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**Space Physics Research Laboratory
2245 Hayward Street
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Report Author(s): Tamas Gombosi

Author(s) Phone: 313/764-7222

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Project Director:
Principal Investigator(s): Tamas Gombosi

Program Technical Officer: Dr. Thomas J. Birmingham
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NASA/Goddard Space Flight Center
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Final Report

Modeling of Nonequilibrium Space Plasma Flows

Program Director: Tamas I. Gombosi

Our team accomplished the following results in the research areas:

Godunov-type numerical solution of the 20 moment plasma transport equations. One of the centerpieces of our proposal was the development of a higher order Godunov-type numerical scheme to solve the gyration dominated 20 moment transport equations. In the first step we explored some fundamental analytic properties of the 20 moment transport equations for a low b plasma, including the eigenvectors and eigenvalues of propagating disturbances. The eigenvalues correspond to wave speeds, while the eigenvectors characterize the transported physical quantities. In this paper we also explored the physically meaningful parameter range of the normalized heat flow components. In the second step a new Godunov scheme type numerical method was developed to solve the coupled set of 20 moment transport equations for a quasineutral single-ion plasma. The numerical method and the first results were presented at several national and international meetings and a paper describing the method has been published in the *Journal of Computational Physics*. To our knowledge this is the first numerical method which is capable of producing stable time-dependent solutions to the full 20 (or 16) moment set of transport equations, including the full heat flow equation. Previous attempts resulted in unstable (oscillating) solutions of the heat flow equations. Our group invested over two man-years into the development and implementation of the new method. The present model solves the 20 moment transport equations for an ion species and thermal electrons in a domain extending from a collision dominated to a collisionless region (200 km to 12,000 km). This model has been applied

to study O⁺ acceleration due to Joule heating in the lower ionosphere.

Analytic investigations of transport phenomena. Another basic element of our proposed research program was the investigation of basic transport properties of various plasma components in different regions of the solar system. These studies led to several interesting results. A full analytic solution (density, flow velocity, parallel and perpendicular pressure) was found to the double adiabatic equations in a rotating planetary magnetosphere. Approximate analytic solutions were found for the heat flow equations in the topside ionosphere. A second-order quasilinear theory was developed to model the effects of wave-particle interactions in geoplasmas. We also developed a new 2D model of flux tube convection and used it to explain unusual phenomena observed during a huge geomagnetic storm.

Modeling of polar wind and plasmaspheric flows. With the help of our SPTP grant we developed a time-dependent, multispecies hydrodynamic model of interhemispheric plasma flow for tilted geomagnetic field lines. The model flux tube connects two reservoirs, each at an altitude of 200 km; these reservoirs represent photochemically controlled regions of the ionosphere. The model successfully describes high speed plasma flows between two photochemically controlled conjugate ionospheres. We also developed new models of superthermal electron transport in the ionosphere and plasmasphere.

Studies of the cometary pick-up process. The pickup of freshly ionized particles in cometary environments turned out to be one of the most fascinating problems of theoretical space plasma physics. The lessons learned at comets can also be applied extensively in a broad range of other areas (such as interstellar pickup, solar wind termination, shuttle outgassing, active experiments, barium releases, planetary magnetospheres). In the last couple of years we addressed several aspects of the cometary pickup problem: wave generation by pickup ions, kinetic description of particle pitch-angle scattering, and first and second order Fermi acceleration of pickup ions. A new transport equation was also derived which preserves causality in the transport of pickup ions.

**Talks and Publications Fully or Partially
Supported
by NAGW-2162**

Ph.D. Thesis

1. Cannata, R.W., Thermal ion upwelling in the high-latitude ionosphere, Ph.D. Thesis, The University of Michigan, 1990.
2. Guiter, S.M., Ph.D. Thesis, The University of Michigan, 1992.

