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(NASA-CR-192113) MAGNETIC FIELD WAVES AT URANUS Semiannual Report (Delaware Univ.) 8 p
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Charles W. Smith, Principal Investigator
Melvyn L. Goldstein, Co-Investigator
Ronald P. Lepping, Co-Investigator
William H. Mish, Co-Investigator
Hung K. Wong, Co-Investigator

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The grant period for funding provided by the NASA Uranus Data Analysis Program (UDAP) to the Bartol Research Institute (BRI) is now in the middle of a one year, no-cost extension. Our efforts in this investigation have been quite productive and we have found numerous interesting observations on which to focus our attention. The results of our analyses are expected to fuel further theoretical investigations for some time to come.

The proposed research efforts funded by the UDAP grant to the BRI involve the study of magnetic field waves associated with the Uranian bow shock. This is a collaborative venture bringing together investigators at the BRI, Southwest Research Institute (SwRI), and Goddard Space Flight Center (GSFC). In addition, other collaborations have been formed with investigators granted UDAP funds for similar studies and with investigators affiliated with other Voyager experiments. These investigations and the corresponding collaborations are included in the report.

The proposed effort as originally conceived included an examination of waves downstream from the shock within the magnetosheath. However, the observations of unexpected complexity and diversity within the upstream region have necessitated that we confine our efforts to those observations recorded upstream of the bow shock on the inbound and outbound legs of the encounter by the Voyager 2 spacecraft.

Upstream wave studies are motivated as a study of the physics of collisionless shocks. Collisionless shocks in plasmas are capable of "reflecting" a fraction of the incoming thermal particle distribution and directing the resulting energetic particle motion back into the upstream region. Once within the upstream region, the backward streaming energetic particles convey information of the approaching shock to the supersonic flow. This particle population is responsible for the generation of upstream magnetic and electrostatic fluctuations known as "upstream waves", for slowing the incoming wind prior to the formation of the shock ramp, and for heating of the upstream plasma. The waves produced at Uranus not only differed in several regards from the observations at other planetary bow shocks, but also gave new information regarding the nature of the reflected particle populations which were largely unmeasurable by the particle instruments.

Four distinct magnetic field wave types were observed upstream of the Uranian bow shock: (i) low-frequency Alfven or fast magnetosonic waves; (ii) whistler wave bursts driven by gyrating ion distributions within the shock ramp; and (iii) two whistler wave types simultaneously observed upstream of the flanks of the shock. In addition, observations of energetic particle distributions by the LECP experiment, thermal particle populations observed by the PLS experiment, and electron plasma oscillations recorded by the PWS experiment proved instrumental to this study and are included to some degree in the papers and presentations supported by this grant.

<u>The Uranian Shock</u>

The Uranian bow shock is a very high Mach number, supercritical shock. The orbit of Uranus dictates that inbound shock crossings would most likely be observed under conditions of a quasi-perpendicular geometry. This was the case. Even the shock crossings on the flank of the shock recorded during the outbound leg proved to be quasi-perpendicular. The ambient thermal plasma in the solar wind was unusually warm during the inbound leg, but returned to normal 19 AU conditions for the outbound leg of the encounter. The ambient density was a factor of 2 above normal. Nevertheless, the ambient plasma conditions were greatly different from past shock encounters and provided a unique opportunity for comparative studies with upstream wave activity at Mercury, Venus, Earth, Jupiter, and Saturn.

Fig. 1 shows the trajectory of the Voyager 2 spacecraft through the Uranian system. The projection of the interplanetary magnetic field (IMF) onto the plane of the planet's orbit is also represented. The quasi-perpendicular shock geometry dictated by normal Parker spiral conditions at 19 AU implied that the spacecraft trajectory would not carry Voyager 2 through the expected ion and electron foreshock regions. For this reason, observations of the energetic ion populations thought to be responsible for the low-frequency upstream waves were indirect and relied on observations of the scattered component. Observations of the energetic particle components responsible for whistler wave activity were equally indirect, relying on inference drawn from the presence of Langmuir oscillations and past studies at other planets as well as theoretical predictions linking wave growth to particle distribution parameters.

