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# Ion Distributions in the Dayside Magnetosheaths of Jupiter and Saturn

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Data from the Voyager 1 and 2 Plasma Science experiment in the dayside magnetosheaths of Jupiter and Saturn are analyzed. The ion distributions throughout the dayside magnetosheaths of both planets are well modeled by a two-temperature proton distribution. The two proton populations have comparable densities, and temperatures of 100 and 1000 eV. Similar two-temperature proton distributions are occasionally observed in earth's magnetosheath. Ion temperatures, densities, and bulk velocities for the four magnetosheath crossings are presented, confirming that sunward flow of up to 100 km/s occurs when the magnetosphere is expanding.

## INTRODUCTION

The magnetosheath is the region between a planet's bow shock and magnetosphere which contains shocked solar wind plasma. The bow shocks at the earth and other planets have received extensive attention in the literature (see *Greenstadt and Fredericks* [1979] and *Russell* [1985] for recent reviews). This work has generally focused on the jump parameters across the shock and microstructure of the shock. Very little has been written on the distribution function of plasma in the magnetosheath region, even though knowledge of these distributions would seem essential for understanding the processes occurring in the shocks. Many early experiments noted the presence of a non-Maxwellian high-energy tail on ion distributions in earth's magnetosheath [*Howe*, 1970; *Hundhausen et al.*, 1969; *Wolfe and McKibben*, 1968; *Montgomery et al.*, 1970]. These high-energy tails contain less than 10% of the total density and become less pronounced away from the immediate vicinity of the shock [*Montgomery et al.*, 1970]. *Formisano et al.* [1973] linked the presence or absence of high-energy non-Maxwellian tails in the proton distribution function to upstream plasma conditions. More recent observations show that some magnetosheath spectra exhibit ion distributions which are well described by two Maxwellians with different temperatures. Observations made from Apollo 15 in the dusk magnetosheath show that two-temperature ion distributions sometimes occur during quiet times (low geomagnetic activity), with the cold component having a temperature of 10–25 eV and a density of about 1 $cm^{-3}$, and the hot component having a temperature of 70–150 eV and a density of 7–10 $cm^{-3}$ [*Sanders et al.*, 1978, 1981]. Measurements in earth's dawnside magnetosphere by the ISEE 1 spacecraft show that during at least one quiet time the ion distribution is well described by two thermal populations of nearly equal density with temperatures of 60 and 500 eV [*Peterson et al.*, 1979]. Although no statistical studies have been done, these two-temperature ion distributions appear to be rare at the earth, having been reported only during quiet times by two experiments.

Observations of the magnetosheaths of Jupiter and Saturn have been made by the Pioneer and Voyager spacecraft. *Wolfe et al.* [1974] calculated proton densities, temperatures, and bulk velocities in the Jovian magnetosheath both inbound and outbound using Pioneer 10 data and assuming that the proton distributions were Maxwellian. *Mihalov et al.* [1976] found that, although many ion distributions observed by Pioneers 10 and 11 in the Jovian magnetosheath are Maxwellian, some have non-Maxwellian characteristics with enhancements at low or high energy. A two-temperature distribution with characteristics of both the unperturbed solar wind and magnetosheath plasma (temperatures of about 3 and 280 eV, respectively) was sometimes observed by Pioneers 10 and 11 near the shock, but these spectra may indicate incomplete shock crossings rather than shock-produced distributions.

Little has been previously reported about the Voyager magnetosheath plasma data at Jupiter and Saturn, except for a listing of the magnetosheath boundaries at the four encounters [*Bridge et al.*, 1979a, b, 1981, 1982]. This paper presents results from an analysis of ion spectra obtained by the Plasma Science instrument (PLS) on Voyagers 1 and 2 in the magnetosheaths of Jupiter and Saturn. Ion distributions throughout the dayside magnetosheaths of both planets are found to be well simulated by protons with a two-temperature distribution. The densities of these two Maxwellian proton populations are comparable, and their temperatures are about 100 and 1000 eV.

## INSTRUMENT AND ANALYSIS

The PLS instrument consists of four modulated-grid Faraday cups which measure ion and electron currents in an energy-per-charge range of 10–5950 eV (for complete details on the instrument see *Bridge et al.* [1977]). The low-resolution ($L$) mode covers this range with 16 contiguous voltage "windows," or channels, and the high-resolution ($M$) mode covers the same voltage range with 128 channels. A complete set of $L$ and $M$ mode spectra is obtained every 96 and 192 seconds, respectively. Three of the detectors (A, B, and C) are oriented in a cluster whose central axis points toward earth and are ideally oriented for measuring solar wind and magnetosheath flow. The D cup is at right angles to this direction but still detects ion fluxes in the magnetosheath where the plasma is subsonic.

A sample set of $M$ mode spectra is shown in Figure 1. Current in femtoamps ($10^{-15}$ A) is plotted versus a logarithmic energy scale. Currents are measured simultaneously in all four cups. The plasma flow is directly into the A, B, and C cups. The D cup is at a right angle to the flow direction, so currents measured in this cup are due to the thermal spread in the ion velocities.



