peaks in the emissions when the 115° SLS (Saturn longitude system) line passes through the noon meridian [Kaiser et al., 1984].
SATURNIAN KILOMETRIC RADIATION

SOURCE REGION

Fig. 1. Combined results from the data of the Voyager Planetary Radio Astronomy experiment [Kaiser and Desch, 1982], from the Magnetometer [Connerney et al., 1983] and the Plasma Science instrument [Sittler et al., 1983] which shows the mapping of the SKR source region to the unstable edge of the equatorial plasmasheet.

This strong emission peak exists in the absence of any apparent magnetic anomaly in the near surface field [Connerney et al., 1984]. There have also been detailed studies performed indicating that the solar wind exerts a strong control over the generation of SKR [Desch, 1982, 1983].

Another magnetosphere with even stronger internal plasma sources is that of Jupiter. Jovian kilometric radiation has two components: narrow bandwidth kilometer wavelength emission (nKOM) and broad bandwidth kilometer wavelength emission (bKOM) [Kaiser and Desch, 1984]. Both have spectral peaks at the same wavelengths, but have different source locations. The nKOM radiation appear to originate in the outer edge of the Io plasma torus near the magnetic equatorial plane. In contrast bKOM originates either within the Io torus or at low altitudes in the auroral zone at $L = 6$. In addition, there is a decameter wavelength emission (DAM) which is Io-associated and appears to come from the magnetic flux tube linking Io and the Jovian ionosphere at $L = 6$ [Kaiser and Desch, 1984]. Two immediate differences with respect to the Saturn magnetosphere are the much stronger plasma source from Io compared to any in the Saturn system and the much stronger magnetic field at Jupiter which is about $20$ times that of Saturn at the equatorial 1 bar level. With the higher Jovian magnetic field, shorter wavelength radiation
such as DAM is expected given the abundance of free energy sources [Goldstein and Goertz, 1983; Hill et al., 1983]. For comparison with Saturn our interest is primarily in the kilometer wavelength range, however. Since the centrifugal flute instability is believed to be operative at the Io torus outer edge [Hill, 1976], it is tempting to compare nKOM generation with SKR generation. The confinement of the emission to the magnetic equatorial region at Jupiter as opposed to the auroral zone at Saturn may possibly be related to the much higher densities in the Io torus at \( L = 6 \) compared to the Saturn magnetosphere at \( L = 16 \). The bKOM radiation appears to be related to the Io-Jovian ionosphere interaction at \( L = 6 \) and would most likely involve a different mechanism than the centrifugal flute instability generating surface MHD waves. Since the locations of the Jovian kilometric sources are still not firmly established it is difficult to speculate further concerning the emission generation mechanisms.

Finally, there is the very different morphology between SKR and similar kilometric radiation from earth, the so-called auroral kilometric radiation (AKR). Whereas SKR is characterized by a high latitude near-noon source location [Kaiser and Desch, 1982], in contrast AKR is characterized by a high latitude near midnight generation region [Gurnett, 1974]. In addition to this very different local time behavior the structure of the plasmasheets of both planets' magnetospheres are apparently quite different: Saturn's having a strong internal plasma source, whereas earth's is much weaker [Sittler et al., 1983].

In the next section, we will show how the MHD waves observed at the outer boundary of the plasmasheet may be causally related to the field-aligned acceleration of electrons to keV energies. The field-aligned electron fluxes will constitute the free energy source for the observed SKR.

**THEORY**

The free energy sources for driving Saturn's nonthermal radio emissions are the centrifugal flute instability-driven MHD waves, and also the hot electrons which populate the region in the vicinity of the plasmasheet's outer boundary. In this section we will show that the MHD wave and trapped hot electron free energies can be converted into keV field-aligned electron fluxes that in turn provide the free energy to drive the observed SKR.