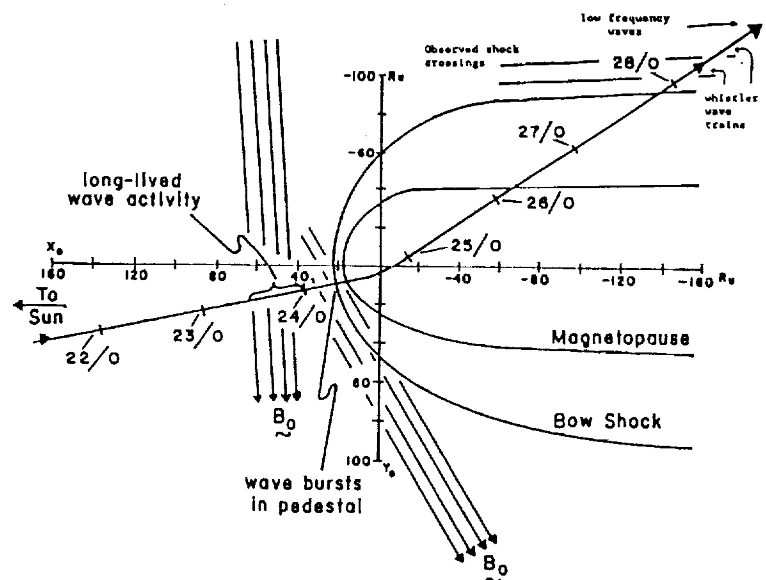

Fig. 1.: Trajectory of the Voyager 2 spacecraft through the Uranian system projected onto the orbital plane of the planet. Shock asymmetry represents shock shape at times of inbound and outbound encounter. IMF direction is shown for two periods of inbound upstream wave activity.

<u>Low-Frequency Waves</u>

Efforts to resolve the low-frequency wave activity have involved collaborations with C.T. Russell at UCLA and the PLS instrument group at MIT. These efforts are detailed in two published papers titled: "Upstream Waves at Uranus", and "Alfven Waves and Associated Energetic Ions Downstream from Uranus". Both papers were published in the Journal of Geophysical

Research and are listed at the end of this report as Russell et al. [1990] and Zhang et al. [1991], respectively.

As expected, no low-frequency wave activity was recorded on the inbound leg of the encounter. The highly azimuthal IMF orientation directed the backstreaming charged particles across the flow of the solar wind and to the side of the shock. The side thus preferred was opposite to the trajectory of the spacecraft as it made its inbound approach. It therefore appears that the spacecraft was never magnetically connected to the shock during the inbound leg of the encounter.

Observations recorded during the inbound trajectory did contain spurious noise signals that closely resembled upstream wave observations. These noise signals appeared at the spacecraft frame frequencies expected of upstream Alfven or fast magnetosonic waves. Resolution of the noise signal was required before the study could go forward.

Low-frequency upstream waves were observed on the outbound leg of the encounter. Fig. 2 (taken from Russell et al. [1990]) compares the spacecraft frame frequencies of low-frequency upstream waves at Mercury, Venus, Earth, and Jupiter with the wave frequencies of the new observations at Uranus. The comparison in Fig. 2 implies that the component of the particle velocity directed in the sunward direction is approximately equal in all cases. This is a simple selection mechanism that requires the particles to move against the solar wind.