Articles in Refereed Journals

1. R. H. Miller, C. E. Rasmussen, T. I. Gombosi and D. Winske, Hybrid simulations of plasmaspheric refilling including convection and injection, *Adv. Space Res.*, *13*, (4)117–(4)120, 1993.
2. K. V. Gamayunov, G. V. Khazanov, E. N. Krivorutsky, T. I. Gombosi and V. N. Oraevskii, Plasma hydrodynamics in view of quasilinear effects, *Planet. Space Sci.*, *41*, 27–33, 1993.
3. K. V. Gamayunov, G. V. Khazanov, A. A. Veryaev and T. I. Gombosi, The effect of the hot, anisotropic magnetospheric protons on the dispersion relation, *Adv. Space Res.*, *13*, (4)121–(4)126, 1993.
4. L. L. Williams, N. Schwadron, J. R. Jokipii and T. I. Gombosi, A unified transport equation for both cosmic rays and thermal particles, *Astrophys. J.*, *405*, L79–L81, 1993.
5. R. H. Miller, C. E. Rasmussen, T. I. Gombosi, V. G. Khazanov and D. Winske, Kinetic simulation of plasma flows in the inner magnetosphere, *J. Geophys. Res.*, *98*, 19,301–19,313, 1993.
6. A. Körösmezey, C. E. Rasmussen, T. I. Gombosi and B. van Leer, Transport of gyration dominated space plasmas of thermal origin II.: Numerical solution, *J. Computational Phys.*, *109*, 16–29, 1993.

7. T. I. Gombosi, J. R. Jokipii, J. Kóta, K. Lorencz and L. L. Williams, The telegraph equation in charged particle transport, *Astrophys. J.*, **403**, 377–384, 1993.
8. G. V. Khazanov, N. A. F., T. I. Gombosi, M. A. Koen and S. J. Cariglia, Analytic description of the electron temperature behavior in the upper ionosphere and plasmasphere, *Geophys. Res. Lett.*, **19**, 1915–1918, 1992.
9. G. V. Khazanov, T. I. Gombosi, A. F. Nagy and M. A. Koen, Analysis of the ionosphere – plasmasphere transport of superthermal electrons: 1. Transport in the plasmasphere, *J. Geophys. Res.*, **97**, 16,887 – 16,895, 1992.
10. A. Körösmezey, C. E. Rasmussen, T. I. Gombosi and G. V. Khazanov, Anisotropic ion heating and parallel O^+ acceleration in regions of rapid $E \times B$ convection, *Geophys. Res. Lett.*, **19**, 2298–2292, 1992.
11. T. I. Gombosi, L. K. Kerr, A. F. Nagy and R. W. Cannata, Helium in the polar wind, *Advances of Space Research*, **12**, (6)183–(6)186, 1992.
12. T. I. Gombosi, M. Neugebauer, A. D. Johnstone, A. J. Coates and D. E. Huddleston, Cometary ion distributions near the pickup energy outside comet Halley's bow shock, *Advances of Space Research*, **11**, (9)275–(9)278, 1991.
13. R. H. Miller, T. I. Gombosi, D. Winske and S. P. Gary, The directional dependence of cometary magnetic energy density in the quasi-parallel and quasi-perpendicular regimes, *Advances of Space Research*, **11**, (9)78–(9)82, 1991.
14. A. F. Nagy, A. Körösmezey, J. Kim and T. I. Gombosi, A two-dimensional, shock capturing, hydrodynamic model of the Venus ionosphere, *Geophys. Res. Lett.*, **18**, 801–804, 1991.
15. M. I. Verigin, K. I. Gringauz, N. M. Shutte, S. A. Haider, K. Szegö, P. Kiraly, A. F. Nagy and T. I. Gombosi, On the possible source of the ionization in the nighttime Martian ionosphere. 1. Phobos-2/HARP electron spectrometer measurements, *J. Geophys. Res.*, **96**, 19,307–19,313, 1991.
16. T. I. Gombosi, An analytic solution to the double adiabatic equations, *Geophys. Res. Lett.*, **18**, 1181–1184, 1991.