Hydromagnetic surface-waves that are excited either by a MHD instability or by an externally applied perturbation have been shown to resonantly mode convert to a kinetic Alfvén wave [Hasegawa, 1976]. Field-aligned electron fluxes may be produced as a consequence of the component of the kinetic Alfvén wave's electric field in the direction of the average local magnetic field. Applications of this theory to the formation of auroral arcs have been made by Hasegawa [1976]. The kinetic Alfvén wave is defined as an Alfvén wave whose wavelength perpendicular to the magnetic field is comparable to the ion gyroradius \( \rho_i \). In essence the kinetic Alfvén wave represents the solution to an MHD surface wave perturbation applied to a density boundary whose gradient is perpendicular to the local field direction. This well describes the conditions obtained at the equatorial plasmasheet boundary at Saturn. From the application of Hasegawa's [1976] results to auroral arcs, we obtain a relation between the magnitude of the externally applied MHD surface wave magnetic field perturbations and the magnitude of the field-aligned potential:

\[
\frac{eV}{T_e} \approx \frac{V_A}{V_{i,T}} \frac{\delta B}{B} \left( \frac{a}{\rho_i} \right)^{1/2}
\]

(1)

where \( e \) is the magnitude of the electron charge, \( \psi \) is the field-aligned potential, \( T_e \) is the temperature of the hot electrons, \( V_A \) is the Alfvén speed, \( \delta B \) is the MHD surface wave amplitude, \( B \) is the ambient field magnitude, \( V_{i,T} \) is the ion thermal velocity, \( \rho_i \) is the ion gyroradius and \( a \) is the thickness of the plasmasheet boundary. For all of these parameters the appropriate values are those of the plasmasheet. Typical values for the plasmasheet parameters listed here are [Sittler et al., 1983; Lazarus and McNutt, 1983] a mean ion mass \( m_i \approx 14 \) amu, \( \rho_i \approx 500 \) km, \( T_e (\text{hot}) \approx 1 \) keV, \( a \approx 10^{-3} LR_s \) where \( L \approx 16 \) is the \( L \) shell of the plasmasheet and \( R_s = 63,971 \) km is Saturn's radius, \( V_A \approx 450 \) km s\(^{-1} \) and \( V_{i,T} \approx 28 \) km s\(^{-1} \) and \( \delta B/B \approx 0.1 \) (R. P. Lepping et al., unpublished manuscript, 1986). Hence we obtain \( eV/T_e \approx 20 \delta B/B \) or \( eV/T_e \approx 2 \) keV. Hence field-aligned electron fluxes of several keV may be expected for Voyager observed plasmasheet boundary observations. For the sake of brevity, we refer the reader to Hasegawa [1976] for a detailed derivation of equation (1).

The analysis presented by Hasegawa [1976] for the field-aligned acceleration of electrons is linear and breaks down when \( eV/T_e \approx 0 (\beta^{-1}) \), where \( \beta \) is the ratio of plasma pressure to magnetic field pressure. Near the outer boundary of the plasmasheet we have from Sittler et al. [1983] \( \beta \approx 0.1 \). Hence the linear analysis is questionable for \( eV/T_e \gtrsim 2 \). Thus to obtain field-aligned electron fluxes with \( E \gtrsim 2 \) keV, the nonlinear development in the mode conversion process of the surface MHD wave into a kinetic Alfvén wave must be considered. This has been done by Hasegawa and Mima [1976] where they show that from a nonlinear analysis of the mode conversion problem a solution in the form of a solitary Alfvén wave is obtained with the same dispersion characteristics as had been obtained earlier for the kinetic Alfvén wave [Hasegawa and Chen, 1975]. Since the exact solitary Alfvén wave solution is good for large values of \( eV/T_e \) and since the solution is expected to have similar field-aligned acceleration effects to that of the linear kinetic Alfvén wave, acceleration of electrons to energies significantly greater than 1 keV is possible.

The theory presented here represents an idealization of the physics operative at the plasma sheet boundary. It does illustrate however the process by which MHD wave energy may be converted to field-aligned electron energy and underlines the need for a hot electron population. The heated electron population produced by the pick-up of exospheric ions originating from Saturn's moons is required since otherwise \( T_e \) would be much less than 1 keV and since \( eV \approx T_e \), the electrons will not have sufficient energy to excite the observed righthand polarized extraordinary mode waves under the conditions required by currently accepted theories for the generation of planetary kilometric radiation [Wu and Lee, 1979].