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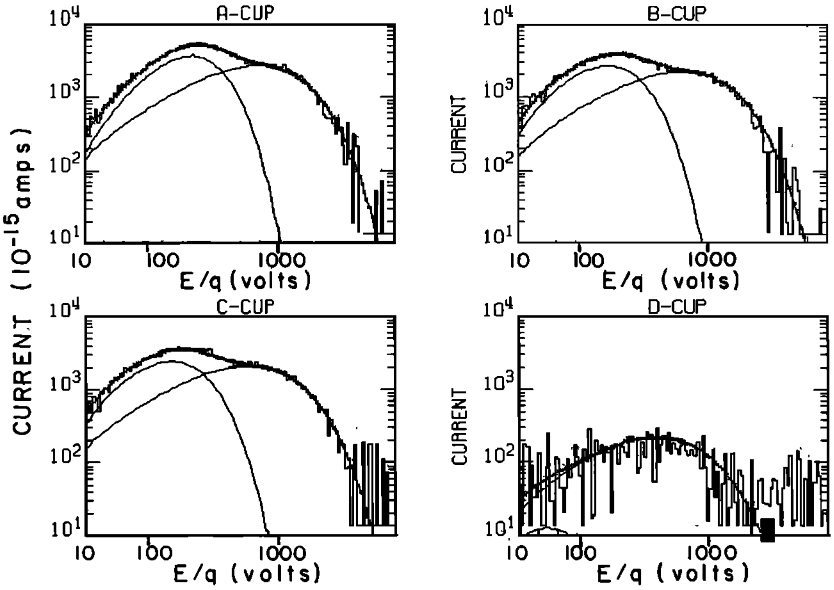


Fig.1. A sample set of M mode spectra from Voyager 2 at 69.5 $R_J$. Overlaying the data is the best fit to the data obtained using a two-temperature proton distribution with ($V_R$, $V_T$, $V_N$) = (-155, 9, -6) km/s, $n_{COLD}$ = 0.74 $cm^{-3}$, $T_{COLD}$ = 53 eV, $n_{HOT}$ = 0.86 $cm^{-3}$, and $T_{HOT}$ = 389 eV.

Plasma fluid parameters are obtained by using a least squares fitting routine to find the density, velocity, and temperature, which, combined with the instrument response (see *Barnett* [1984] and *Barnett and Olbert* [1986]), best simulates the data. It is assumed that plasma distributions are convected isotropic Maxwellians and that both ion populations have the same bulk velocity.

## DATA AND RESULTS

Figure 1 shows the data and best fit to a set of *M* mode spectra in the dayside magnetosheath taken by the Voyager 2 PLS instrument about 69.5 Jovian radii ($R_J$) from Jupiter. The two-temperature character of the distribution is apparent in the data from the A, B, and C cups. The fit shown overlaying the data models the ion distribution using two proton components, a cold component with a density of 0.74 $cm^{-3}$ and a temperature of 53 eV, and a hot component with a density of 0.86 $cm^{-3}$ and a temperature of 389 eV. The simulated currents obtained using these fit parameters fit the data well in all four cups. This set of spectra has also been fit assuming that the lower-energy component is protons and the higher-energy component is alpha particles. In this case, good fits are again obtained in the A, B, and C cups with a proton density of 0.84 $cm^{-3}$ and a temperature of 57 eV, and an alpha density of 0.42 $cm^{-3}$ and temperature of 649 eV. The simulated currents in the D cup, however, are a factor of 2–3 lower than the observed currents. The ratio between the proton and alpha temperatures and densities are also much different than one would expect based on upstream solar wind parameters. In the solar wind, alpha particles make up 5–12 % of the total solar wind density, and the proton and alpha temperatures are usually within a factor of 2 (see Figures 3–6). Thus fitting the two magnetosheath components using protons and alphas would require that the percentage of alpha particles increase by a factor of 3 across the shock and that alphas be heated 5–8 times as much as the protons in the shock. This seems unreasonable based on our knowledge of earth's bow shock and magnetosheath, justifying the conclusion that both ion populations are predominately composed of protons. It is certain that an alpha population containing 5–10 % of the total ion density does underly the main proton population, but this should have a minimal effect on the results presented here. The assumption that ion distributions are isotropic is largely vindicated by the ability of the simulations to match the data in all four detectors, although the presence of a small degree of anisotropy cannot be ruled out.

Figure 2 shows the persistence of the two-temperature ion distributions throughout the Jovian and Saturnian magnetosheaths as sampled by both Voyagers 1 and 2. The spectra shown span the radial range from 48 to 86 $R_J$ and 62 to 97 $R_J$ for Voyagers 1 and 2, respectively, at Jupiter and cover the range from 19.4 to 26 $R_S$ at Saturn. The fits shown superimposed on the data in all cases assume both ion components are protons and are a result of obtaining the best fit in all four cups, although only one cup from each set of spectra is shown in the figure. Although there are variations in the shape of the of the spectra and the relative densities and temperatures of the cold and hot components, the characteristic two-temperature signature exists throughout all four Voyager passages through the dayside magnetosheaths of Jupiter and Saturn.

