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**Particle Acceleration and Transport in the Tail
and at the Front Side of the Magnetosphere**

**Principal Investigator (Task 1)
Lynn M. Kistler
Research Assistant Professor**

**Principal Investigator (Task 2)
Eberhard Möbius
Associate Professor**

**Co-Investigator
Martin A. Lee
Professor**

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Institute for the Study of Earth Oceans and Space
University of New Hampshire
Durham, NH 03824

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TAIL AND AT THE FRONT SIDE OF THE
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Abstract

The work under this grant involved studies of

- The acceleration and heating of ions in the course of magnetospheric substorms and the spatial distributions of the ion populations in the magnetotail (Task 1, L.M. Kistler, PI)
- The comparison of in-situ acceleration at the bow shock and the leakage of energetic particles from the magnetosphere as sources of energetic ions upstream of the Earth's bow shock (Task 2, E. Möbius, PI).

Under task 1, the following studies have been performed:

- A determination of total pressure changes in the plasma sheet during substorms (*Kistler et al.*, 1992).
- A superposed epoch analysis of the pressure distributions, and how those distributions change with substorm onset (*Kistler et al.*, 1993)
- A determination of the field configuration changes during a substorm from the changes in the pressure distributions (*Kistler et al.*, 1993)
- A determination of the energetic particle flux decay during the recovery phase of substorms, showing that the decay is a function of energy per charge, in agreement with theoretical predictions (*Kistler et al.*, 1994)
- A comparison of the timing of particle injections in the plasma sheet at 18 Re with injections at geosynchronous orbit showing that in some cases the injections are essentially simultaneous (paper in progress)
- A case study of the contribution of molecular ions to the plasma sheet (paper in progress)
- A study of the pitch angle distributions of ring current ions during geomagnetic storms, and the subsequent decay of those ions (*Jordanova et al.*, 1994)

Under task 2, the following studies have been performed:

- A statistical analysis of the spatial distribution of upstream ions, their energy spectra and fluxes has been conducted which showed a clear connection with solar wind and interplanetary magnetic field parameters. (*Trattner et al.*, 1994)
- A comparison of the energy densities of energetic ion populations and magnetic fluctuations upstream of the bow shock has been carried out with a result in very good agreement with a self-consistent wave particle interaction (*Trattner et al.*, 1991, 1994)

- A study of the magnetospheric and solar wind source of energetic ions upstream of the bow shock has been performed (paper in progress).
- The transport through and reflection at a quasi-perpendicular bow shock of He⁺ has been studied (ongoing in PHD thesis)
- He⁺ pick up ions as a third source of energetic ions at the quasi-parallel bow shock have been studied. (ongoing study in PHD thesis)
- Studies of the general conditions for particle acceleration at the bow shock and the leakage from the magnetosphere were conducted as input to define future data analysis and modeling efforts (*Möbius*, 1992, *Lee*, 1992; *Möbius*, 1994)

Introduction

This report will outline the results of our work on ions in the magnetotail and upstream of the magnetopause under NASA grant NAG5-1548 . The goal of task 1 is to understand particle injection, acceleration, heating and loss in the magnetotail during magnetospheric substorms, and to determine the contribution of various plasma sources to the tail particle populations. The goal of task 2 is to understand the physical processes which govern the acceleration of particles at the bow shock and the leakage of energetic particles out of the magnetosphere. Our efforts have resulted in the publication of 9 papers, 16 contributed talks and 9 invited talks since the beginning of this grant.

Task 1: Tail Studies (L.M. Kistler)

A determination of total pressure changes in the plasma sheet during substorms

Using AMPTE/CCE and AMPTE/IRM data, we have determined the particle pressure and total pressure as a function of radial distance in the plasma sheet before and after the onset of substorm-associated ion enhancements. The particle energy of maximum contribution to the pressure increases from about 12 to about 27 keV with substorm onset. We find that in the plasma sheet, the particle pressure increases while the magnetic pressure decreases, with the total pressure remaining approximately constant. Inside of $10 R_e$ the total pressure tends to increase with the injection whereas outside $10 R_e$ the total pressure decreases. These changes are consistent with previous measurements of pressure changes at substorm onset, and can be understood in terms of the unloading of energy in the magnetosphere. In addition, the radial pressure gradient observed in the 7-12 R_e region agrees very well with that necessary to maintain stress balance for an isotropic plasma. These results are published in *Kistler et al.*, 1992.

