VOL. 6, NO. 10 GEOPHYSICAL RESEARCH LETTERS OCTOBER 1979

STRUCTURE AND PROPERTIES OF JUPITER'S MAGNETOPLASMADISC

D. D. Barbosa, D. A. Gurnett, W. S. Kurth and F. L. Scarf

Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242
TRW Defense and Space Systems Group, One Space Park, Redondo Beach, California 90278

Abstract. Voyager 1 plasma wave observations have revealed the existence of an Earth-like continuum radiation trapped in Jupiter's magnetospheric cavity at frequencies below the solar wind plasma frequency. This radiation serves as an accurate diagnostic of the local electron number density throughout most of Jupiter's outer magnetosphere and yields information regarding the gross configuration of the magnetoplasmadisc as well as its kinematical properties. Using magnetic field observations, we are able to construct radial profiles of plasma pressure, density, and temperature from 20-80 R_J in the early morning plasma sheet along with plasma sheet crossings and estimated thicknesses. The study suggests that hot protons ($\sim$ 10 keV) are the dominant constituents of the plasma sheet ($\simeq$ 4.2 R_J average thickness) out to 80 R_J beyond which centrifugal effects take over and distort the sheet towards the rotational equator.

Introduction

It is now well established that a thin azimuthal current sheet exists in Jupiter's magnetic equatorial plane and is a dominant feature of the (as yet) observed Jovian magnetosphere [Smith et al., 1974, 1976; Ness et al., 1979]. Charged particle measurements record very large increases in energetic particle fluxes in the near vicinity of the sheet and provide strong support for the current sheet picture. One unresolved question, however, was the thermal composition of the plasma sheet and the identity and energy of the major current-producing species. Were heretofore measured particle fluxes with relatively high instrument thresholds in energy merely superthermal tracers of minimum $\vec{B}$ conditions in the current sheet or were they actually a measure of very hot plasma conditions in the sheet? Another nagging problem concerned centrifugal effects which were presumed to play the leading role in shaping the Jovian magnetosphere. But why then did Jupiter's main dipole magnetic equator organize the data so well with relatively few hints in the Pioneer 10/11 experiments of centrifugal effects coming into play? Previous efforts directed towards answering these questions have already been given by Goertz (1976), Walker et al. (1978), Van Allen (1979), and Goertz et al. (1979).

The Voyager Plasma Wave System (PWS) [Scarf and Gurnett, 1977] can shed light on these important questions having the capability to measure total electron number density thoughout most of the outer Jovian magnetosphere. The purpose of this letter is to report the results of a preliminary study of the early morning Jovian plasma sheet traversed by Voyager 1. Using the published results of the GSFC magnetometer [Ness et al., 1979], we are able to construct radial profiles of the characteristic plasma properties, pressure, density, and temperature, from 22 R_J - 80 R_J on the outbound leg together with estimated plasma sheet crossings and thicknesses, the former of which agree very well with both magnetometer [Ness et al., 1979] and plasma experiments [Bridge et al., 1979]. Our study indicates the possibility of at least three major plasma spatial regimes occuring with increasing radial distance: (1) a near-Jupiter inner magnetosphere dominated by the Jovian magnetic dipole, (2) an extensive magnetoplasmadisc resulting from hot proton diamagnetic effects, and (3) a cooler magnetoplasmadisc distorted significantly by centrifugal effects towards the rotational equator.

Observations

Figure 1 shows a 24-hour plot of wave measurements taken by the PWS spectrum analyzer on March 7, 1979. This example shows five identifiable plasma sheet crossings occuring at approximately 0236, 0924, 1240, 2008, and 2240 UT. The key to the identification is the existence of a quasi-steady broadband electromagnetic radiation above the local plasma frequency but below the solar wind plasma frequency which permeates much of the Jovian magnetosphere [Scarf et al., 1979]. This radiation has many characteristics similar to the Earth's continuum radiation [Gurnett, 1975] and provides a powerful diagnostic to outline the spatial profile of the plasma sheet, as indicated by the superimposed solid lines in Figure 1, over a large range of plasma frequency (electron density). A full analysis of the properties of this Jovian Continuum Radiation is forthcoming.