An ion distribution consisting of two Maxwellian proton populations has been used to simulate ion data and derive plasma fluid parameters throughout the dayside magnetosheaths of Jupiter and Saturn. At Jupiter, ion spectra from all the dayside Voyager magnetosheath crossings are used to derive plasma properties. The spectra obtained at Saturn are often contaminated by noise at high energies due to damage the PLS instrument suffered in the Jovian radiation belts. This, combined with the lower flux of ions due to Saturn's larger distance from the sun, lowers the signal-to-noise ratio in the spectra obtained, causing the spectra to be generally more difficult to analyze and the fit parameters obtained to be more uncertain. For this reason, less spectra have been analyzed at Saturn, and the magnetosheath regions encountered by Voyager

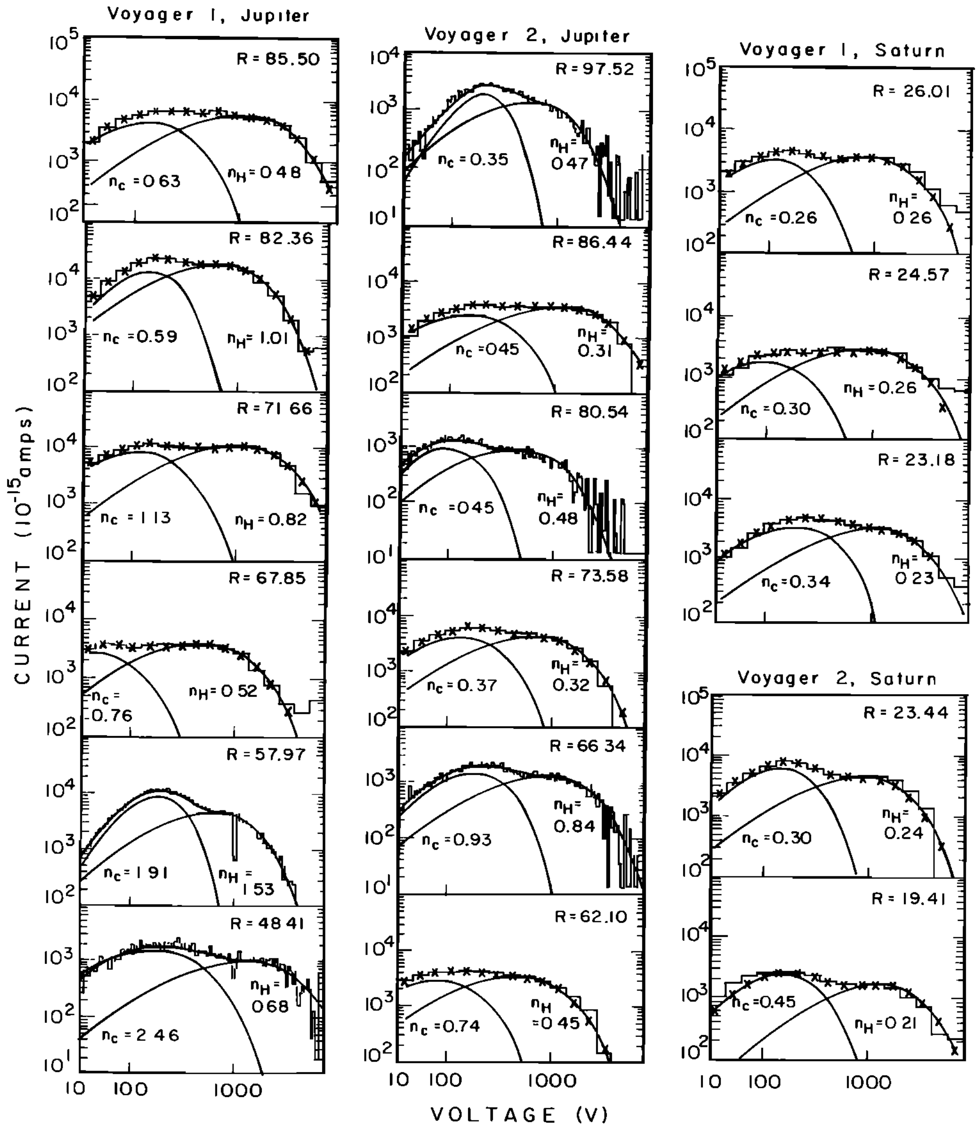


Fig. 2. Sample ion spectra spanning the magnetosheaths of Jupiter and Saturn during the Voyager encounters showing the persistent bimodal temperature structure. Also shown are the best fit to the data and hot and cold proton densities in units of $cm^{-3}$.