A superposed epoch analysis of the pressure distributions, and how those distributions change with substorm onset

Using a superposed epoch analysis of AMPTE/IRM data, we have determined the development of the pressure profiles in Z with time relative to substorm onset in the plasma sheet at $R=15-19 R_e$. These profiles were then used to determine the current distribution. The current distribution shows a dramatic change with substorm onset. Before onset the current is concentrated close to the neutral sheet. After onset the current is more uniformly distributed throughout the plasma sheet. These results are published in *Kistler et al.*, 1993.

A determination of the field configuration changes during a substorm from the changes in the pressure distributions

Using the pressure distribution in Z discussed above and the known radial gradient in the total pressure, we have determined the field configuration changes during a substorm. The stretching of the field during the loading phase and the progression of the dipolarization at substorm onset is clearly evident in this analysis. These results are published in *Kistler et al.*, 1993.

A determination of the energetic particle flux decay during the recovery phase of substorms

Using both case studies and a superposed epoch analysis, we have characterized how the energetic particles in the plasma sheet decay with time during the recovery phase of a substorm. We have found that the decay rates are the same for different species at the same energy per charge, not at the same velocity or rigidity. We have modeled the expected decay in two ways: by determining the decay rate assuming an adiabatic expansion of the plasma sheet, and by calculating the expected loss times due to drift out of the plasma sheet. We find that both of these processes would give an energy per charge dependence, although in both cases the expected decay rates are higher than observed. The reasons for this are under study. This work was presented at the 1992 Fall AGU meeting in San Francisco, and are published in *Kistler et al.*, 1994.

A comparison of the timing of particle injections in the plasma sheet at 18 Re with injections at geosynchronous orbit

At substorm onset a dispersionless injection of ions and electrons is usually observed close to geosynchronous orbit. We have looked for correlations between these substorm injections and energetic particle behavior farther down the tail using two methods: examining a number of case studies and performing a superposed epoch analysis. The case studies were done using data from the energetic particle detectors on the Los Alamos geosynchronous satellites and the SULEICA instrument on AMPTE IRM. We identified cases in which an injection was observed at geosynchronous orbit, and IRM was close to its apogee of 18.8 Re. In some cases, a dispersionless injection is also observed at the IRM location, with time delays varying from within a minute of the injection at geosynchronous to 40 minutes after the geosynchronous injection. With the superposed epoch analysis, we were able to organize the IRM data by Z location in the plasma sheet. The results indicate that the location of the IRM in Z in the plasma sheet partly explains the timing differences. When IRM is located close to the neutral sheet, the injection is observed almost

simultaneously with the geosynchronous injection. When the IRM is located closer to the lobe, the injection occurs at a later time. However, individual differences between events also play a significant role. These results were presented at the 1993 Spring AGU meeting, and a paper on this study is in progress.

A case study of the contribution of molecular ions to the plasma sheet

Molecular ions have been observed during magnetic storms in the ring current using the SULEICA instrument (Klecker et al., 1986). We have identified one geomagnetic storm in which large fluxes of molecules were observed in the plasma sheet at 16 Re. The $(\text{NO}^+ + \text{O}_2^+)/\text{O}^+$ ratio was as high as 0.5. We have compared the abundances observed by IRM in the plasma sheet with simultaneous observations by CCE in the ring current, and find that the $(\text{NO}^+ + \text{O}_2^+)/\text{O}^+$ ratio is higher and more variable in the plasma sheet than in the ring current, indicating that the molecules are first injected into the plasma sheet, and then transported to the ring current region. A paper on these results is in progress.

A study of the pitch angle distributions of ring current ions during geomagnetic storms, and the subsequent decay of those ions

The pitch angle distributions of the ion species H^+ , O^+ , He^+ , and He^{++} from 1 keV/e to 200 keV/e during the main phase of geomagnetic storms were determined as a function of local time and L-value using data from the AMPTE/CCE/CHEM instrument. These distributions were then used as input to a model for determining the decay of ions during storm recovery phase. Initial results were presented at the Fall 1994 AGU meeting (Jordanova et al, 1994). This study is still in progress, in order to both understand the initial main phase distributions, and to further model the recovery.

