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Plasma wave turbulence at planetary bow shocks

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Voyager 1 observations of plasma wave turbulence at Saturn's bow shock are discussed and compared with corresponding data from Jupiter, Earth, and Venus. The results suggest that the plasma instabilities that develop at the lower Mach number bow shocks of the terrestrial planets differ from those found at the high Mach number bow shocks of the outer planets.

AS the solar wind streams out from the Sun, its flow speed remains constant, but its plasma density, ion and electron temperatures, and mean interplanetary magnetic field strengths all have distinct and varying radial profiles. Thus, the dimensionless interplanetary parameters that determine how microscopic plasma processes develop change with heliocentric distance. We therefore expect to find significant radial variations in several important interplanetary plasma phenomena. This is very important to collisionless shock studies, in particular, because some combinations of plasma parameters occurring naturally in the solar wind have not yet been attained experimentally.

The planetary bow shock also forms in the solar wind, and this means that the characteristics of these very high Mach number discontinuities will vary across the Solar System as the expanding wind encounters each planet at a different radial position. As the processes that develop at the bow shock directly affect the properties of the post-shock plasma that actually impacts the ionopause or magnetopause, comparative planetary studies must include comparison of the bow shock turbulence spectra and associated wave–particle interaction phenomena. We now discuss recent Voyager 1 observations of plasma wave turbulence at Saturn's bow shock, and present an initial comparison of these wave measurements with corresponding data from Jupiter, Earth and Venus. The results suggest that the plasma instabilities that develop at the lower Mach number bow shocks of the terrestrial planets differ from those found at the high Mach number bow shocks of the outer planets. Thus the state of the post-shock plasma varies significantly from one planet to another.

Saturn bow shock crossings

As noted by Gurnett *et al.*[1], the solar wind upstream from Saturn was remarkably quiet in the 10 Hz–56 kHz range covered by the Voyager 1 plasma wave instrument. The only regular signals observed in this region were repetitive series of Saturn radio emissions[1,2]. We also detected a single cluster of intense 3 kHz noise bursts between 17.05 and 17.20 on 11 November 1980, when the Voyager to Saturn distance was 32.4 R_S. We interpret these 3-kHz waves as electron plasma oscillations associated with suprathermal electrons streaming back from the shock, but when these emissions disappeared, Voyager was still in the solar wind. Terrestrial experience with similar sequences of observations suggests that the bow shock was actually near the spacecraft just after 17.00, but that the shock surface receded back towards the planet in response to a change in solar wind conditions. Similar 3-kHz bursts were detected again after 23.22, and these waves persisted until 23.27 when Voyager made its only inbound bow shock crossing at a radial distance of 26.1 R_S. Figure 1 shows all of the 16-channel wave measurements for this event, and it can be seen that the shock was thin and well-defined in terms of the low frequency ($f \leq 1$ kHz) wave activity. These bandpass channel amplitude profiles are very similar to those found when Voyager 1 approached Jupiter[3,4], and in both cases, the post-shock magnetosheath noise levels seem to be exceptionally low.