2 between 26.6 and 28.0 $R_S$ and between 29.0 and 31.6 $R_S$ have been not been included in this study because of particularly severe noise problems.

Figures 3–6 show plasma parameters from Voyagers 1 and 2 in the dayside magnetosheaths of Jupiter and Saturn and in the adjacent solar wind. The location of the spacecraft (solar wind, magnetosheath, or magnetosphere) is indicated on the figures, as are the locations of the magnetopause and bow shock crossings. When the spacecraft is in the solar wind, there are large radial velocities, low densities, and low temperatures. Magnetosheath regions have lower velocities and higher temperatures and densities. The densities in the outer magnetosphere are too low for plasma parameters to be obtained.

The top three panels of Figures 3–6 show the three components of the plasma bulk velocity in *RTN* coordinates, where *R* is radially outward from the sun, *T* completes a right-handed coordinate system defined by *R* and *N*, and *N* is perpendicular to the ecliptic and points northward. The fourth panel shows the total ion density. The fifth panel gives the percentage of the total density contained in the hot component if the spacecraft is in the sheath or the percentage of alpha particles present if the spacecraft is in the solar wind. The bottom panel gives the temperature of the two plasma components present; the hot and cold proton temperatures are given for the magnetosheath, and the proton and alpha particle temperatures are given for the solar wind. The top five panels use circles and triangles to indicate parameters obtained from *L* and *M* mode spectra, respectively. To avoid confusion, the temperature plot uses the same symbol for temperatures derived from *L* and *M* mode spectra. Depending on the location of the spacecraft, diamonds and crosses represent either the temperatures of protons and alphas in the solar wind or temperatures of the hot and cold proton populations in the magnetosheath. Sometimes the alpha peak in the solar wind outside Saturn's bow shock is overwhelmed by noise; in these cases, only the proton temperature and density are plotted. The formal 1-sigma errors from the fits to these parameters (see *Bevington* [1969]) are comparable to or less than the point size on the plots.

The radial velocity decreases by about a factor of 4 across the

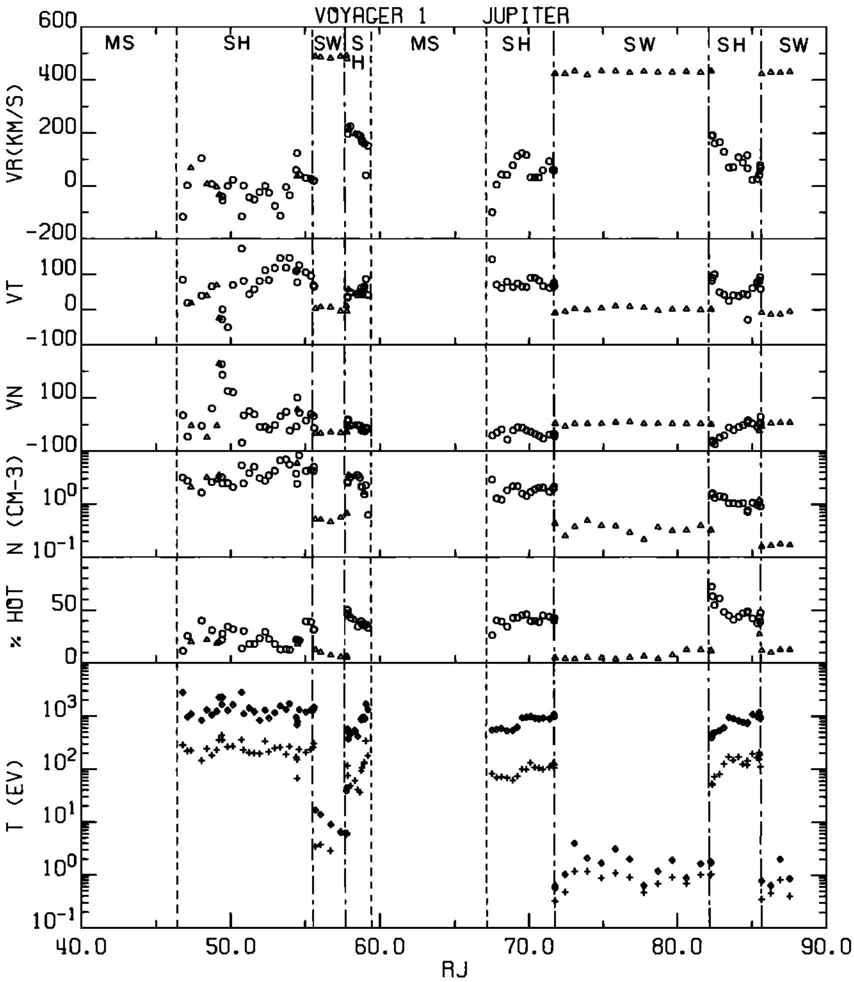


Fig. 3. Ion bulk velocity, total ion density, percentage of total density in the hot proton (magnetosheath) or alpha (solar wind) component, and temperatures of the two ion populations in the solar wind and Jovian magnetosheath during the Voyager 1 encounter. The bow shock and magnetopause locations are given by alternating long- and short-dashed lines and by short-dashed lines, respectively. The regions of solar wind (SW), magnetosheath (SH), and magnetospheric (MS) plasma are labeled at the top of the plot.