One may also notice the continuum extends down to ELF frequencies in the ultralow density regions ($<10^{-5}$ cm^{-3}) of the magnetodisc "lobes" when the spacecraft was at $\sim$ 200° System III (1965) longitude (λ_{III}). Although the spacecraft was at northern latitudes on this day we also see evidence for a low density 20° lobe at $\simeq$ 2130 UT and much more clearly at 1100 UT. Closer inspection reveals that the centroids of the 200° lobes appear to lag 200° by approximately one hour (36°). These lobes could very well correspond to regions of open magnetic field lines as suggested by the study of Goertz et al. (1976). The "gap" separating the lobes at the given frequency delineates the plasma sheet. However, a definite component of the continuum also exists at 3.11 kHz which shows only a slight modulation by the plasma sheet but is recorded at significant intensity throughout the day. The interpretation that the plasma sheet is transparent at this frequency while exhibiting a strong cutoff at the adjacent lower channel allows us to place a firm upper limit to the electron density for four of the five crossings shown. The crossing at 0236 UT indicates more variability at 3.11 kHz and we therefore extend the upper limit to 5.62 kHz for this crossing and estimate f_p as $\simeq$ 3.11 kHz.

Our analytic procedures then involve the following two classes of crossings: (1) firm upper and lower limits provided by neighboring channels which bracket the electron density to within a factor of $\simeq$ 3 (the second, third, and fourth crossings are of this type), and (2) firm upper and lower limits which bracket the electron density to within a factor of 10 but permit an estimate of the actual plasma frequency [the first (fifth) crossing suggests f_p is somewhat less than 3.11 kHz (greater than 1.78 kHz)].

Information regarding the thickness of the plasma sheet is also available. A meaningful measure would be FWHM of density but the finite channel separation restricts us to measuring a thickness somewhere between a half to a third maximum. The third crossing in Figure 1 gives an ideal gap at 1.78 kHz for which the penetration time ΔT is measured. The actual crossing is taken to be the midpoint of the gap for this case. To convert the penetration time to a sheet thickness we assume an equal plasma distribution above and below a sheet tilted 10° to the rotational equator and, neglecting spacecraft motion, employ zenographic coordinates of the spacecraft at the center crossing to determine the quantity z_0/R where z_0 is the sheet half-thickness for a given wave channel dropout and R is the spacecraft radial distance. If θ and λ are the sheet tilt angle and spacecraft latitude, respectively, the relation used is

Paper number 9L1224.
0094-8276/79/009L-1224$01.00

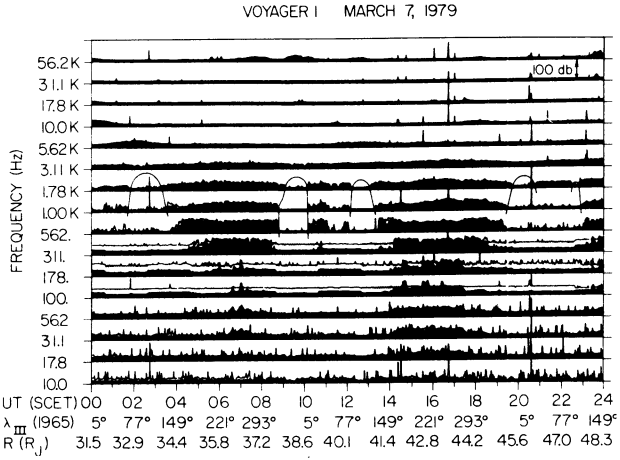

Fig. 1. Plasma wave observations during early morning outbound traversal of the Jovian magnetosphere from 31 R_J to 48 R_J. Plasma sheet penetrations are indicated as solid lines which show the continuum cutoff as a gap in the intensity time profiles.

$$\Delta\phi = \sin^{-1}(\cot\theta \tan\lambda + q) - \sin^{-1}(\cot\theta \tan\lambda - q) \qquad (1)$$

where

$$q = \frac{z_0/R}{\sin\theta\cos\lambda} \qquad (2)$$

$\Delta\phi = \Omega\Delta T$, and Ω is the rotation frequency of Jupiter. It is clear that in this simple computational model, the equatorial crossing does not occur at the midpoint of a gap but is offset by an amount $\Delta\Delta T$ towards earlier (later) times for a N-S(S-N) crossing [nonlinearity of $\sin^{-1}$ function]. However, for the greatest majority of the crossings the offset is calculated to be $\lesssim$ 10 min which is the maximum error maintained throughout.