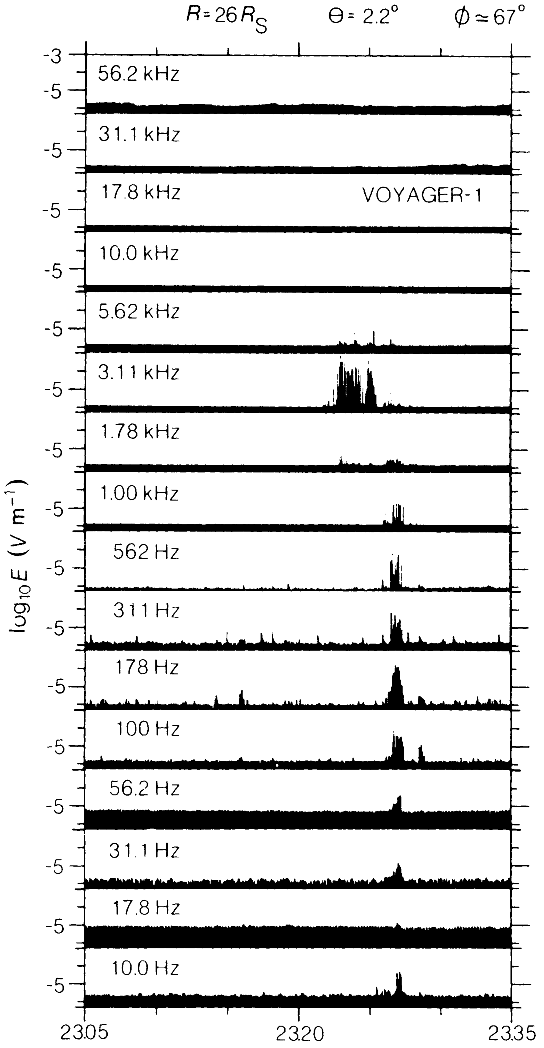

Fig. 1 Sixteen-channel measurements of plasma wave amplitudes at the inbound crossing of Saturn's bow shock. Several sporadic interference effects have been deleted. The 31.1-kHz and 56.2-kHz levels represent radio emissions from Saturn, and we interpret the 3.1-kHz waves as electron plasma oscillations.

Just before 12.27, the wind speed (V) and density (N) were[5] 420 km s^{-1} and 0.11 ions cm^{-3}, and the magnetic field strength (B) was[6] about 0.3 nT. Here, the upstream proton and electron temperatures were $\sim 1.5 \times 10^4$ K and 2.3×10^4 K, respectively (J. Scudder, personal communication). For these parameters, the Alfvén speed, $V_A (= [B^2/4\pi N m_+]^{1/2})$, is only 20 km s^{-1}, and the magnetosonic wave speed, V_{ms} $(= [V_A^2 + V_s^2]^{1/2}$, with $V_s = [(5kT_+/3 + kT_-)/m_+]^{1/2})$, is ~ 28 km s^{-1}. Hence, the Mach numbers for the collisionless shock of Fig. 1 are remarkably high ($M_{ms} = V/V_{ms} = 15$, and $M_A = V/V_A = 21$), and this event is probably one of the highest Mach number collisionless shocks for which any *in situ* observations are available.

Before comparing plasma wave measurements for the relatively well-defined dayside bow shock crossings at Saturn, Jupiter, Earth and Venus, we discuss characteristics of the outbound bow shock encounter with Saturn on the nightside almost midway between local midnight and dawn. During the interval 05.50 to 06.18 on 16 November when Voyager 1 was at

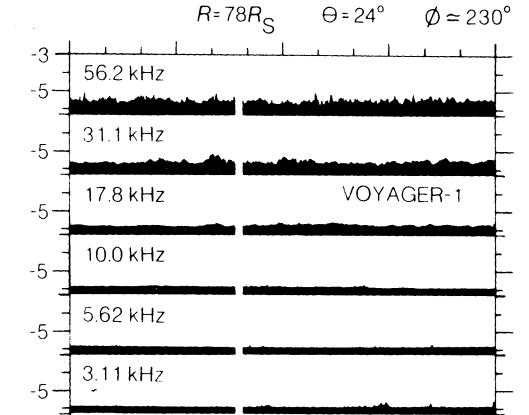

Fig. 2 Sixteen-channel measurements of plasma wave amplitudes at the diffuse outbound crossing of the bow shock. Here, the 10–56 kHz waves are Saturn radio emissions, and the gap between 05.53:23 and 05.54:11 corresponds to an interval when the Voyager tape recorder was acquiring waveform data.

78 R_S, the spacecraft traversed a relatively diffuse transition layer separating the magnetosheath from the solar wind. Figure 2 shows the relative thickness of the outbound shock and the variability in the plasma wave amplitude profiles; this is characteristic of a quasi-parallel shock configuration that is usually associated with an extensive region of upstream disorder, and it seems that after 06.18, much turbulence was present for an extended period. Ness *et al.*[6] noted the elevated r.m.s. magnetic field noise levels which indicate that enhanced low frequency electromagnetic wave activity was present after 06.18. The plasma wave instrument was able to detect Saturn-associated bursts of ion acoustic waves and electron plasma oscillations out to at least early December more than 400 R_S away from Saturn. These results are readily understandable because at 9.5 AU, the Parker spiral model leads to an average interplanetary field oriented almost perpendicular to the Saturn–Sun line. Thus, the Saturn 'upstream region' or 'foreshock', which can develop when the B-field intersects the shock surface, was encountered after closest approach rather than before.

Planetary bow shock turbulence spectra

Pioneer Venus Orbiter provided the first data on plasma wave activity at the bow shock of a planet other than Earth in December 1978, and in March and July 1979, the Voyager spacecraft transmitted corresponding information from Jupiter's bow shock. Following the 1980 Voyager 1 encounter with Saturn, it is possible to present a preliminary comparison of wave–particle interactions at four planetary bow shocks, but a comprehensive analysis must await Voyager 2 Saturn data.