Task 2: Upstream Studies (E. Möbius)

Statistical analysis of the spatial distribution, energy spectra and fluxes of energetic upstream ion populations

A survey of the fluxes and energy spectra of the diffuse ion distributions upstream of the quasi-parallel bow shock was performed with the complete AMPTE IRM data set which covers the periods September - December 1984 and 1985. An exponential decrease of the fluxes with the distance along the magnetic field lines was found for both H^+ and He^{2+} whose e-folding distance varies from $\approx 3 R_E$ for 10 KeV/e to $\approx 6 R_E$ for 80 KeV/e. This is in accordance with a model based on diffusion of the ions in upstream magnetic fluctuations. Using the measured spatial distributions the ion fluxes were then normalized to zero bow shock distance for a correlation study with interplanetary field and solar wind parameters. A good correlation of the total H^+ and He^{2+} fluxes with the solar wind density supports strongly the solar wind source of the diffuse ions. The e-folding energy of the ion spectra shows a good correlation with component of the solar wind velocity parallel to the interplanetary magnetic field, which is in accordance with acceleration of these particles by a Fermi type process. This work has been carried out partly during a visit of K.-H. Trattner (now at the Space Science Division of ESTEC, Noordwijk, Netherlands) funded under this grant. The results have been published in *Trattner et al., 1994*.

Statistical comparison of the energy densities of energetic ion populations and magnetic fluctuations upstream of the bow shock

A comparison of the local energy densities of diffuse energetic ion distributions and of low frequency waves with the predictions of the self-consistent treatment of the related wave-particle interaction in Alfvénic fluctuations (Lee 1982) has shown a remarkable agreement. This emphasizes the importance of the intrinsic connection between the upstream particle and wave phenomena. These results have been published in *Trattner et al., 1991, 1994*. It could also be demonstrated that a coupled treatment of the particle-wave interaction is possible without additional assumptions on specific ion loss processes. The results were presented at the IAGA Meeting by *Lee et al., 1993*. A paper is in progress.

Study of the magnetospheric and solar wind source of energetic ions upstream of the bow shock

For a selection of energetic upstream ion events the abundances and energy spectra of H^+ , He^{2+} and O^+ have been compared for the upstream region and the magnetosphere using AMPTE IRM and AMPTE CCE. O^+ which

is clearly a magnetospheric ion species is always suppressed as compared with H^+ and He^{2+} in the upstream region. On the other hand the energy spectrum of H^+ and He^{2+} is always softer upstream than in the magnetosphere, whereas O^+ shows the same spectrum in both locations. These features persist no matter which pitch angle range of the magnetospheric ions is selected. The observations are consistent with local acceleration of H^+ and He^{2+} at the bow shock and magnetospheric leakage of O^+ . A paper is in progress.

In a simple model which includes transport by diffusion across the magnetosheath and through solar wind as well as diffusive acceleration at the bow shock the leakage efficiency for O^+ at the magnetopause could be estimated. This is part of an ongoing PHD Thesis.

Transport through and reflection at the quasi-perpendicular bow shock of He^+ pick up ions

The trajectories of He^+ pickup ions across an ideal perpendicular bow shock have been modelled. For a typical pickup ion distribution (a filled sphere centered in the solar wind velocity) the trajectories can be separated into three distinct families: (1) for He^+ ions with $v < 0.5 v_{sw}$ a specular reflection with subsequent energy gain in the $v \times B$ electric field is observed; ions with higher velocity either (2) perform a partial gyromotion downstream and enter the upstream region again or (3) gyrate completely downstream depending on their velocity components perpendicular to the shock normal. This is in accordance with observations on AMPTE IRM. Part of the results have been reported at the Spring AGU (*Möbius et al. 1993*). The topic is part of an ongoing PHD Thesis.

In collaboration with V. Shapiro of UCSD and R. Sagdeev of University of Maryland, Lee has initiated an analytical study of the low-speed ions which encounters a quasi-perpendicular shock. These ions may become trapped between the shock potential and the upstream magnetic field which returns them to the shock. As described qualitatively by R. Sagdeev in 1965, these ions can "surf" along the shock front parallel to the motional electric field and gain substantial energy in that direction before being able to traverse the shock. We have calculated the final energy of the transmitted or reflected ions and predicted the final energy spectrum of a distribution of transmitted interstellar pickup ions. A paper describing the results is in preparation. Initial results were presented at the Gordon Conference on Space Physics (1994) and the 1994 Fall Meeting of the AGU.