Figure 2 presents a total of twenty plasma sheet crossings as determined from the Voyager PWS. We note that the first two crossings were actually determined not by continuum dropouts but by the presence of $(n + \frac{1}{2})$ odd half-harmonic electron plasma waves located at the Jovian magnetic equator [Scarf et al., 1979]. We have also indicated the approximate locations of minimum $|\vec{B}|$ and maximum J (10 - 5950 eV) electron fluxes taken from Ness et al. (1979) and Bridge et al. (1979). There is good agreement with both these experiments. Calculated plasma sheet thicknesses are also shown as solid vertical lines and the total length of the line gives the sheet thickness scaled to the radial distance abscissa. The average sheet thickness for twelve cases with well defined gaps is $\simeq$ 4.2 R_J. This is somewhat larger than that expected on theoretical grounds [Goertz, 1976]. We have no rigorous way of assessing our error in determining the sheet thicknesses. However, as can be seen from Figure 1, the gaps at 1.78 kHz were used for the first four crossings and since they are representative of the other eight cases, we are confident we are measuring sheet thickness somewhere between a half and third maximum of density. Voyager PWS also has wideband coverage from 50 Hz to 12 kHz at selected periods of the magnetosphere traversal. A later examination of this data may provide very precise determinations of f_p and FWHM if this mode is recording during plasma sheet penetrations.

Summary and Interpretation

The electron number density in hand, we are in a position to determine plasma temperature if the plasma pressure is known in the sheet. To obtain this quantity we use the magnetic field observations in Figure 2 of Ness et al. (1979) in the manner described by Walker et al. (1978). A smooth curve was drawn through the lobe values of $|\vec{B}|$ and the difference in magnetic energies was found at each minimum $|\vec{B}|$ crossing to give the plasma pressure in the sheet as

$$p = (B^2_{lobe} - B^2_{ps}) / 8\pi \qquad (3)$$

The results are plotted in Figure 3a of our summary figure. On March 8, the magnetic field increased anomalously and departed from the more usual slow decrease with increasing spacecraft distance [see Ness et al. (1979)]. We have separated out four crossings around this time from the averaging process and the remaining thirteen crossings can be seen to fit a power law very well. The electron density is plotted in Figure 3b. The shaded region corresponds to upper and lower limits and the single points are our best estimate of plasma frequency. A power law fit to the f_p estimates is shown also and we note that it falls in between and tracks nicely the limits which are the solid numbers and our major concern. Figure 3c presents our determination of the plasma temperature in the plasma sheet. The bounds on the temperature are determined by dividing density limits into the discrete points of (3a) and the smooth curve is the result of just dividing the power law fits. The relation used is

$$p = nkT \qquad (4)$$

Since n is the total electron density, we are measuring an average particle energy (effective temperature) such that

$$T \equiv \frac{1}{n} \sum_i n_i T_i \qquad (5)$$

and the sum is over a multi-component plasma with non-thermal features which may consist of cold protons (n_C), hot protons (n_H), plus etc. Since we have used values for the four anomalous (high B_{lobe}) crossings, the smooth curve falls outside of the limits at the points indicated by the three vertical arrows. If we use instead the values of the smooth curve in (3a) at these points, the power law curve for temperature then falls within "average" limits as indicated in (3c). This period in time may be indicative of local acceleration processes occurring in the magnetodisc, the possibility of which was suggested by Simpson and McKibben (1976) and by Schardt et al. (1978). The inferred plasma temperatures are quite compatible with those determined by Walker et al. (1978) as upper limits on T.

We may now draw conclusions regarding the nature of the Jovian magnetoplasmadisc. The discussion of Goertz (1976) is very useful here in organizing our conclusions. Since Van Allen (1979) has shown that energetic electrons give a minor contribu-

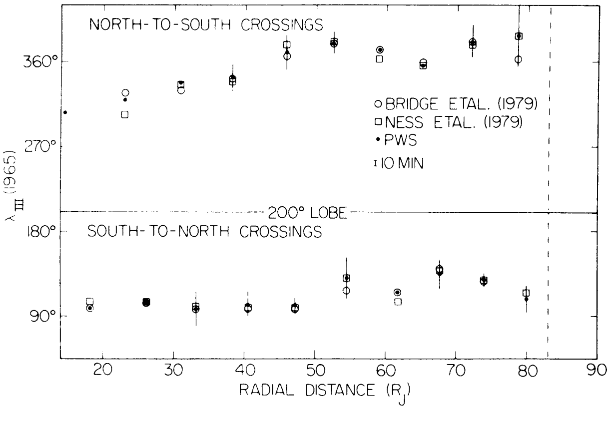

Fig. 2. Plasma sheet crossings (indicated by dots) are shown at λ_{III} (1965) longitude of occurrence. Estimated thicknesses are measured by the length of the solid line scaled to the radial distance abcissa. Beyond the dashed line no identifiable double sheet crossings were observed and the last point at 86 R_J is interpreted as a plasma sheet closest approach.

