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The research carried out may be divided into four main areas, each involving a number of sub-projects. The main areas are: (1) MHD theory of magnetospheric micropulsations, (2) Kinetic magnetospheric waves, (3) Ballooning modes in the geo-magnetospheric; and (4) Development of a general theory of ballooning modes. The work has resulted in 10 articles listed at the end of the report. Keywords: Magnetohydrodynamics,

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February 21, 1990

Dr. Henry Radoski
Program Officer
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Dear Dr. Radoski,

Enclosed please find six copies of the Final Technical Report
on our Magnetospheric Pulsations Grant No. AFOSR-86-0167.

We believe that our work has been quite fruitful, resulting
in a variety of interesting results, and would like to thank you
very much for supporting our research.

Sincerely yours,

Elie Hameiri
Principal Investigator

Enclosures

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Analytical Studies of Magnetospheric Pulsations
Final Technical Report, Grant #AFOSR-86-0167
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The research carried out under this grant may be divided into four main areas, each involving a number of sub-projects. The main areas are: (I) MHD theory of magnetospheric micropulsations, (II) Kinetic magnetospheric waves, (III) Ballooning modes in the geo-magnetosphere, and (IV) Development of a general theory of ballooning modes. Our work has resulted in the 10 articles listed at the end of this report. A detailed description of our results is given in the following:

I. MHD Theory of Magnetospheric Micropulsations

I.1. The Effects of Finite Ionospheric Conductivity on ULF Waves
(E. HAMEIRI AND M. KIVELSON)

This investigation was intended to provide an explanation for the absence of ULF activity in the night side of the geomagnetosphere. We have investigated the effect the ionosphere has on the boundary conditions to be imposed on the magnetosphere. The appropriate boundary conditions were obtained in the limit of a very thin atmosphere. They hold irrespective of which MHD wave is considered, Alfven or magnetoacoustic, as well as for the inhomogeneous case where all waves are coupled. Surprisingly, this fundamental result was not known before, although it was known that pure Alfven waves and pure magnetoacoustic "fast" waves are affected differently by the ionosphere, a result which we recover.

The difference between the day and night sides of the magnetosphere is modelled by assuming the ionosphere to have a discontinuous conductivity across the dawn-dusk meridian. (The night-side conductivity is in reality a factor of 10 smaller than in the day-side.) For simplicity, weak coupling between Alfven and fast waves is assumed by using a density profile which is weakly dependent on the radial position. Asymptotic analysis (in the coupling parameter) shows that a global standing wave has a frequency closer to the Alfven frequency on the day-side than to the one on the night-side. This global wave may transfer its energy resonantly to the Alfven wave in the day-side magnetosphere. The ionospheric discontinuous conductivity induces a discontinuous solution in the magnetosphere. In the limit of vanishing ionospheric discontinuity, the solution becomes continuous, unlike some earlier results by Yarker and Southwood *(Planet. Space Sci., 1986)*.

A paper describing these results is in preparation and will be submitted to *J. Geophys. Res.*

I.2. Alfven Wave Resonance in General Geometry and Finite Pressure
(M. MOND, E. HAMEIRI, P.N. HU)

Most of past investigations of the coupling between "fast" magnetosonic and Alfven waves considered the simplified zero pressure model in some simple magnetic

configuration, with all inhomogeneities depending on one coordinate only (the one perpendicular to magnetic field lines). This enables a reduction of the problem to an ordinary differential equation, where the wave coupling is manifest via a singularity of the equation. Our work deals with finite pressure plasma in arbitrary magnetic geometry, in which a singularity is not apparent. Nevertheless, resonance phenomena do occur, where the resonance layer is localized about a (curved) field line such that the bounce frequency of the infinitely localized Alfven waves propagating along it matches the frequency of the fast wave propagating across the field.

In order to study the coupling in detail we use an asymptotic expansion procedure developed by Hameiri (1981). This method uses flux coordinates and distinguishes between different behavior along and across the field. The results show the same logarithmic singularity as in the straight field line case, but this time centered about the curved field.