bow shock from the solar wind to the magnetosheath, as predicted by the Rankine-Hugoniot relations for a supercritical (magnetosonic Mach number ($M_{MS}$) > 3) shock (see Table 1 for shock parameters). The flow is diverted at the shock so as to flow around the magnetosphere, resulting in $V_T$ being predominately positive at Jupiter where the magnetosheath crossings occur in the morning sector and negative at Saturn where the magnetosheath crossings are in the afternoon sector. Normal velocities are generally small except close to magnetosheath boundaries since the spacecraft are generally close to the ecliptic plane. The exception is Voyager 1 at Saturn, which left the ecliptic to encounter Titan and observes southward magnetosheath flow.

The measured radial velocity in the magnetosheath results from a superposition of the velocity of the shocked solar wind flow and the velocity resulting from the movement of the bow shock and magnetopause due to changes in the solar wind pressure. Thus one expects the measured magnetosheath velocity to be lower when the magnetosphere is expanding (after crossings from the solar wind to the magnetosheath and before crossings from the magnetosheath to the magnetosphere) and higher when it is contracting (after crossings from the magnetosphere to the magnetosheath and before crossings from the magnetosheath to the solar wind). The spacecraft velocity is small compared to the expected speed of the boundaries [*Siscoe et al.*, 1980]. This effect is most apparent near the magnetosheath boundaries at Jupiter. The first Voyager 1 bow shock crossing at Jupiter at 85.6 $R_J$ occurred during an expansion phase, and radial velocities just inside the shock are near zero. This expansion reverses, and radial velocities approach 200 km/s before the shock is recrossed at 82.3 $R_J$. Similarly, the Voyager 1 radial velocities decrease before the magnetopause crossings at 46 and 67 $R_J$ and increase before the shock crossing into the solar wind at 58 $R_J$. The motion of the boundaries is fast enough that the flow reverses and becomes as high as 100 km/s sunward. The presence of sunward flow in the magnetosheath during the Voyager 1 passage through the magnetosheath was pointed out by *Siscoe et al.* [1980]; these results provide quantitative verification of their conclusions. The Voyager 2 radial velocities also show this effect, increasing before the shock crossing at 68.8 $R_J$ and decreasing when approaching the magnetopause crossing at 58 $R_J$. There is no obvious change in the spectra at the boundaries between inward and outward flow. The Voyager 2 spectra at 62.1 $R_J$ has an