17. T. I. Gombosi, The plasma environment of comets, *Rev. Geophys. Suppl.*, *29*, 976–984, 1991.
18. R. H. Miller, T. I. Gombosi, S. P. Gary and D. Winske, The directional dependence of magnetic fluctuations generated by cometary ion pick-up, *J. Geophys. Res.*, *96*, 9479, 1991.
19. R. H. Miller, S. P. Gary, D. Winske and T. I. Gombosi, Pitch-angle scattering of cometary ions into monospherical and bispherical distributions, *Geophys. Res. Lett.*, *18*, 1063–1066, 1991.
20. T. I. Gombosi, M. Neugebauer, A. D. Johnstone, A. J. Coates and D. E. Huddleston, Comparison of observed and calculated implanted ion distributions outside comet Halley's bow shock, *J. Geophys. Res.*, *96*, 9467, 1991.
21. S. M. Guiter, T. I. Gombosi and C. E. Rasmussen, Diurnal variations on a plasmaspheric flux tube: Light ion flows and F region temperature enhancements, *Geophys. Res. Lett.*, *18*, 813–816, 1991.
22. T. I. Gombosi and C. E. Rasmussen, Transport of gyration dominated space plasmas of thermal origin I.: Generalized transport equations, *J. Geophys. Res.*, *96*, 7759–7778, 1991.

Invited Talks

1. T. I. Gombosi, Wave-particle interaction at comets, *Gordon Research Conference on Active Phenomena in Solar System Plasmas*, Plymouth, NH, July 13–17, 1992.
2. T. I. Gombosi, G. V. Khazanov, J. U. Kozyra, A. Korosmezey, A. Miller, A. F. Nagy and C. E. Rasmussen, Generalized transport equations in mesoscale modeling of ionosphere-magnetosphere coupling, *AGU Chapman Conference on Micro and Meso-Scale Phenomena in Space Plasmas*, Kauai, Hawaii, February 17–22, 1992.
3. G. V. Khazanov and T. I. Gombosi, The effects of the hot, anisotropic magnetospheric protons on the MHD dispersion relation, *29th Plenary Meeting of COSPAR*, Washington, D.C., August 28–September 5, 1992.

4. T. I. Gombosi, Mass loading at Titan and comets, *ESTEC Symposium on Titan*, Toulouse, France, September 9–12, 1991.
5. T. I. Gombosi, Transport and acceleration of pickup ions upstream of shocks, *1991 Cambridge Workshop in Theoretical Geoplasma Physics*, Cambridge, Massachusetts, June 24–28, 1991.
6. T. I. Gombosi, Particle acceleration at comets, *Workshop on Particle Acceleration in Cosmic Plasmas*, Newark, Delaware, December 12–14, 1991.
7. T. I. Gombosi, Cometary particle acceleration, *20th General Assembly of IUGG*, Vienna, Austria, August 11–24, 1991.

Contributed Talks

1. A. Körösmezey, C. E. Rasmussen and T. I. Gombosi, Generalized transport equations for the polar wind, *AGU Spring Meeting*, Montreal, Canada, May 12–16, 1992.
2. G. V. Khazanov, T. I. Gombosi and A. F. Nagy, Heating and cooling of the plasmasphere, *AGU Spring Meeting*, Montreal, Canada, May 12–16, 1992.
3. S. M. Guiter, C. E. Rasmussen and T. I. Gombosi, Modeling of annual variations in plasmaspheric density, *AGU Spring Meeting*, Montreal, Canada, May 12–16, 1992.
4. C. E. Rasmussen, A. Körösmezey, T. I. Gombosi, G. V. Khazanov and J. U. Kozyra, Anisotropic ion heating and parallel O^+ acceleration in regions of rapid $E \times B$ convection, *AGU Spring Meeting*, Montreal, Canada, May 12–16, 1992.
5. C. J. Alexander and T. I. Gombosi, Multispecies gas flows in the interior of comets, *AGU Spring Meeting*, Montreal, Canada, May 12–16, 1992.
6. T. I. Gombosi, J. R. Jokipii, K. Lorencz, J. Kota and L. L. Williams, The telegraph equation in charged-particle transport, *AGU Spring Meeting*, Montreal, Canada, May 12–16, 1992.

