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This grant, NAGW 3962, supported our continuing efforts towards an increased understanding of the solar wind interaction and ionospheric processes at Venus and Mars. This work centered on a systematic development of a new generation of three dimensional magnetohydrodynamic {MHD} numerical code, which models the interaction processes of the solar wind with a non-magnetic planets, such as Venus and Mars. We have also worked on a number of different, more specific and discrete studies, as various opportunities arose.

The Aerospace Engineering Department of the University of Michigan has among its faculty some of world's best computational fluid dynamicists. A few years ago some of us in the planetary science and space physics community in the Atmospheric, Oceanic and Space Science Department recognized the opportunity that the presence of these individuals provided and proposed to develop multidimensional MHD codes, with an adaptevily refined unstructured grid system. Funding was received to develop such exciting, new numerical codes for magnetospheric and cometary studies. This in turn led us to realize that "piggybacking" on these developments we can open the door to a new class of MHD models to study Venus and Mars at a relatively small added cost and effort.

As a first step in this process we built an axisymmetric model in which the solar wind interacts with a hard, perfectly conducting sphere. Even that model provided, in certain respects, significant improvements over previous ones. Our model included 1) an axisymmetric volume of 48x24 R_V, which is large enough to include the unperturbed solar wind on the frontside and the tail in the back, 2) grid sizes which provide high resolution in high gradient regions, such as the shock, 3) a finite volume MUSCL-type {monotonic upwind scheme for conservation laws} numerical scheme, which is both robust and accurate and also minimizes numerical dissipation and dispersion {thus representing shocks and other discontinuities very well} and 4) a framework in which boundary conditions can be applied in a systematic way that is consistent with local physics.

The transport equations for the mass density, bulk velocity vector, pressure and magnetic field vector, which were solved in the model, are the well known equations of ideal MHD:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \bullet \left(\rho \mathbf{u}\mathbf{u} + pI + \frac{B^2}{2\mu_o} I - \frac{\mathbf{B}\mathbf{B}}{\mu_o} \right) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho u^2 + \frac{3}{2}p + \frac{B^2}{2\mu_o} \right) + \nabla \bullet \left(\frac{1}{2}\rho u^2 \mathbf{u} + \frac{5}{2} p\mathbf{u} + \frac{(\mathbf{B}\bullet\mathbf{B})\mathbf{u} - \mathbf{B}(\mathbf{B}\bullet\mathbf{u})}{\mu_o} \right) = 0 \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \bullet (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = 0 \tag{4}$$

These equations can be rearranged and written in the following dimensionless, conservative form widely used in computational fluid dynamics:

$$\frac{\partial \tilde{\mathbf{U}}}{\partial t} + \left(\tilde{\nabla} \bullet \tilde{\mathbf{F}}\right)^{T} = 0 \qquad (5)$$

where $\tilde{\mathbf{U}}$ is the eight dimensional state vector and $\tilde{\mathbf{F}}$ is an 8x3 dimensional flux diad. The set of eight equations given by (5) are the single-fluid MHD equations that are solved in our model. As indicated before, our model includes two strong components which makes it well suited for the kind of global scale problems with regions of high gradients, such as the interaction of the solar wind with unmagnetized and magnetized bodies. The first is a data structure that allows for the adaptive refinement of the mesh as necessary and the second component is a second order MUSCL-type numerical scheme, based on an approximate Riemann solver for ideal MHD. The adaptive criteria for the mesh is based on $\nabla \bullet \mathbf{u}$, $\nabla \times \mathbf{u}$ and $\nabla \times \mathbf{B}$. The data structure, the MUSCL scheme and the Riemann solver have been described in detail in a variety of publications [*Leer*, 1979; *Roe*, 1981; *DeZeeuw and Powell*, 1992; *Gombosi et al.*, 1994].

The axisymmetric model was run for γ =5/3 and unperturbed solar wind parameters of β=0.6 and an acoustic Mach number of 3. This Mach number was chosen, because of the previously published work of Luhmann et al. [1986]. Figure 1, in the attached paper by DeZeeuw et al. [1996a] shows the final "self-adapted grid structure for steady state conditions that was used in this axisymmetric study {this figure also shows the track of Pioneer Venus Orbit 1642, the magnetic field data from which was compared to the calculated values}. This grid structure already shows a great deal of information concerning the interaction processes; the locations of the finest grid structures correspond to the greatest gradients. The smallest grid sizes, corresponding to 0.063 R_V, are around the bow shock, the low solar zenith angle ionosheath region, and the tail shocks, while the largest grid sizes are found in the unperturbed solar wind and correspond to 2.025 R_V. This adapted grid refinement means that the total number of grid points in this effectively two dimensional {because of symmetry} calculation needs only 8324 cells, yet it provides a much better spatial resolution than an unstructured 130x65 grid, which would require similar computing resources. This model ran on an HP PA-RISC workstation and did not require a supercomputer.