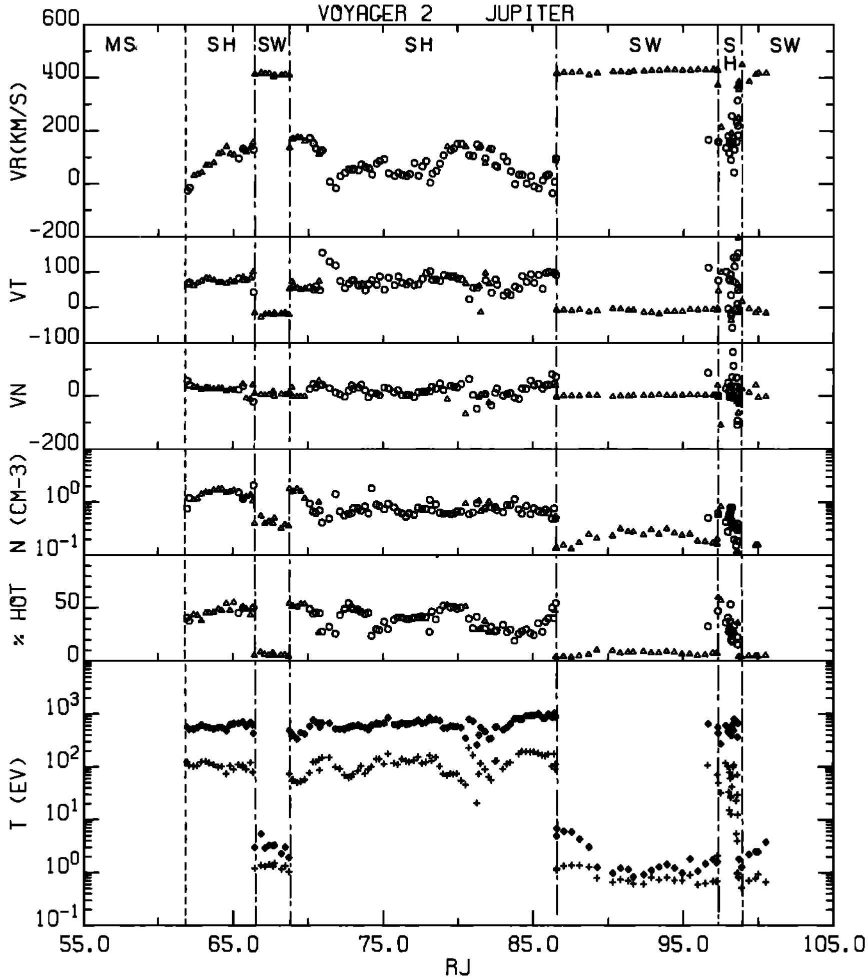


Fig. 4. Ion bulk velocity, total ion density, percentage of total density in the hot proton (magnetosheath) or alpha (solar wind) component, and temperatures of the two ion populations in the solar wind and Jovian magnetosheath during the Voyager 2 encounter. The bow shock and magnetopause locations are given by alternating long- and short-dashed lines and by short-dashed lines, respectively. The regions of solar wind (SW), magnetosheath (SH), and magnetospheric (MS) plasma are labeled at the top of the plot.

outward flow velocity of 15 km/s but is not markedly different in appearance from other spectra shown. At Jupiter where the magnetosheath may be encountered over a distance of up to 50 $R_J$ the radial velocities could be useful tools for monitoring solar wind pressure variations upstream if direct monitoring is not possible.

The densities increase by about a factor of 4 across the shock from the solar wind to the magnetosheath, also in accord with the Rankine-Hugoniot relations. The percentage of the density in the hot proton component varies between 20 and 50% for all four magnetosheath crossings. This compares to an alpha population which makes up 4–12% of the solar wind density. The temperature of the cold proton population in the magnetosheath varies from 50 to 400 eV, with a median temperature of about 100 eV. The temperature of the hot proton component varies from 400 to 2000 eV, with a median of about 800 eV. Thus the temperature of the hot protons is 6–10 times that of the cold protons, and the temperature profiles of each component track each other quite closely, maintaining a fairly constant temperature ratio. The percentage of ions in the hot component is anticorrelated with the temperature of both proton populations, an effect most clearly seen in the Voyager 2 Jupiter data but also present in the Voyager 1 Jupiter data. The total density is not correlated with either of these parameters. For comparison, the ratio of the alpha to proton temperature in the solar wind varies from 1.5 to 7, with a median of about 2.

## DISCUSSION

The preceding section demonstrated that observed ion distributions in the dayside magnetosheath of Jupiter and Saturn are well simulated by two Maxwellian proton distributions with comparable densities and temperatures of about 100 and 800 eV. The only similar distributions reported in the earth's magnetosheath occurred during a quiet time in the dawn magnetosheath when the magnetosheath flow was stable over many hours [*Petersen et al.*, 1979]. The two-temperature distributions may result from a type of shock interaction which is rare at earth but more common at Jupiter and Saturn. The shock crossing distance in planetary radii, the magnetosonic Mach number $M_{MS}$, and the ratio of thermal pressure to magnetic pressure (β) are shown in Table 1. All shocks crossed are quasi-perpendicular (the angle between the solar wind magnetic field and the shock normal is greater than 50). The