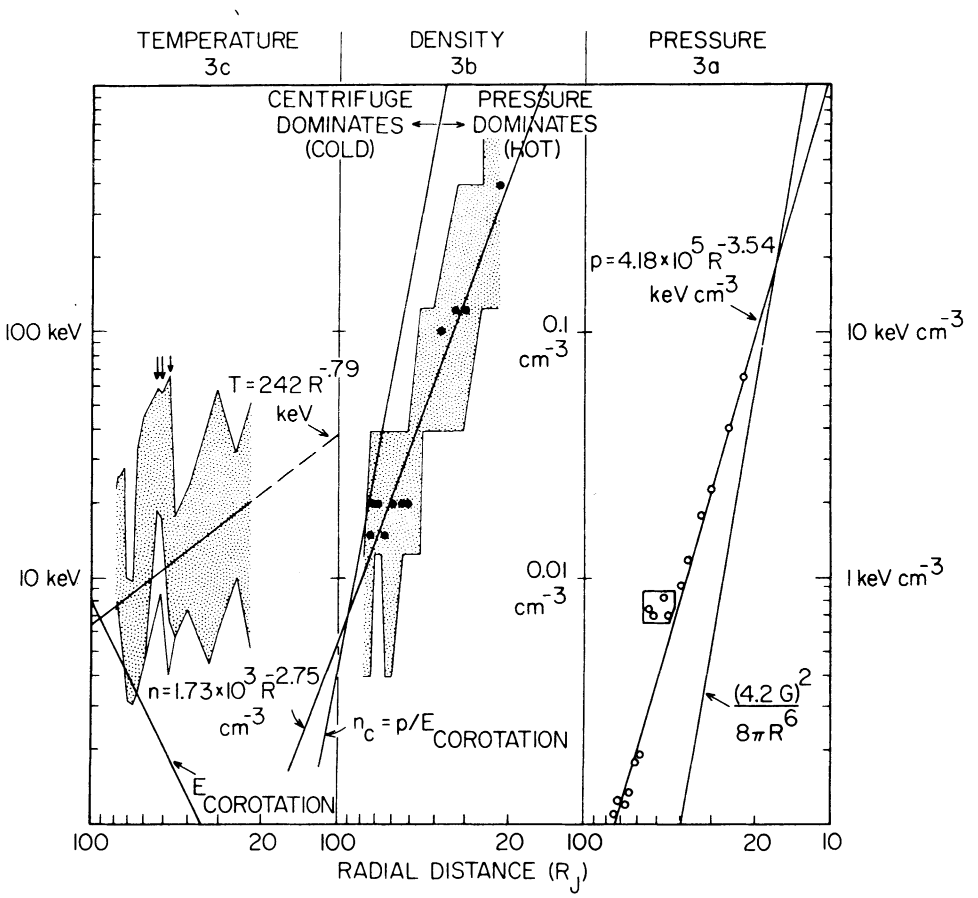

Fig. 3. Summary diagram of plasma sheet properties. (a) Pressure: obtained from Ness et al. (1979) magnetic field observations. (b) Density: upper and lower bounds on electron density as indicated by shaded region. Best estimates of actual density are indicated as dots to which the smooth curve was fitted. (c) Temperature: shaded region gives firm limits on plasma temperature and smooth curve is a best estimate.

tion to total plasma pressure, we focus on hot ions, in particular, hot protons. The proton corotation energy is plotted in (3c) and we note that the temperature falls significantly above $E_{Corotation}$ suggesting that centrifugal forces are of secondary importance for $R < 92$ R_J. In terms of number density we plot in (3b) the quantity $n_c = p/E_{Corotation}$. This serves as a criterion for hotness (coldness) in that for known plasma pressure, if the density falls below (above) n_c, plasma pressure (centrifugal effects) prevail. Goertz (1976) has argued that under these conditions of hot plasma the distortion of the current sheet away from the main dipole magnetic equator should be small. Double sheet crossings were in fact observed up to $\simeq$ 80 R_J. While the crossover occurs in (3b) at 92 R_J we note that at 80 R_J the ratio $n_c/n = 1.5$ is not extremely large. In view of the sensitivity of the crossover point to the steepness of the curves and the subjectiveness in estimating f_p, we believe our results are consistent with the picture that a transition occurs at 80-90 R_J beyond which centrifugal effects take over and the current sheet begins to deviate significantly away from the magnetic equator towards the rotational equator. Bridge et al. (1979) suggest that this point marks the transition to a tail-like configuration imposed by the solar wind. While solar wind impressed effects are likely to occur eventually, there may still be room for centrifugal warping to occur before this.