7. G. V. Khazanov and T. I. Gombosi, Magnetospheric convection and the effects of wave-particle interaction on the plasma temperature anisotropy in the equatorial plasmasphere, *AGU Fall Meeting*, San Francisco, CA, December 7-11, 1992.
8. R. H. Miller, C. E. Rasmussen, G. V. Khazanov, A. F. Nagy, T. I. Gombosi and D. Winske, A hybrid simulation of the interaction between the plasmasphere and ring current, *AGU Fall Meeting*, San Francisco, CA, December 7-11, 1992.
9. K. G. Powell, T. I. Gombosi and C. E. Rasmussen, Development of a multidimensional MHD model of planetary magnetospheres on adaptive grids, *AGU Fall Meeting*, San Francisco, CA, December 7-11, 1992.
10. T. I. Gombosi, G. V. Khazanov, A. Körösmezey, R. H. Miller, A. F. Nagy and C. E. Rasmussen, Comparison of 20 moment, hydrodynamic and semikinetic polar wind models, *AGU Fall Meeting*, San Francisco, CA, December 7-11, 1992.
11. K. M. Chick and T. I. Gombosi, Inner coma image simulation, *AGU Fall Meeting*, San Francisco, CA, December 7-11, 1992.
12. A. Körösmezey, T. I. Gombosi and C. E. Rasmussen, Application of higher-order moment equations to the polar wind, *29th Plenary Meeting of COSPAR*, Washington, D.C., August 28-September 5, 1992.
13. S. M. Guiter, T. I. Gombosi and C. E. Rasmussen, Two-stream modeling of diurnal variations on a plasmaspheric flux tube, *29th Plenary Meeting of COSPAR*, Washington, D.C., August 28-September 5, 1992.
14. R. H. Miller, T. I. Gombosi and D. Winske, A kinetic simulation of polar wind outflow, *29th Plenary Meeting of COSPAR*, Washington, D.C., August 28-September 5, 1992.
15. P. Király, V. Koppányi, K. Szegő, I. T.-Szűcs, R. Grard, A. Pedersen, A. Skalsky, T. I. Gombosi and A. F. Nagy, Implications of electron measurements in the Mars environment, *COSPAR Colloquium 4 on "Critical Problems in the Plasma Environments of Comets and Other Non-Magnetized and Weakly Magnetized Bodies"*, Ann Arbor, MI, August 24-27, 1992.

16. K. M. Chick and T. I. Gombosi, Multiple scattering of light in a coma with an axisymmetric dust jet, *23rd Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Palo Alto, California, November 4–8, 1991.
17. C. J. Alexander and T. I. Gombosi, Multispecies gas flows in the interior of comets, *23rd Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Palo Alto, California, November 4–8, 1991.
18. S. M. Guiter, T. I. Gombosi and C. E. Rasmussen, Modeling of plasmaspheric refilling with a two-stream model, *AGU Spring Meeting*, Baltimore, Maryland, May 28–31, 1991.
19. A. Körösmezey, T. I. Gombosi and C. E. Rasmussen, Application of higher-order moment equations to the polar wind, *AGU Spring Meeting*, Baltimore, Maryland, May 28–31, 1991.
20. K. Lorencz and T. I. Gombosi, Diffusion of pick-up particles near bow shocks, *AGU Spring Meeting*, Baltimore, Maryland, May 28–31, 1991.
21. G. V. Khazanov, Y. V. Konikov and T. I. Gombosi, The role of Coulomb collisions on the thermal structure of gyration dominated space plasmas, *AGU Fall Meeting*, San Francisco, CA, December 9–13, 1991.
22. T. E. Cravens, G. Ye and T. I. Gombosi, Comparison of pickup ion distributions at comet Halley from a quasilinear model and observations, *AGU Fall Meeting*, San Francisco, CA, December 9–13, 1991.
23. C. E. Rasmussen, S. M. Guiter and T. I. Gombosi, Modeling of annual variations in plasmaspheric density, *AGU Fall Meeting*, San Francisco, CA, December 9–13, 1991.
24. S. M. Guiter, T. I. Gombosi and C. E. Rasmussen, Modeling of plasmaspheric refilling with a two-stream model, *AGU Fall Meeting*, San Francisco, CA, December 9–13, 1991.
25. T. I. Gombosi, An analytic solution to the steady-state double adiabatic equations, *AGU Fall Meeting*, San Francisco, CA, December 9–13, 1991.