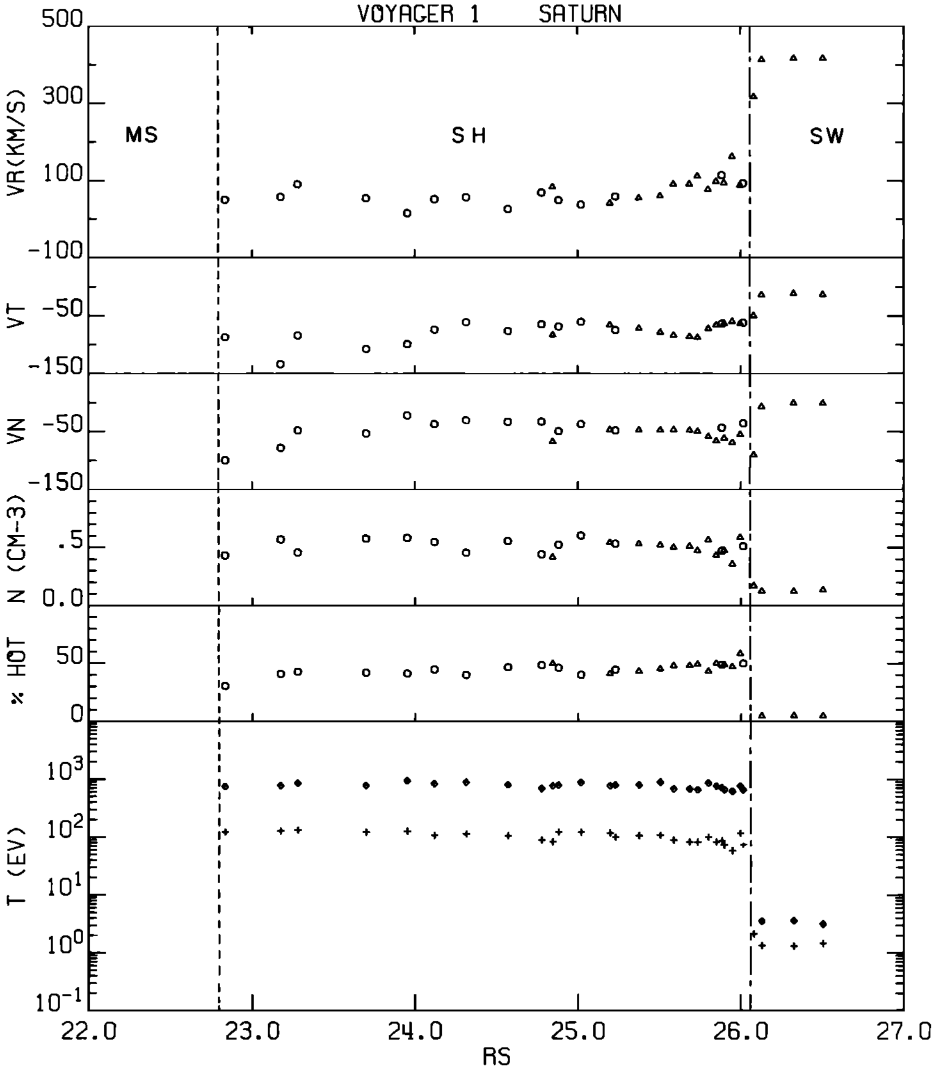


Fig. 5. Ion bulk velocity, total ion density, percentage of total density in the hot proton (magnetosheath) or alpha (solar wind) component, and temperatures of the two ion populations in the solar wind and Saturnian magnetosheath during the Voyager 1 encounter. The bow shock and magnetopause locations are given by alternating long- and short-dashed lines and by short-dashed lines, respectively. The regions of solar wind (SW), magnetosheath (SH), and magnetospheric (MS) plasma are labeled at the top of the plot.

solar wind M mode spectra immediately preceding (or succeeding) the shock crossing is used to determine the flow velocities, plasma densities, and ion temperatures used in calculating the parameters in Table 1. In calculating $M_{MS}$ the shock is assumed to be stationary; actual shock velocities may be as high as 100 km/s, so the actual values of $M_{MS}$ could differ from the tabulated values by up to 25%. The magnetic field used is the 96s average from the Voyager Magnetometer instrument covering the time period when the plasma data is measured. The solar wind electrons are often too cold for the Voyager instrument to measure at these distances, so the polytropic relation of *Sittler and Scudder* [1980] which is based on observations between 0.45 and 4.6 AU is used to estimate electron temperatures for use in computing these parameters. The shock parameters given here are rough estimates intended to indicate the wide range of shock parameters which result in two-temperature proton distributions. At the inbound bow shocks at Saturn for which good magnetosheath data is available the upstream $M_{MS}$ was 14.0 and 7.7 and $\beta$ was 1.4 and 0.54 for Voyagers 1 and 2, respectively. At Jupiter, values of $\beta$ in the solar wind near shock crossings range from 0.18–11, and $M_{MS}$ values range from 4–19. Thus all the shocks are super critical ($M_{MS} > 3$), and the data set covers the range from low to high $\beta$. The lower values of $\beta$ and $M_{MS}$ are in a range which is not

**Table 1. Upstream Magnetosonic Mach Numbers and Plasma β at the Jovian and Saturnian Bow Shocks**

| V1 Jupiter | | | V2 Jupiter | | | V1 Saturn | | | V2 Saturn | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $R_J$ | $M_{MS}$ | $\beta$ | $R_J$ | $M_{MS}$ | $\beta$ | $R_S$ | $M_{MS}$ | $\beta$ | $R_S$ | $M_{MS}$ | $\beta$ |
| 85.6 | 8.7 | 0.26 | 98.6 | 3.9 | 0.18 | 26.1 | 14.0 | 1.4 | 23.6 | 7.7 | 0.54 |
| 82.3 | 11.8 | 0.72 | 97.3 | 12.1 | 0.71 | | | | | | |
| 71.7 | 11.6 | 0.79 | 86.6 | 17.0 | 2.8 | | | | | | |
| 57.8 | 17.6 | 6.6 | 68.8 | 12.1 | 1.1 | | | | | | |