The role of plasma instabilities in the pick-up processes of newly-born ions in flowing plasmas has been considered by a number of authors [Wu and Davidson, 1972; Wu and Hartle, 1974; Wu et al., 1973; Hartle and Wu, 1973; Curtis, 1981; Winske et al., 1984]. The encounter of the International Cometary Explorer with the comet Giacobini-Zinner has shown that the cometary pick-up ions possess distribution functions consistent with the interaction process between cometary ions and the solar wind being stochastic [Gloeckler et al., 1986]. These observations confirm the earlier theoretical speculations that plasma instability processes play a large role in the interactions of newly-born ions with flowing plasmas. Barbosa et al. [1985] have considered the role of lower hybrid waves in the anomalous heating of plasma near Io's torus. In their paper, Barbosa et al. show that newly picked up ions in Io's torus can produce a ring distribution in the corotating frame
of Jupiter's magnetospheric ions. The ion distribution function provides the free energy source to drive lower hybrid waves which heat the electrons and produce a hot electron component. The pick-up energy of O\(^+\) ions at \(L = 16\) for Saturn is \(\sim 2\) keV. Unfortunately, the much lower magnetic field strengths in Saturn's outer plasmasheet compared to the field strengths near Io's torus do not permit a detailed study of the pick-up process-related electron heating and associated lower hybrid waves. The typical electron cyclotron frequency, \(f_{ce}\), near Saturn's equator at \(R \approx 16\) \(R_p\) is \(f_{ce} \approx 280\) Hz [Connerney et al., 1984] which gives a lower hybrid frequency for a heavy ion dominated plasma with a mean atomic mass of \(\approx 12-16\) amu of \(f_{LM} \approx 2\) Hz. The lower hybrid frequency is thus far below the frequency range in which the Voyager plasma wave receiver has good coverage \((f > 100\) Hz) [Kurth et al., 1983]. However, Kurth et al. [1983] have shown, using Voyager 1 inbound observations, that plasma noise tentatively identified as electrostatic bursts associated with the chorus wave interacts with the equatorial plasmasheet. The authors considered a two-stream instability of electrons as the generator of the burst. Within the framework of the theory presented here, the electron populations forming the stream would be composed of the field-aligned accelerated electrons and the background magnetospheric electrons. We note that, even lacking the lower hybrid wave observations at Saturn, enough of the artifacts of the pick-up process exist, such as hot electrons, a corotating heavy ion population, and a hot electron temperature gradient directed radially outward [Sittler et al., 1983], to establish the existence of pick-up related electron heating.

The observed solar wind dependence of SKR [Desch, 1982, 1983] results, in the theoretical framework developed here, from a change in configuration of Saturn's magnetosphere in response to solar wind bulk pressure variations. In the limit of low solar wind pressure, such as occurs when Saturn is immersed in Jupiter's magnetic tail [Desch, 1983] the configuration of Saturn's magnetosphere should be dipole like out to distances much greater than \(L \approx 16\) on both the dayside and nightside. In contrast, during Voyager 1's encounter with Saturn, when Saturn was in the solar wind, the dayside field lines at \(L \approx 16\) were located at \(16\) \(R_p\) on the dayside but were estimated to be at \(\approx 30\) \(R_p\) on the nightside [Goertz, 1983]. The greater distances to which the nightside plasmasheet extends is believed to give rise to a tailward wind of the plasma and loss of the nightside plasmasheet beyond \(L \approx 16\) [Hill and Dessler, 1976; Goertz, 1976]. The nightside tailward plasmasheet loss, as discussed earlier, gives rise to the steep density gradient at the outer plasmasheet edge which is required for the centrifugal flute instability on the dayside. The centrifugal stresses on the nightside plasmasheet will increase with the increasing distance to which the plasma travels due to elongation of the nightside field lines owing to the solar wind-magnetosphere interaction. We note that Sittler et al. [1983] observed the plasmasheet out to \(L \approx 25\) on Voyager 2 outbound when Saturn may have been in Jupiter's magnetotail. In contrast, the plasmasheet terminated at \(L \approx 25\) on Voyager 2 outbound when Saturn was in the solar wind. Since the solar wind pressure will determine the nightside field elongation which, in turn, will control the gradient formation process that drives the centrifugal flute instability, solar wind control of SKR is expected. We note that in the limiting case of total cutoff of the solar wind the azimuthal symmetry of the magnetosphere and lack of tail loss should yield density gradients that are below the threshold required for the centrifugal flute instability [Goertz, 1983].