Two cases were examined in detail. In the first case, the commonly used box model was employed. However, in our calculations, the density was assumed to vary along the field lines giving rise to a varying Alfven speed along the lines. The resonant condition was calculated and was shown to depend on line averaged quantities rather than on local values along the particular line. Then, the singular solutions were derived and the net Poynting flux across the resonant field line was calculated in order to demonstrate resonant energy absorption. In the second case, a dipole magnetic field was used. In this model the magnetic field lines are curved and the value of the magnetic field is not constant along them. Thus, this model represents quite a general configuration. Here again the singular solutions were calculated and the energy absorption mechanism was demonstrated by calculating the net Poynting flux across the resonant field ine.

A paper describing these results has appeared in *J. Geophys. Res., 1990*.

I.3. Review of Micropulsation Theory (S. HAMAGUCHI AND W. GROSSMANN)

The theory of long period magnetic pulsations was reviewed in order to assess the current status of the understanding of the geomagnetic micropulsations and to find some related open problems in this field. In this review, a theory of the Alfven resonance, which was initiated independently by Southwood, Chen, and Hasegawa in the 1970's, and a theory of the Kelvin-Helmholtz instability, are mainly discussed. Historically, the micropulsations of the Earth's magnetic field were first reported in a paper by Stewart in 1861 as a large magnetic storm of several hundred γ observed at the Kew Obsevatory in England. These micropulsations were later categorized according to their frequencies and found to b resonant oscillations of particular magnetic field lines of the Earth. It is now believed that there are two different mechanisms causing such oscillations of the Earth's magtic field lines. One is an external mechanism, namely, a monochromatic oscillation is excited away from the resonant field lines by, for example, the Kelvin-Helmholtz instability at the magnetopause. The other mechanism is an internal one, namely, excitation of a monochromatic wave inside

the magnetosphere, such as the density gradient at the plasma pause, giving rise to drift waves. In the present work, we have extensively reviewed the former mechanism causing the micropulsations.

This review has appeared as a Courant Institute Report, 1989.

II. Kinetic Magnetospheric Waves

II.1. Generation of ULF Waves in the Polar Cusp Region by Velocity Shear Driven Kinetic Alfven Waves (G.S. LAKHINA)

The polar cusp is a region where the solar wind plasma can enter the magnetosphere rather directly. In this region hot ions are found to be literally flowing down along the cusp field lines. It is known that the cusp region contains keV protons (of magnetosheath origin) flowing down and proton beams (possibly accelerated ionospheric protons) streaming up the magnetic field direction in the altitude range of 5-7 R_E. Recently, there have been observations of up-swelling ion events, which are cold ion beams from the ionosphere, in the high latitude region including the polar cusp region. Heos 2 data indicated large spatial variations (e.g. $L_v \sim 100 - 200$ km, where $L_v = (dV_B/V_B dx)$ is the velocity gradient scale length) in the ion flow pattern close to cusp boundaries. Therefore sufficient large velocity shear $S = (dV_B/\omega_{cB} dx) \lesssim 0.1 - 1$ is expected to be present for keV ion beams near the polar cusp boundries, where V_B is the streaming velocity and ω_{cB} is the gyrofrequency of the beam ions.

The polar cusp is a region where intense plasma wave activity takes place, e.g. ULF-ELF waves, broadband electrostatic noise (BEN), electrostatic electron cyclotron waves, etc. In the past, there were proposed mechanisms based on essentially Kelvin-Helmholtz instability driven by the velocity shear to explain the ULF magnetic fluctuations. These mechanisms are based on electrostatic modes and, therefore, are not reliable in providing a good interpretation for the ULF waves which are electromagnetic in nature. In this work we investigate the kinetic Alfven modes driven by velocity shear of the ion beams to explain the ULF waves observed in the polar cusp region. A prominant feature of the kinetic Alfven wave is that it has a sizable parallel electric field which can heat the plasma, and may accelerate the charged particle leading to their precipitation. We were able to derive the dispersion relation for the kinetic Alfven modes under the local approximation, and to analyze it for two special cases, namely cold or hot ion beams. We conclude that the velocity shear can serve as the free energy source in the excitation of low frequency electromagnetic modes in the cusp region, especially near the cusp boundary where relatively large velocity shears are present.

This work was submitted to *Astrophys. Space Sci., 1989.*

II.2. Source of Bursty Radio Emissions from Uranus (B. BUTI, G.S. LAKHINA)

During its encounter with Uranus, Voyager 2 observed radio waves in the frequency

range of 78-850 kHz on the night-side of Uranus. This radio emission, known as Uranus kilometric radiation (UKR), consists of a smoothly varying component and a bursty component. Both of these components have left-hand polarization, but their temporal characteristics are quite different. Changes in intensity of the smooth component occur on time scales of hours, whereas large intensity variations were observed for the bursty pulses on time scales of tens of seconds.