The results of these calculations were presented at a number of different national and international meetings and published [*Nagy et al.*, 1994; *Luhmann et al.,* 1995; *DeZeeuw et al, 1996a*]. The calculated magnetic field with that measured during orbit 1642, by the magnetometer carried aboard Pioneer Venus [*Russell et al.*, 1980] is shown as Figure 2 in the attached paper. The observed interplanetary field during this orbit was approximately 7.6° from the nominal solar wind direction, thus close to the assumed "parallel" conditions in the model. In Figures 2a and 2b we show the comparisons between the measured and calculated components of the magnetic field parallel and perpendicular to the flow axis for this trajectory. The data were averaged to a resolution of 15s in order to eliminate high-frequency fluctuations. There is good agreement in both the bow shock and field reversal locations, although the magnitude of the parallel component in the central region is underestimated by the model. These axisymmetric calculations suggest that the induced magnetotail disappears when the interplanetary field remains radial for times, of the order of the solar wind flow time past the Venus obstacle, and weakens when the field rotates through a near-radial orientation on shorter time scales. This study also suggested that for periods of prolonged flow-aligned interplanetary field, flow and field "vortices" may appear in the wake.

The initial, first runs with our fully three dimensional MHD model were produced under this grant. Pursuing a careful and systematic evolution of our code, the first thing we did is to run it for axisymmetric conditions to insure that we get the same result as we did with our earlier model; this we did. Next we ran the code in a fully 3D mode, corresponding to measured parameters from Pioneer Venus Orbit 438, which allowed us to compare our results with observations and gasdynamic calculations [*Luhmann et al.*, 1986]. The assumed obstacle for these calculations was a hard conducting sphere. The measured parameters of the unperturbed solar wind, which were used as input for these calculations, were as follows: acoustic Mach number=12, Alfvenic Mach number=6, unperturbed solar wind density=10 cm^{-3} and plasma temperature=10^5 ^oK. The results of these first 3D model calculations were presented at a number of national and international meetings [*Nagy et al.,* 1996a; *DeZeeuw et al.,* 1996b; *Nagy et al.,* 1966b]. The smallest grids, in these calculations, corresponded to 0.05 $R_V{}^3$ and the largest to 50 $R_V{}^3$. The calculations covered a volume of 900x600x600 R_V; the choice of such a large volume assured that the results were not dependent on the boundary conditions. The calculated variations in the field strength, were found to be consistent with the direction of the assumed IMF. The change in the magnetic field across the shock was found to be small where the shock is quasi-parallel, but there is a strong "band" of magnetic field in the other quadrants where the shock is quasi-perpendicular. The lobes in the tail were clearly visible and the polarities and orientation are controlled by the assumed IMF direction. The currents in the central plasma sheet were also be obtained from the model. The calculations have also found the existence of the "polar jet", consistent with the earlier results of Tanaka [1993]. We also compared the calculated value of $B^2/2$ for 0^o and 30^o solar zenith angles, with the normalized, mean, measured values from [*Zhang et al.*, 1991] for the SZA range 0-30^o; a reasonably good agreement in the calculated and measured magnetic barrier behavior was found.

During the last year a few "studies of opportunities" were also carried with the support of the current grant. The principal investigator, participated in the Venus II Conference held at the University of Arizona, during January 1995. The axisymmetric MHD model results were presented at that time, and we also agreed to write a chapter on Ionosphere: Energetics [*Nagy and Cravens*, 1997] for the Venus II Book. At that meeting, Dr. W. C. Knudsen presented some results from his Pioneer Venus RPA [*Knudsen et al.*, 1980] measurements, which showed that the H^+ and O^+ temperatures differed significantly during solar cycle maximum, nighttime conditions. We modified our existing ionospheric energy code to see if theoretical calculations are consistent with these measured findings, and found good agreement between the calculated and measured ion temperatures. We found that the main reason for the difference in the temperatures is the difference in the thermal conductivities of the two ions. The effective H^+ conductivity is several times larger than the O^+ one for the assumed nighttime conditions. In order to carry out these calculations we had obtained the appropriate expression for ion thermal conductivities, which include the effects of collisions with neutrals. This effect is not of any significant importance in the terrestrial ionosphere and until these calculations was also neglected in past studies of the Venus ionosphere. These newly obtained expressions for the ion thermal conductivities and comparisons between the measured and calculated ion temperatures were published [*Knudsen et al.*, 1996].