The IMP-6 study of Rodriguez and Gurnett[7] serves as a reference for analysis of plasma waves at the terrestrial bow shock, and Fig. 3*c* shows the average electric field spectra detected at 36 representative crossings of the shock surface. For these crossings, the average solar wind density was 5.2 particles cm^{-3}, and the average magnetic field strength was 7.5 nT; these values yield a mean electron plasma frequency ($f_{pe} = 9{,}000\sqrt{N}$) of 20.5 kHz, an ion plasma frequency ($f_{pi} = 210\sqrt{N}$ for protons) of 480 Hz, and an electron cyclotron frequency ($f_{ce} = 28B$) of 210 Hz. These characteristic frequencies, along with the 1.65 kHz value that is appropriate for the corresponding Buneman mode[8] characteristic frequency, f_B ($=[m_e/m_i]^{1/3} f_{pe}$) are marked at the top of Fig. 3.

Rodriguez and Gurnett studied how the plasma wave spectrum varied with changes in Alfvén and sonic Mach numbers, plasma β-value ($\beta = 8\pi NK[T_e + T_i]/B^2$), ion temperature, electron-to-ion temperature ratio, solar wind density and shock normal angle. Plots of the mid-frequency (200 Hz–4 kHz) E-field amplitude against T_e/T_i showed a strong positive correlation, and a weaker one when the low frequency (20 Hz–200 Hz) E-field amplitude was used, but the extreme shapes of the shock spectra shown in Fig. 3*c* were not discussed in association with any particular groups of upstream plasma parameters. Indeed, as the upstream parameters associated with the Rodriguez and Gurnett data set varied over a huge range ($0.5 \leq N \leq 19$ cm^{-3}, $2 \leq B \leq 17$ nT, $1.5 \leq M_A \leq 26.6$, $0.03 \leq \beta \leq 4.5$), there was no *a priori* reason to expect to find characteristic changes in shock spectra as we moved inward towards Venus or out to Jupiter and Saturn. Nevertheless, Fig. 3*a*, *b*, *d* strongly suggests that the bow shock spectra at the other planets differ significantly from those detected at Earth.

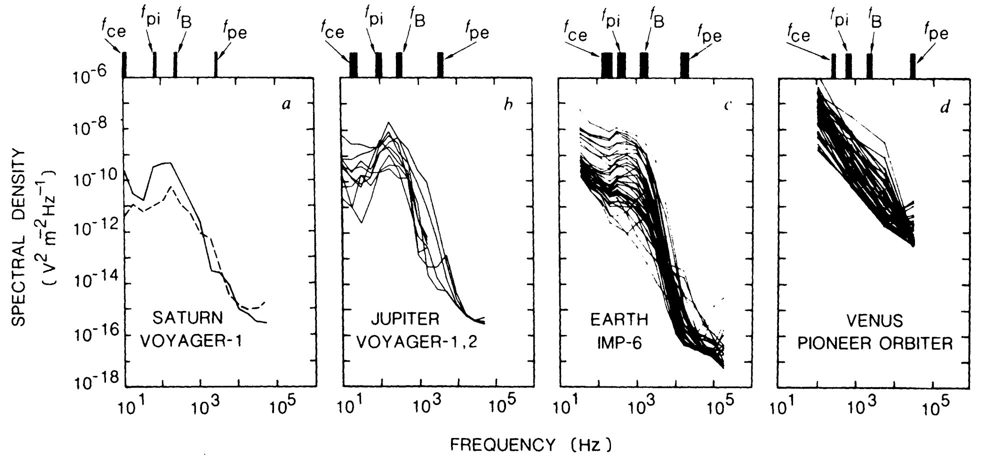

Fig. 3 Multi-planet comparison of plasma wave spectra. *a* Was constructed using the 16-channel amplitude measurements of Figs 1 and 2. The solid and dashed spectra represent the inbound and outbound crossings, respectively. The characteristic frequencies shown at the top are the electron cyclotron frequency (f_{ce}), the ion plasma frequency (f_{pi}), the Buneman mode frequency (f_B), and the electron plasma frequency (f_{pe}). Although the spectra for Earth (*c*), Jupiter (*b*) and Saturn (*a*) all have a primary or secondary peak in the noise spectrum between f_{pi} and f_B, the intense low frequency enhancement which is evident in most terrestrial spectra and all the Venus observations is not found at Jupiter or Saturn.

