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titled:

Magnetic Field Waves at Uranus

to

The Bartol Research Institute
of the University of Delaware

Administered Under the Auspices of
The Uranus Data Analysis Program

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The grant period for funding provided by the NASA Uranus Data Analysis Program (UDAP) to the Bartol Research Institute (BRI) was 2 years and ran from December 1, 1988 until November 30, 1991 including a one-year, no-cost extension. Our efforts in this investigation were quite productive and we found numerous interesting observations on which to focus our attention. The results of our analyses have fueled further theoretical investigations that are now ongoing and formed the basis for our successful two-year proposal to the NASA NDAP program.

The research efforts funded by the UDAP grant to the BRI involved the study of magnetic field waves associated with the Uranian bow shock. This was a collaborative venture bringing together investigators at the BRI, Southwest Research Institute (SWRI), and Goddard Space Flight Center (GSFC). In addition, other collaborations were 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. We hope to revisit the magnetosheath observations at some point in the future.

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 excited by energetic protons originating at or behind the bow shock; (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 and argued to arise from resonance with energetic electrons. 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.

The Uranian Shock

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 quasiperpendicular geometry. This was the case. Even the shock crossings on the flank of the shock recorded during the outbound leg proved to be quasiperpendicular. 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.

Low-Frequency Waves

Efforts to resolve the low-frequency waves involved collaborations with C. T. Russell at UCLA and the PLS instrument group at MIT. These efforts are detailed in two 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 not magnetically connected to the shock for any significant period 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.

While it is thought that the proton distribution responsible for the low-frequency waves should be cold and beam-like, the trajectory did not favor such observations. 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.

Whistler Wave Bursts

We 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. The spacecraft frame polarizations of the waves suggest 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 quasiperpendicular shock. The Voyager 2 instrumentation (both thermal plasma and energetic particle experiments) are incapable of observing particles with the expected energy of the gyrating proton distribution. We found predicted growth rates, propagation directions, and spacecraft frame frequencies in good agreement with 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 some 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. 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 quasiperpendicular shock is the source of the gyrating beam distribution function.

Dual Whistler Waves

We 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. 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.

Continuing Efforts

The work begun under the support of the UDAP program continues today under support by the NASA NDAP program. We have begun a study of magnetic waves upstream of Neptune's shock in the hope of finding further evidence for the two whistler mode sources that we discussed in connection with Uranus. We have also submitted a manuscript to The Journal of Geophysical Research which extends the analysis of electron beams as a potential source of dual whistler mode waves by adapting that analysis to commonly observed parameters at 1 AU. We have shown that this mechanism should be a fairly common source of whistler mode waves upstream of Earth's bow shock and at interplanetary shocks. For reasons that are not yet clear, Neptune's foreshock appears to be remarkably quiet and free of significant wave activity. However, this result is preliminary and further analysis of the highest resolution data is necessary before conclusive statements can be made on this subject. It is still possible that Neptune will yield further understanding of these interesting shock processes.

Since the close of this grant, C. W. Smith has had the opportunity to present undergraduate seminars at James Madison University, Bates College, and Bowdoin College. The purposes of these seminars were to expose undergraduates to the opportunities of Space Plasma Physics and provide a general overview of the heliosphere as viewed through in-situ measurements. The material developed under the support of this grant has figured prominently in those presentation as examples of what can be learned from spacecraft observations.

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., 96, 15,841-15,852, 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.