Solar wind control in the scenario presented here is not the direct consequence of solar wind energy input, but rather the indirect result of reshaping the free energy source driven by the mass loading and associated exospheric ion pick-up processes in the rapidly rotating Saturn magnetosphere.

We note that the expected loss of plasma down the Saturn magnetotail [Goertz, 1983] due to centrifugal effects forms not only the basis for the free energy source which drives the dayside Saturn kilometric radio emissions, but also explains the absence of a nightside SKR source. The disruptive loss of the nightside plasmasheet results in the loss of the plasmasheet population which in the earth's nightside magnetosphere is considered to contain the earth's AKR energy source [Wu et al., 1982]. Thus a windlike loss of plasmasheet plasma down the magnetotail operates as a free energy sink at Saturn as opposed to the magnetotail source of plasma for the plasmasheet at earth.

Finally, in the case of the jovian magnetosphere which is much more heavily mass-loaded than Saturn's magnetosphere, the nKOM component of jovian kilometric radiation appears to emanate from the outer edge of the Io torus may be generated by a mechanism similar to that discussed here. There exist other components of jovian nonthermal radiation namely DAM and bKOM, that may be closely tied to the interaction of Io itself with the jovian ionosphere.

**DISCUSSION**

Although the theory presented here can give the solar wind dependence of SKR, due to the solar wind's effect on magnetosphere configuration, and the local time peak near the noon meridian owing to the maximum growth of the centrifugal flute instability, the conditions presented here so far are only necessary; they are not sufficient. In particular, the deposition of field-aligned energetic electrons with energies 1–10 keV into the high latitude ionosphere represents only one condition for SKR generation. The ionosphere must still have a sufficiently low electron plasma density so that the ratio of the electron plasma frequency to the electron gyrofrequency \(\omega_{pe}/\omega_{ce} \leq 0.2\). This limit was obtained through a detailed study of the ionospheric conditions needed for the generation of the earth's auroral kilometric radiation (AKR) by Benson [1985] and is consistent with theoretical predictions by Wong et al. [1982]. Since \(\omega_{pe}/\omega_{ce} \sim n_e^{1/2}/B\) where \(n_e\) is the ionospheric electron density and \(B\) is the ambient magnetic field, we see that all other things being equal the strongest emissions will occur when \(n_e\) is minimized for a given \(B\). The importance of the \(\omega_{pe}/\omega_{ce}\) ratio was demonstrated at Uranus, where the dominance of the nightside emissions over the dayside emissions predicted [Curtis, 1985] on the basis of \(\omega_{pe}/\omega_{ce}\) ratios expected for the sunlit dayside and depleted nightside ionosphere has apparently been verified (J. Warwick et al., private communication, 1986). For Saturn, the strong emission peaking at one longitude, 115° SLS, when it passes through the noon meridian suggests that the \(\omega_{pe}/\omega_{ce}\) ratio must be significantly different from these at other longitudes. Among the possibilities that suggest themselves, there is the chance of a large magnetic anomaly with variation of at least a factor of 2 or more in the near surface magnetic field magnitude. However, such variations are not consistent with Voyager magnetometer observations [Connerney et al., 1984] unless higher order moments are involved. An alternative explanation would involve an ionospheric plasma depletion of perhaps a factor of 10 related to some fixed atmospheric process. Future research may reveal how one longitude maintains a \(\omega_{pe}/\omega_{ce}\) ratio significantly different from all others.
Although the wave observations of R. P. Lepping et al. (unpublished manuscript, 1986) support the mechanism that we have proposed, the data from the Voyager encounters with Saturn do not allow us to uniquely determine that the proposed mechanism is the only one operative. Another potential mechanism involves an extension of a process that was originally put forward by Cornwall et al. [1971] to explain the observations of stable auroral red arcs (SAR arcs) at the earth.