A Masters thesis project was also completed recently, which looked at the issue of the maintenance of the nightside ionosphere, using Pioneer Venus observations from both the solar cycle maximum phase of the mission as well as the recent entry phase, which corresponds to moderate solar cycle conditions. This study led to the conclusion that day-to-night atomic ion transport is dominant during high solar activity, while during moderate solar activity conditions the combined effects of electron precipitation and reduced day-to-night transport are responsible for maintaining the nightside ionosphere of Venus. A paper reporting these results was published [*Dobe et al.*, 1995].

References.

Dobe, Z., Nagy, A.F., and Fox, J.L., A theoretical study concerning the solar cycle dependence of the nightside ionosphere of Venus, *J. Geophys. Res., 100,* 14507, 1995.

DeZeeuw, D.D., and Powell, K.G., An adaptively refined Cartesian mesh solver for the Euler equations, *J. Comp. Phys., 104,* 55, 1992.

De Zeeuw, D. L., Nagy, A. F., T. I. Gombosi, K. G. Powell and J. G. Luhmann, A new axisymmetric MHD model of the interaction of the solar wind with Venus, *J. Geophys. Res., 101,*4547, 1996a.

De Zeeuw, D. L., Nagy, A. F., T. I. Gombosi, K. G. Powell and J. G. Luhmann, 3D multiscale MHD model of the solar wind interaction with Mars, Spring AGU Meeting, Baltimore, 1996b.

Gombosi, T.I., Powell, K.G., and Zeeuw, D.L., Axisymmetric modeling of cometary mass loading on an adaptively refined grid: MHD results., *J. Geophys. Res., 99,* 21, 1994.

Knudsen, W.C., Bakke, J., Spenner, K., and Novak, V., Pioneer-Venus orbiter planar retarding potential analyzer plasma experiment, *IEEE Trans. Geosci. Electron., 18,* 54, 1980.

Knudsen, W.C., Nagy, A.F., and Spenner, K., Lack of thermal equilibrium between H+ and O+ temperatures in the Venus nightside ionosphere, *J. Geophys. Res.., 102,* 2185, 1997.

Leer, B.v., Towards the ultimate conservative difference scheme, V, A second-order sequel to Godunov's method, *J. Comp. Phys., 32,* 101, 1979.

Luhmann, J.G., Warniers, R.J., Russell, C.T., Spreiter, J.R., and Stahara, S.S., A gas dynamic magnetosheath field model for unsteady interplanetary fields: Application to the solar wind interaction with Venus., *J. Geophys. Res., 91,* 3001, 1986.

Luhmann, J. G., S. H. Brecht, J. R. Spreiter, S. S. Stahara, R. S. Steinolfson, and A. F. Nagy, Global solar wind interaction at Venus; Models, Venus II: Geology, Geophysics, Atmosphere and Solar Wind Environment Conference, Tucson, Az., 1995.

Nagy, A. F., D. L. DeZeeuw, T. I. Gombosi, K. G. Powell and J. G. Luhmann, A new axisymmetric MHD model of the interaction of the solar wind with Venus, *EOS*, 411, AGU Fall Meeting, 1994.

Nagy, A.F., and Cravens, T.E., Ionosphere: Energetics, *Venus II,* U. of Arizona Press, 189-223, 1997.

Nagy, A. F., D. L. De Zeeuw, T. I. Gombosi, K. G. Powell and J. G. Luhmann, 3D multiscale MHD model of the solar wind interaction with Venus, Spring AGU Meeting, Baltimore, 1996a.

Nagy, A. F., D. L. De Zeeuw, T. I. Gombosi, K. G. Powell and J. G. Luhmann, 3D multiscale MHD model of the solar wind interaction with Venus and Mars, Western Pacific AGU Meeting, Brisbane, 1996b.

Roe, P.L., Approximate Riemann solvers, parameter vectors, and difference schemes., *J. Comput. Phys., 43,* 357, 1981.

Tanaka, T., Configurations of the solar wind flow and magnetic field around the planets with no magnetic field: Calculations by a new MHD scheme, *J. Geophys. Res., 98,* 17251, 1993.

Zhang, T.L., Luhmann, J.G., and Russell, C.T., The magnetic barrier at Venus, *J. Geophys. Res., 96,* 11145, 1991.