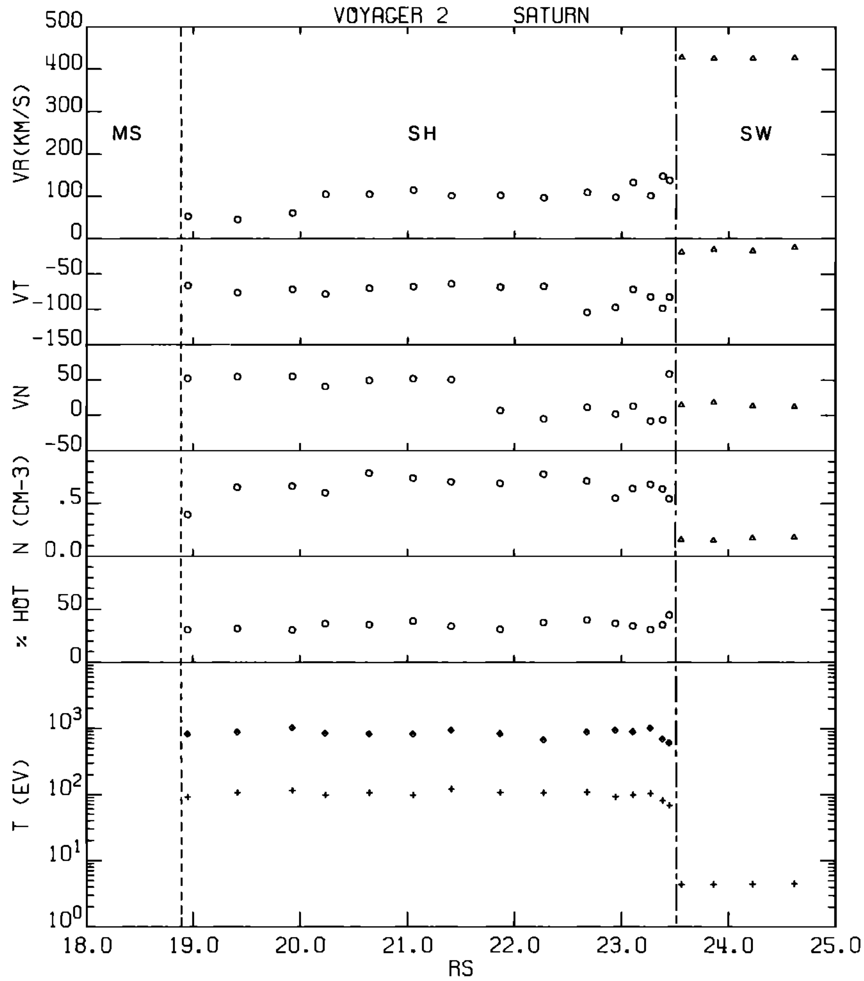


Fig. 6. Ion bulk velocity, total ion density, percentage of total density in the hot proton (magnetosheath) or alpha (solar wind) component, and temperatures of the two ion populations in the solar wind and Saturnian magnetosheath during the Voyager 2 encounter. The bow shock and magnetopause locations are given by alternating long- and short-dashed lines and by short-dashed lines, respectively. The regions of solar wind (SW), magnetosheath (SH), and magnetospheric (MS) plasma are labeled at the top of the plot.

uncommon at earth. Thus some other effect particular to Jupiter and Saturn must be responsible for producing these two-temperature proton distributions. This mechanism was apparently not operative at the time of the Pioneer encounters with Jupiter, when many of the proton distributions were single Maxwellians [*Mihalov et al.*, 1976].

We have looked for similar ion distributions in Uranus's dayside magnetosheath. They are not present. The $M_{MS}$ and $\beta$ values at the only dayside bow shock crossing at Uranus are about 15 and 3 [*Bagenal et al.*, 1986], similar to values at some of the Jovian and Saturnian shock crossings. Despite this similarity, most of the spectra obtained in the Uranian magnetosheath are fit fairly well by a single Maxwellian; some do have high-energy tails, but the persistent two-temperature distributions seen at Jupiter and Saturn are not seen (see *Bagenal et al.* [1986] for sample Uranian magnetosheath spectra).

The last point to consider is the evolution of these distributions as the magnetosheath plasma moves past the planet. This problem can be addressed by looking at distributions in the nightside magnetosheath. While it is difficult to map the plasma from the dayside to the magnetosheath, one can naively assume that magnetosheath plasma from near the subsolar point ends up close to the outbound magnetopause boundary. Spectra from the Voyager 1 and Voyager 2 outbound magnetosheath crossings at Jupiter and from the Voyager 1 outbound crossing at Saturn have been fit. It is difficult to determine if the two-temperature distribution is still present for several reasons. One is a noise problem; the PLS instrument suffered damage from its encounter with the Jovian radiation belts before passing through the magnetosheath outbound, causing a noise problem a higher energies. Another is that the observed ion distributions vary in time. Some are best fit with single proton Maxwellians, some with two proton Maxwellians, some with protons and alphas, and some cannot be simulated at all using Maxwellians. This could be the result of interactions with the magnetopause or of sampling plasma which has crossed the shock under different shock conditions (that is, a different shock normal angle for solar wind plasma entering at the sides of the magnetosphere). Thus it will take more analysis of outbound spectra to determine if the two-temperature distributions observed in the dayside magnetosheath persist to the tailward magnetosheath or if these distributions have time to relax to single Maxwellians.

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