The 48 Venus spectra on Fig. 3*d* have been discussed elsewhere[9]: these spectra are limited because the Pioneer Venus instrument has only four filter channels and it uses short antennas which are affected by spacecraft interference. Nevertheless, the shock processes at Venus seem to generate much higher levels of low frequency ($f \leqslant f_{pi}$) plasma wave turbulence than do the corresponding processes at Earth [we use N(Venus) $\simeq$ (12 ± 4) electrons cm^{-3} and B(Venus) $\simeq$ (10 ±) nT to compute the characteristic frequencies shown at the top of Fig. 3*d*].

Recently the nine jovian spectra shown in Fig. 3*b* have been compared with the IMP-6 data[10]. The Voyager 1 and 2 measurements were all obtained during the dayside inbound passes, and the characteristic frequencies shown at the top correspond to $N \cong (0.225 \pm 0.075)$ electrons cm^{-3} and $B \simeq (0.8 \pm 0.2)$ nT. The low frequency enhancement in electric field intensity, evident in most of the terrestrial wave spectra and all of the Venus observations, was not present at Jupiter. Assuming that these low frequency waves represent whistlers, it was speculated that whistler-mode noise may not be as important the jovian bow shock as at Earth and Venus. Alternatively, the Jupiter spectral peaks at higher frequencies could be attributable to plasma conditions in the distant solar wind that yield enhanced generation of ion acoustic or Buneman mode oscillations, rather than suppressed levels for the whistlers.

Figure 3*a* shows the Voyager 1 Saturn bow shock spectra derived from the measurements of Figs 1 and 2; the solid lines connect one-minute averages for the inbound crossing, and the dashed lines refer to the outbound case. The Jupiter and Saturn shock spectra are quite similar and both have intensity peaks near the f_{pi} and f_B characteristic frequencies. It is difficult to identify these wave modes, however, as ion acoustic waves have phase speeds small compared with the solar wind speed; thus, Doppler effects could account for large frequency shifts, and these waves may have $f \leqslant f_{pi}$ in the solar wind rest frame. As the heliocentric distance increases, there appears to be a significant and consistent variation in the average bow shock turbulence, and we should therefore examine how some relevant interplanetary parameters vary from one planetary orbit to another.

A complete investigation of the variations in bow shock microstructure requires comparative study of the electron and ion temperatures, thermal anisotropies, heat flux moments, and distribution function shapes, as well as comparison of the macroscopic upstream parameters such as magnetic field vector, solar wind velocity, and wind density. Note that the average spectra shown in Fig. 3 can be associated with changes in average Mach number. Specifically, using $M_A = V/V_A$ and $V_A = (B/(4\pi N m_+{}^{1/2})$, the mean B and N values cited above give M_A(Venus) = 6.3, M_A(Earth) = 5.6, M_A(Jupiter) = 11, and M_A(Saturn) = 21. This suggests that there may be a relation between Mach number and spectral shape.

Support for this speculation comes from reanalysis of the IMP-6 bow shock observations. Although the result is not strongly evident in Fig. 3*c*, three of these spectra have 'outer planet' shapes in the sense that for these cases, the wave level at $f \simeq 100$ Hz is much lower than the level at $f \simeq 100$–1,000 Hz. These peaked terrestrial spectra were detected when the upstream conditions yielded a subset of high Mach numbers (P. Rodriguez, personal communication), and this tends to support a hypothesis that the Jupiter and Saturn shock spectra have unusual characteristics, primarily because the solar wind Mach numbers at the outer planets tend to be much higher than the customary values near 0.7–1.0 AU.

Discussion

On theoretical and experimental grounds it is known[11,12] that several distinct dissipation mechanisms develop in collisionless shocks and that the dominant interaction depends strongly on the Mach number. For low Mach numbers ($M \leqslant M^* \simeq 2$–3), the shock is resistive, and for $M > M^*$, viscous dissipation becomes important. Above a second critical Mach number, $M^{**} \approx 6$–7, theory[11] requires other types of dissipation, but these very high Mach number shocks have not been intensively analysed. We now find that upstream conditions at the outer planets generally yield Mach numbers considerably higher than M^{**}, and thus it is of great interest to find that the Jupiter and Saturn bow shock crossings have plasma turbulence spectra that resemble those found at Earth when M is high. The Jupiter and Saturn characteristics are also unusual in that the jump in electron temperature across the shock is enormous ($T_e^2/T_e^1 \approx 15$ at Jupiter[13]) and the magnetosheath wave levels are extremely low.

In conclusion, our study of the bow shocks at Jupiter and Saturn has provided insight into collisionless shock microstructure for an important new plasma regime, and helps to understand shocked plasmas of non-equilibrium characteristics that seem to be different from those found in the terrestrial magnetosheath.

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