We have shown that a model based on the nonlinear interaction of upper-hybrid waves and the whistler solitons occurring on the high latitude field lines near the south magnetic pole of Uranus, can very nicely interpret the observed characteristics of the bursty UKR emissions. For example, the frequency range, the bandwidth, the burst duration, the left-hand polarization and the modulation frequency calculated according to this model match extremely well with the observations. About 50 solitons are sufficient to explain the observed average radio flux.

A paper describing these results has appeared in *Geophys. Res. Letts., 1988*.

III. Ballooning Modes in the Geo-Magnetosphere

III.1. Excitation of Ballooning Modes at the Plasmapause (G.S. LAKHINA, M. MOND, E. HAMEIRI)

Experimental observations indicate that some ULF pulsations (e.g., Pc3 — Pc5) are associated with the plasmapause during disturbed periods of geomagnetic activity. During disturbed periods, a significant population of hot particles from the ring current and from the plasma sheet can be present at the plasmapause; consequently the plasma pressure can be comparable to the magnetic pressure. Such a situation can lead to excitation of ballooning as well as interchange modes.

The ballooning mode instability was studied in the presence of azimuthal plasma flows induced during geomagnetically disturbed periods. The flow was taken to be a rigid rotation. A general sufficient criterion for the ballooning mode stability was derived as $\delta W \geq 0$ (where δW represents the change in the potential energy) which involves the integration over an entire field line. A local stability analysis at the equatorial plasmapause region shows that the ballooning modes could be spontaneously generated via instability under at least two conditions: one is similar to the usual interchange condition, and the second to the quasi-interchange modes. Both of these local instability conditions can be derived from the general $\delta W \geq 0$ stability criterion. Finally an exact solution for the equilibrium state with shear flow was derived analytically, and δW was computed numerically. It was found that the flow cannot spontaneously excite the ballooning modes; it could only further stabilize (or destablilize) the ballooning spectrum if originally the system is stable (or unstable). The analysis could provide a useful tool for the interpretation of some of the low frequency modes observed near the equatorial plasmapause.

This work is presently in press in *J. Geophys. Res., 1990*.

III.2. Ballooning Modes in the Earth's Magnetotail (G.S. LAKHINA, E. HAMEIRI, M. MOND)

Observations by ISEE3, and some other satellites, indicate the presence of field-aligned sheared bulk plasma flows and low frequency magnetic pulsations in the plasmasheet boundary layer region. Since the plasma pressure is finite, and the tail magnetic field lines have a finite curvature, the ballooning modes could be excited. We have derived an approximate equilibrium state solution in the far magnetotail, based on the assumption that the variation in the tailward direction is much slower than the cross-tail variation. Consistent with this approximate equilibrium, we have approximated the ballooning mode equation, and were able to solve it exactly and obtain a necessary and sufficient condition for their stability. This condition can be cast in a variational form, as a requirement that the variation of the potential energy (δW) due to the mode be positive definite for stability.

It was found that instability tends to occur when the magnetic curvature κ (pointing towards the center of curvature of the magnetic field line), and the gradient of the total kinetic pressure $\nabla(p + \frac{1}{2}\rho|\mathbf{v}|^2)$, are pointing in the same direction. This can easily occur in the magnetotail.

This work was submitted to *J. Geophys. Res., 1989.*

IV. Development of a General Theory of Ballooning Modes

IV.1. Ballooning Modes in the Presence of Shear Rotation (E. HAMEIRI, S.T. CHUN)

It is known that large transverse flows are present in the region between the magnetopause and plasmpause, originating in the tail region of the magnetosphere. The kinetic energy there is comparable to the magnetic energy. We have therefore further developed the ballooning mode theory to include sheared flow effects (non-rigid rotation). In this work we have ignored the effect of boundary conditions and considered infinitely long magnetic field lines in a toroidal configuration, as in fusion devices. Our results show a basic difference between the sheared flow case and the rigidly rotating flow. In a rigidly rotating plasma one may move to an observation frame rotating with the plasma, where instead of seeing a flow one feels a "gravitational" effect due to the centrifugal force. This indicates that ballooning theory in this case is rather similar to the no-flow situation. However, when the flow is non-rigid there is no natural observation frame. Indeed, we find that ballooning modes do exist in this case, but are described by an equation which depends *explicitly* on time even though the original equations did not involve time in this way. We have derived a condition on the rotation profile which guarantees the stability of the ballooning modes. Approximately speaking, it indicates that the driving force of the instability is not the kinetic pressure alone but rather the sum of the pressure plus flow pressure.