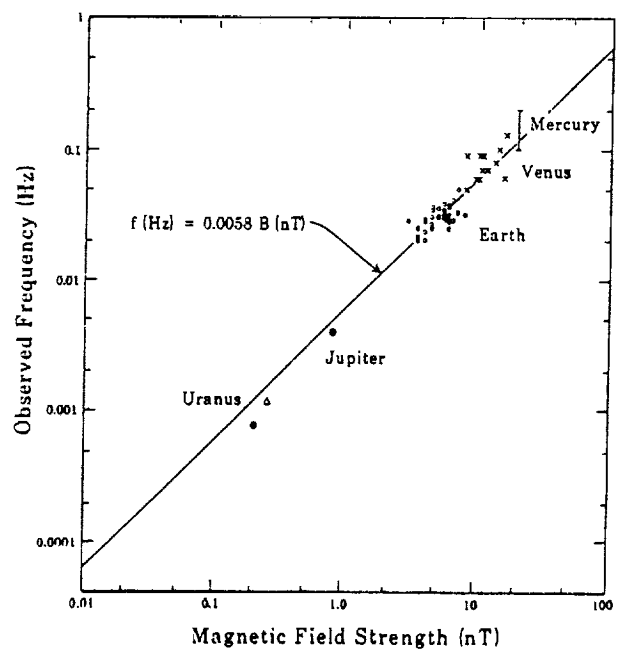

Fig. 2.: Magnetic field strength vs. spacecraft frame frequency of low-frequency upstream waves at five planets. Linear scaling of frequency with field strength implies that particle speeds are comparable and that source mechanisms are the same.

The energetic proton population thought to be responsible for these waves was not directly observed. However, a highly scattered energetic proton population was observed for several extended periods during the outbound leg. While it is thought that the proton distribution responsible for these waves should be colder and more beam-like, the trajectory did not favor such an observations, as noted above. Rather, a remnant of that distribution formed from the particles scattered by the interplanetary magnetic fluctuations was convected downstream to the spacecraft where it was observed. The waves, which propagate at approximately one tenth the solar wind speed, are thought to have been generated in this same region and convected in approximately the same manner.

Fig. 2 was recently updated (M. Zhang, J. W. Belcher, J. D. Richardson, V. M. Vasyliunas, R. P. Lepping, N. F. Ness, and C. W. Smith, Low-Frequency Waves in the Solar Wind Near Neptune, Geophys. Res. Lett., 18, 1071-1074, 1991) to include observations of low-frequency waves at Neptune.

Whistler Wave Bursts

We have examined the magnetic field observations recorded upstream of the shock during the inbound leg of the encounter in search of upstream wave activity. The results of this examination were presented in the paper by Smith et al. [1989] titled: "Whistler Wave Bursts Upstream of the Uranian Bow Shock". While we found no low-frequency waves of the type described above and observed during the outbound leg, we did observe two extended periods of whistler wave activity in association with highly azimuthal field orientations.

An extended period of activity was observed immediately upstream of and within the shock ramp. These observations were in the form of intense whistler wave bursts of very large amplitude and short duration. Fig. 3 (taken from Smith et al. [1989]) shows the first two such observations recorded just prior to entrance into the ramp. The spacecraft fame frequencies of the waves are 40 and 20 mHz, respectively. The spacecraft frame polarization of the waves suggests propagation at speeds in excess of the solar wind speed.

We performed an instability analysis for these observations based on the assumed presence of gyrating proton distributions associated with the quasi-perpendicular shock. The Voyager 2 instrumentation (both thermal plasma and energetic particle experiments) are incapable of observing particle with the expected energy of the gyrating proton distribution. We found predicted growth rates, propagation directions, and spacecraft frame frequencies in good agreement with

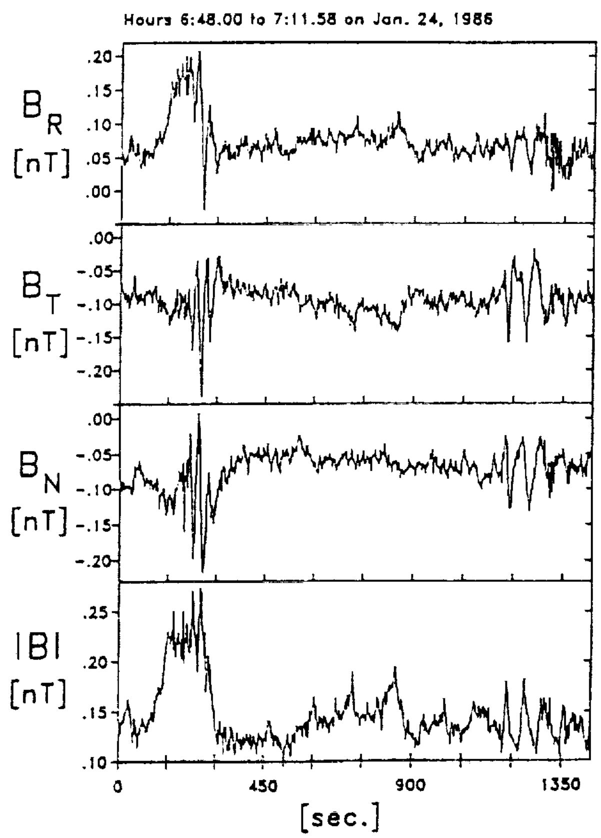

Fig. 3.: Two whistler wave bursts observed upstream of shock ramp at Uranus. First is coincident with field rotation while second is not.