In the picture presented by Cornwall et al., the outward expansion of the plasmasphere during the recovery phase of geomagnetic substorms into the ring current gives a density ratio of cold plasmaspheric plasma to energetic ring current ions favorably to the generation of ion cyclotron turbulence. A large fraction of the turbulence energy is then transferred into electron heating via electron Landau damping. The resulting external flux would be directed into the ionosphere via field-aligned electron fluxes. In the case of Saturn, the ring current lies well within the outer edge of the plasmasheet and hence would not be involved in a process analogous to that at earth. However, within the framework of the centrifugal flute instability discussed here, we expect the mixing of hot outer magnetosphere plasma with that of the colder plasmasheet to resemble that of the ring current–plasmasphere mixing discussed by Cornwall et al. [1971] and the study of artificial cool plasma injected into the ring current [Cornwall, 1972]. The situation may be then favorable to additional field-aligned heating of pick-up electrons and could power the observed nonthermal radio emissions at Saturn. Further data is required to see whether the pitch and angle anisotropy of the hot ions or the current density of any field-aligned currents associated with the centrifugal flute instability is sufficient to drive the ion cyclotron instability. We emphasize, however, that in both the acceleration of electrons by kinetic Alfven waves as well as the heating of electrons by ion cyclotron turbulence, the centrifugal flute instability plays a necessary role in the formation of the free energy source or sources which drives the SKR.

SUMMARY AND CONCLUSIONS

We have shown that as a result of centrifugal force due to Saturn's rotating magnetosphere and satellite-derived mass loading, MHD waves are produced as the result of the centrifugal flute instability [Goertz, 1983; R. P. Lepping et al., unpublished manuscript, 1986] which can accelerate field-aligned electrons to energies of several keV. The means of converting the field-aligned MHD wave free energy to field-aligned electron energy involves the wave-mode conversion mechanism originally due to Hasegawa [1976]. The conversion of the MHD waves to kinetic Alfven waves allows in turn a coupling of energy from the macro or MHD scale to the micro or kinetic scale. Given that the plasmasheet boundary density gradient is expected to be steepest due to photoinization of exospheric neutrals near the noon meridian, SKR will be strongest there.

The field-aligned electron fluxes can then generate kilometric radiation in the right-hand extraordinary mode as predicted by Wu and Lee [1979] provided that the electron plasma frequency to electron gyrofrequency ratio is sufficiently small.

The mass loading of Saturn's magnetosphere that leads to the centrifugal flute instability and hence to SKR also provides the mechanism for depleting the free energy source for nighttime emissions from Saturn similar to AKR observed at earth. The free energy source for the nighttime radiation is lost down the tail of Saturn's magnetosphere due to centrifugal effects [Hill and Dessler, 1976; Goertz, 1976, 1983]. Finally, solar wind control of the SKR is an indirect consequence of configurational changes in the Saturnian magnetosphere induced by solar wind pressure variations.

ACKNOWLEDGMENTS. We would like to thank T. W. Hill of Rice University, C. K. Goertz of the University of Iowa, M. L. Kaiser, M. D. Desch, J. K. Alexander, and J. E. P. Connerney, all of NASA/GSFC for their helpful suggestions and comments. We would also like to thank S. Myers for the preparation of the manuscript. Finally, we would like to thank both reviewers for their comments and advice. This work was supported by the NASA Program in Planetary Atmospheric Research RTOP 154-60-80-32.

The Editor thanks D. D. Barbosa for acting as Associate Editor and A. Hasegawa and B. Tsurutani for their assistance in evaluating this paper.

REFERENCES


S. A. Curtis, R. P. Lepping, and E. C. Sittler, Jr., Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

(Received March 6, 1986; revised May 22, 1986; accepted June 20, 1986.)