This work was published in *Physical Review A, 1990.*

IV.2. Ballooning Modes in Space Plasmas (E. HAMEIRI, P. LAURENCE, M. MOND)

Ballooning modes, which are pressure driven motions and waves localized to a particular field line, may be the source of ULF pulsations in the magnetosphere. They may also play a role in other circumstances, such as the heating of the solar corona. We have undertook to review and expand the ballooning mode theory, which was developed for laboratory (fusion) plasmas, to the case of space plasmas. The main difference is the boundary conditions to be imposed, since typically in space situations, the magnetic field enters the boundary of the plasma, while in the laboratory, field lines are typically confined to the interior of the device. We have developed the appropriate boundary conditions for a perfectly conducting boundary (tied field lines), for a conducting boundary (the ionosphere), and for an insulating boundary (an atmosphere). In addition, the effects of gravity and plasma rotation were incorporated.

We have derived the ballooning equations for arbitrary magnetic configurations, and from it have obtained necessary and sufficient conditions for stability. We have shown that "interchange" stability criteria available in the literature are merely special cases of our ballooning results. Moreover, for magnetospheric-like magnetic field (with zero toroidal component) we have shown that ballooning modes are the most unstable MHD modes. As an application, we have applied our theory to heating of the solar corona. The coronal magnetic loop is tied below the solar photosphere. Turbulence in the sun generates ballooning modes which travel back and forth in the loop. If the mode frequency matches with the driving frequency we get resonance and high wave amplitude. The energy is then available for Ohmic heating.

This work was submitted for publication in *J. Geophys. Res., 1989.*

IV.3. Alfven Wave Solitons in Inhomogeneous Plasmas (G.S. LAKHINA)

As a first step towards dealing with nonlinear ballooning modes, we investigate nonlinearities of Alfven waves. In a weakly inhomogeneous plasma, the large amplitude Alfven waves propagating parallel to the ambient magnetic field are shown to evolve into accelerated Alfven solitons. Nonlinear interaction of the accelerated Alfven solitons with the Langmuir waves results in the emission of coherent radiations at the frequency $\omega_o \simeq (\omega_A + \omega_L)$, where ω_A and ω_L are the Alfven wave and the Langmuir wave frequencies, respectively. Analytical expression for the power radiated per unit solid angle from a soliton is derived for two cases of inhomogeneity profiles, namely, the linear profile and the parabolic profile. For the case of uniform plasmas, the emission occurs via decay type process or resonant modes. In the presence of inhomogeneity, non-resonant modes provide a new channel for the emission of radiation. The power radiated per unit solid angle for the non-resonant modes could be several orders of magnitude higher than that for the case of resonant modes. The results for this radiation process are of general nature, and could be applied to several astrophysical situations.

This work was submitted to *Astrophys. J., 1989.*

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1. B. Buti and G.S. Lakhina, Source of bursty radio emissions from Uranus, *Geophys. Res. Lett.*, **15**, 1149, 1988.

2. S. Hamaguchi and W. Grossmann, Theory of long-period magnetic pulsations, Courant Institute Report MF-120, Nov. 1989.

3. E. Hameiri and S.T. Chun, Stability of ballooning modes in a rotating plasma, *Phys. Rev. A.*, **41**, 1186, 1990.

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7. G.S. Lakhina, B. Buti and N. Tsintsadze, Radiation from accelerated Alfven solitons in inhomogeneous plasmas, submitted to *Astrophys. J.*, 1989.

8. G.S. Lakhina, E. Hameiri and M. Mond, Ballooning instability of the Earth's plasma sheet region in the presence of parallel flow, submitted to *J. Geophys. Res.*, 1989.

9. G.S. Lakhina, M. Mond and E. Hameiri, Ballooning mode stability at the plasmapause, *J. Geophys. Res.*, 1990, in press.

10. M. Mond, E. Hameiri and P.N. Hu, Coupling of MHD waves in inhomogeneous magnetic field configurations, *J. Geophys. Res.*, **95**, 89, 1990.