the observed wave characteristics. The intermittent nature of the waves appears to suggest some degree of instability for the Uranian shock, perhaps in rough agreement with simulations of high Mach number, perpendicular shocks.

A second class of whistler wave observations were also recorded during the inbound leg of the encounter. These were seen as much as 18 hours prior to the shock crossing during a 7 hour period of highly azimuthal IMF orientation. Based on wave frequency, minimum variance direction, and polarization we argued that these waves had successfully propagated from the shock ramp where they had most likely been generated in the same manner as the above whistler wave bursts. The waves were not observed before or after this period when the IMF was more radially aligned. Recent examinations of the PWS data have indicated that magnetic connection to the shock was unlikely during this 7 hour period. These facts further reinforce the assumption of a gyrating ion source.

Uranian upstream whistler waves excited by a gyrating ion beam are closely related to a similar class of observations at comets. In cometary foreshocks, the pick-up process is responsible for the gyrating beam distribution. In planetary foreshocks, such as in this case at Uranus, particle reflection at a quasi-perpendicular shock is the source of the gyrating beam distribution function.

Dual Whistler Waves

We have examined the magnetic field observations recorded upstream of the shock during the outbound leg of the encounter in search of upstream wave activity. These efforts are described in the paper by Smith et al. [1991] titled: "Whistler Waves Upstream of the Uranian Bow Shock: Outbound Observations". High resolution (16 vectors/sec) detail data was employed to allow adequate resolution of the high frequency waves.

We found three instances of whistler wave activity associated with the shock crossings. Some of the shock crossings had no associated upstream whistler wave activity. The reason for this is not now understood. One of the events recorded during the outbound leg was relatively nondescript and displayed measurable activity both upstream and downstream of the shock. The two other events displayed dual-wave signatures with two distinct whistler waves active at the same time. The spacecraft frame frequencies of the two waves were approximately 0.1 and 1 Hz. Fig. 4 (taken from Smith et al. [1991]) shows the computed power spectrum for one of these two events along with the polarization and minimum variance analyses. While the 0.1 Hz wave is obliquely propagating and appears to be consistent with previous observations at Earth and elsewhere, the parallel propagating 1 Hz wave appears to be a new phenomenon. We argued that a suprathermal electron population represents the most likely source of these waves and provided an instability analysis in keeping with this assertion.

It may be the case that the 1 Hz wave observed at Uranus is related to the 10 - 100 Hz signals frequently observed within the Earth's electron foreshock. Further analysis is required before this possibility can be claimed. We are planning to pursue this new result with a parametric survey of the instability in hopes of establishing its possible relationship to other observations. We will also be extending the analysis to include gyrating electron beams which possess perpendicular energy distributions similar to the anisotropic beam used in the above analysis.