26. A. Körösmezey, T. I. Gombosi and C. E. Rasmussen, A polar wind model with higher order moment equations, *20th General Assembly of IUGG*, Vienna, Austria, August 11–24, 1991.
27. R. H. Miller and T. I. Gombosi, An effective collision frequency for polar wind generated by wave particle interactions, *20th General Assembly of IUGG*, Vienna, Austria, August 11–24, 1991.
28. C. E. Rasmussen, A. Körösmezey, T. I. Gombosi and R. H. Miller, The flow of heat on collisionless and diverging field lines, *20th General Assembly of IUGG*, Vienna, Austria, August 11–24, 1991.
29. T. I. Gombosi, J. R. Jokipii, J. Kóta, K. Lorencz and L. L. Williams, Telegraph equation in charged particle transport, *20th General Assembly of IUGG*, Vienna, Austria, August 11–24, 1991.
30. K. M. Chick and T. I. Gombosi, Light scattering in a cometary atmosphere, *22nd Annual DPS meeting of the American Astronomical Society*, Charlottesville, Virginia, October 22–26, 1990.
31. S. M. Guiter, T. I. Gombosi, C. E. Rasmussen and p. b. Workshop on Plasmasphere Refilling, The University of Alabama in Huntsville, Huntsville, Alabama, October 15–16, 1990., Diurnal variation in a plasmaspheric flux tube, *Workshop on Plasmasphere Refilling*, Huntsville, Alabama, October 15–16, 1990.
32. T. I. Gombosi, Upstream region acceleration of implanted cometary ions, *32nd Annual Meeting of the Division of Plasma Physics of the American Physical Society*, Cincinnati, Ohio, November 12–16, 1990.
33. S. M. Guiter and T. I. Gombosi, Modeling an effect of the tilt of the earth's dipole field, *AGU Spring Meeting*, Baltimore, Maryland, May 29–June 1, 1990.
34. T. I. Gombosi, M. Neugebauer, A. D. Johnstone and A. J. Coates, Comparison of observed and calculated implanted ion distributions outside comet Halley's bow shock, *AGU Spring Meeting*, Baltimore, Maryland, May 29–June 1, 1990.
35. R. H. Miller, T. I. Gombosi, S. P. Gary and D. Winske, Directional dependent plasma wave energy densities generated by cometary ion pickup, *AGU Spring Meeting*, Baltimore, Maryland, May 29–June 1, 1990.

36. A. F. Nagy, T. I. Gombosi, K. Szegö, R. Z. Sagdeev, V. D. Shapiro and V. I. Shevchenko, Venus Mantle–Mars Planetosphere: What are the similarities?, *28th COSPAR Plenary Meeting*, The Hague, The Netherlands, June 25–July 6, 1990.
37. T. I. Gombosi, M. Neugebauer, A. D. Johnstone, A. J. Coates and D. E. Huddleston, Study of implanted proton and oxygen ion distributions outside comet Halley's bow shock using a quasi-parallel shock model and Giotto observations, *28th COSPAR Plenary Meeting*, The Hague, The Netherlands, June 25–July 6, 1990.
38. T. I. Gombosi, Numerical modeling of He⁺ outflow from the high latitude topside ionosphere using a new three ion polar wind model, *28th COSPAR Plenary Meeting*, The Hague, The Netherlands, June 25–July 6, 1990.
39. R. H. Miller, T. I. Gombosi, S. P. Gary and D. Winske, Energy density of forward and backward propagating MHD turbulence generated by the cometary pick-up process, *28th COSPAR Plenary Meeting*, The Hague, The Netherlands, June 25–July 6, 1990.
40. J. Kim, A. Körösmezey, A. F. Nagy and T. I. Gombosi, Two-dimensional model calculations of high velocity ion flows in the Venus ionosphere, *AGU Fall Meeting*, San Francisco, California, December 3–7, 1990.
41. A. Körösmezey, T. I. Gombosi and C. E. Rasmussen, Preliminary results of a polar wind model with anisotropic temperatures, *AGU Fall Meeting*, San Francisco, California, December 3–7, 1990.
42. T. I. Gombosi, L. K. Kerr, A. F. Nagy and R. W. Cannata, Modeling of He⁺ dominated polar wind outflow, *AGU Fall Meeting*, San Francisco, California, December 3–7, 1990.
43. S. M. Guiter, T. I. Gombosi and C. E. Rasmussen, Modeling of plasmaspheric refilling with a two-stream model, *AGU Fall Meeting*, San Francisco, California, December 3–7, 1990.
44. R. H. Miller, T. I. Gombosi, S. P. Gary and D. Winske, Wave generation and pitch-angle scattering due to cometary ion pickup, *AGU Fall Meeting*, San Francisco, California, December 3–7, 1990.