He⁺ pick up ions as a third source of upstream ions at the quasi-parallel bow shock

A number of case studies in upstream ion events under quasi-parallel conditions were performed when a significant flux of energetic He⁺ was observed. It was the first priority to determine whether these ions are leaking from the magnetosphere like O⁺ ions or whether they originate from the pick up ions. The relative abundance of He⁺ over O⁺ as compared with the respective composition observed simultaneously in the magnetosphere provides strong support for the interplanetary origin of these ions. This view is also supported by the directional distribution of He⁺ ions which is generally similar to that of H⁺ and He²⁺ ions. At this point we try to understand why the occurrence of He⁺ in the upstream ion distributions is so variable. While it is observed with a relatively high percentage in some events, it seems to be absent (to the level of instrumental sensitivity in others). No correlation with magnetospheric variations and the occurrence of magnetospheric O⁺ could be found. This study is part of an ongoing PHD Thesis.

Definition of future data analysis and modeling efforts on magnetospheric leakage and acceleration at the bow shock

In addition to the data analysis efforts with the AMPTE data sets and related modeling work reviews on the current state of the understanding of leakage and bow shock acceleration were compiled and the requirements for future progress in this area was studied. Progress on the understanding of the bow shock environment provides the basic ingredients for detailed modeling of more remote sites, such as interplanetary shocks and the heliospheric termination shock (*Lee 1992; Möbius 1992; Möbius 1994*).

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a) Publications

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b) Invited Talks

- Möbius, E., Energetic Particle Populations in the Earth's Magnetosphere, *IUGG General Assembly*, Vienna, August 1991.
- Lee, M.A., Particle Acceleration in the Heliosphere, *Conference on Particle Acceleration in Cosmic Plasmas*, Bartol Research Institute, Newark, Delaware, December 1991.
- Möbius, E., Perspectives of Future Observations on Particle Acceleration in the Heliosphere, *Conference on Particle Acceleration in Cosmic Plasmas*, Bartol Research Institute, Newark, December 1991.

Kistler, L.M., Pressure Changes in the Plasma Sheet During Magnetospheric Substorms, *Space Science Seminar*, Dartmouth College, Hanover NH, January 1992.

Möbius, E., Sources and Acceleration of Energetic Particles in Planetary Magnetospheres, *IAU Colloquium 142*, Particle Acceleration Phenomena in Astrophysical Plasmas, University of Maryland, January 1993.

Möbius, E., Sources and Acceleration of Energetic Particles in Front of the Earth's Bow Shock, *Physics Seminar*, Bartol Research Institute, University of Delaware, February 1994.

Kistler, L.M., Substorms in the earth's magnetosphere, Physics Seminar, Michigan State University, East Lansing, MI, April 1994.

Kistler, L.M., Plasmasheet dynamics during substorms, *CLUSTER Workshop on physical measurements and mission oriented theory*, Toulouse, France, November 1994.

Möbius, E., Studies with Cluster Upstream and Downstream of the Bow Shock - An Experimenter's Perspective, *CLUSTER Workshop on physical measurements and mission oriented theory*, Toulouse, November 1994.

c) Contributed Talks

Möbius, E., L.M. Kistler, M.N. Vahia, B. Klecker, F.M. Ipavich, Comparison of the Abundances and Energy Spectra of Energetic Particles Upstream of the Earth's Bow Shock and in the Magnetosphere, *Fall AGU Meeting*, San Francisco, December 1990.

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Lee, M.A., On the Coupled Behavior of Reflected Ions and Low-Frequency Waves Downstream of Quasi-Perpendicular Shocks, *Fall AGU Meeting*, San Francisco, December 1991.

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- Kistler, L.M., E. Möbius, W. Baumjohann, Suprathermal Ion Behavior during substorm Recovery Phase, *AGU Fall Meeting*, San Francisco, December 1992.
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- Lee, M.A., Ion Thermalization Downstream of the Quasiperpendicular Bow Shock, *AGU Spring Meeting*, Baltimore, May 1993.
- Lee, M.A., E. Möbius, K.-H. Trattner, Ion-excited Wave Intensities Upstream of Earth's Bow Shock: Comparison of Theory and AMPTE IRM Observations, *IAGA Scientific Assembly*, Buenos Aires, Argentina, August 1993.
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- Jordanova, V.K., L.M. Kistler, J.U. Kozyra, G.V. Khazanov, and A.F. Nagy, The effect of collisional processes on the pitch angle distributions of the ring current ions, *AGU Fall Meeting*, San Francisco, CA, December 1994.