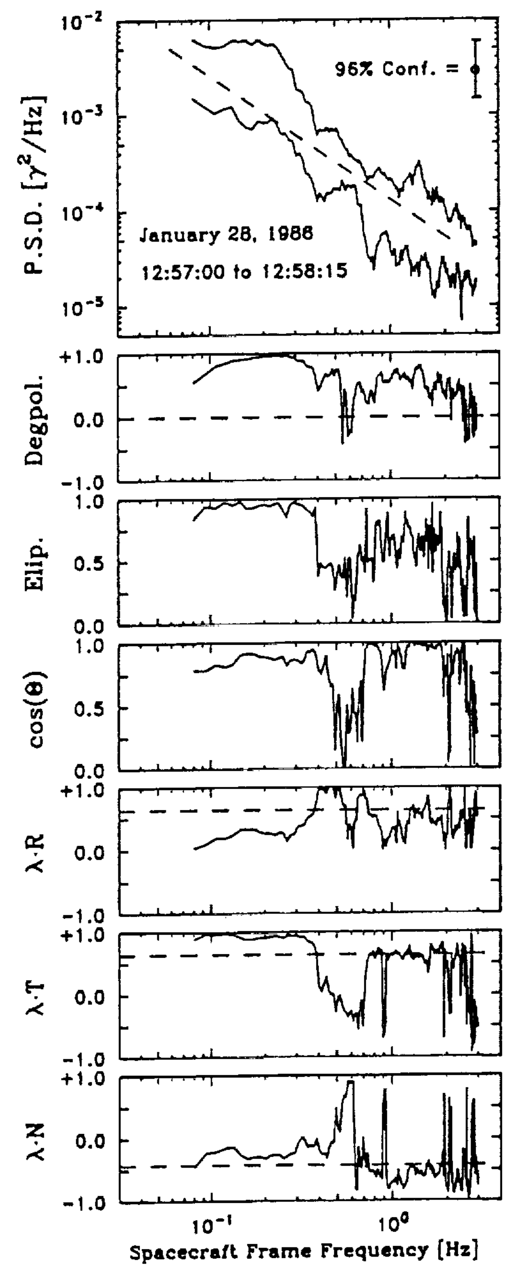

Fig. 4.: Analysis of one period of whistler wave activity during outbound leg demonstrating dual-wave activity. Waves are seen at approximately 0.2 and 1.5 Hz. Spacecraft frame polarizations are right-handed, indicating propagation speeds in excess of the solar wind speed. The 1.5 Hz signal is propagating along the magnetic field while the 0.2 Hz wave is propagating across the field in the "T" direction.

<u>Continuing Efforts</u>

We are hoping to close this phase of the investigation by surveying the parametric dependences of the dual whistler wave instability. It is not now well understood under what conditions the two whistler waves can be simultaneously excited by an electron beam. Both ambient and beam parameters need to be examined. Both anisotropic electron beams and gyrating electron beams are under consideration. It is anticipated that this analysis will lead to a better understanding of the conditions that lead to this unique set of observations. In addition, it is anticipated that this study will reveal the relationship between these observations at Uranus and the two classes of whistler waves at Earth.

This analysis will take us to the close of the funding period. We envision continuing the examinations we have begun under the UDAP funding with further theoretical and observational investigations motivated, at least in part, by the results of this investigations. Among other issues to be considered, we hope that at a later date we may return to the data recorded at the flanks of the Uranian shock to gain a better understanding of the structure of the shock in this region.

Papers Published in Refereed Journals:

Smith, C. W., M. L. Goldstein, and H. K. Wong, Whistler Wave Bursts Upstream of the Uranian Bow Shock, J. Geophys. Res., A94, 17035-17048, 1989.

Russell, C. T., R. P. Lepping, and C. W. Smith, Upstream Waves at Uranus, J. Geophys. Res., A95, 2273-2279, 1990.

Zhang, M., J. W. Belcher, J. D. Richardson, and C. W. Smith, Alfven Waves and Associated Energetic Ions Downstream from Uranus, J. Geophys. Res., A96, 1647-1660, 1991.

Smith, C. W., H. K. Wong, and M. L. Goldstein, Whistler Waves Associated with the Uranian Bow Shock: Outbound Observations, J. Geophys. Res., in press, 1991.

Seminars, Invited, and Contributed Presentations:

"Whistler Wave Bursts Upstream of the Uranian Bow Shock", Fall Meeting of the American Geophysical Union, San Francisco, December 1988.

"Upstream Waves and Particles in the Heliosphere: An Overview", Space Plasma Physics Group, Massachusetts Institute of Technology, January 1989.

"Upstream Waves at the Outer Planets", Magnetospheres of the Outer Planets Meeting, Annapolis, Maryland, August 1990.

"Electron Beam Driven Whistler Waves Upstream of the Uranian Bow Shock", Fall Meeting of the American Geophysical Union, San Francisco, California, December 1990.