Finally in (3a) we have plotted the dipole magnetic energy density at the equator for a 4.2 G surface field. The crossover at $\simeq$ 17 R_J marks another transition from a surface dipole magnetically dominated plasma to a hot diamagnetic plasma regime which distends the magnetic field into a disc.

This study has suggested at least three magnetospheric regimes based on plasma energetics:

(1) $1 < R < 17$ R_J: inner magnetosphere dominated by Jupiter's main dipole
(2) $17 < R < 80$ R_J: hot magnetoplasmadisc with little deviation from main dipole magnet equator [Van Allen et al. (1974)]
(3) $80 < R <$?: cooler magnetoplasmadisc with significant centrifugal effects; e.g., warping towards the rotational equator [Smith et al. (1974)]

The above discussion raises some very interesting theoretical questions. The stability of a rapidly rotating magnetosphere has received a good deal of attention [e.g., Michel and Sturrock (1974)]; however, the consequences and implications of a hot tenuous magnetoplasmadisc have received little or no theoretical evaluation. Goertz (1976) has considered the possible effects of hot plasma, but Goertz et al. (1979) argue for $T/E_{Corotation} << 1$ throughout most of the < 100 R_J magnetosphere.

The trend for temperature to decrease slowly with increasing distance is notable. The possibility that, in fact, $T \sim R^{-1}$ is within the temperature limits in Figure 3c and may suggest that an adiabatic relationship, $T \sim |\vec{B}| \sim R^{-1}$, exists for hot protons diffusing outwards. A composition study of the plasma sheet to determine if solar wind abundances are absent can serve as a check on the direction of proton migration.

Since Bridge et al. (1979) report temperatures $\sim$ 50 eV in the vicinity of the Io (Ion) torus, the obvious question is where did this hot proton plasma come from? An energy dependent transport process which sifts out cold plasma could be present. However, the observations of field-aligned proton streaming in the middle magnetosphere [Sentman et al., 1975; 1978] may provide a clue to a possible strong ionosphere/magnetosphere interaction resulting in hot protons.

Of course, significant heavy ion concentrations have been detected in Jupiter's magnetosphere [Bridge et al., 1979; Krimigis et al., 1979] and the possibility that another species of ionic charge Ze and mass AM_p is dominant over protons must be considered. The effect would be to raise $E_{Corotation}$ by a factor A and raise T by a factor Z. The transition density n_c would be lowered by a factor Z/A. However, if either O^+ or S^{++} were dominant, inspection of Figure 3b indicates that the transition to the cold magnetoplasmadisc would occur at R $\sim$ 34 R_J. However, double sheet crossings were observed out to 80 R_J with well-spaced separations suggesting a rigid disc with $\simeq$ 10° tilt was still maintained [see Bridge et al. (1979) and Krimigis et al. (1979) for further discussion of this important point]. This fact, together with the hypothesis of hot protons which organizes our results neatly, which is consistent with Pioneer 10 observations, and which provides a quantitative explanation of the "80 R_J effect", leads us to suspect that hot protons ($\sim$ 10 keV) prevail as the dominant species over any competing ion by a factor at least as large as A/Z in number density in the magnetoplasmadisc. Should observations reveal that a heavy ion like S^{++} is dominant, then our results may be reconcilable with a bent disc model hinged at $\simeq$ 34 R_J and below Voyager 1 latitudes ($\simeq$ 5°) for distances greater than 80 R_J.

Our interpretations rely on the argument that hot plasma diamagnetic effects inhibit centrifugal warping in latitude [i.e. $\delta\theta \simeq 0$]. However, it is apparent in Figure 2 that azimuthal warping, $\delta\phi$, occurs as it did for Pioneer 10 outbound. Northrop et al. (1974) suggest that finite Alfvén wave propagation times from the Jovian surface to the plasmadisc can explain the systematic lag with increasing distance. Inasmuch as this effect does not explicitly depend on plasma temperature but only on mass density, we may expect this type of rotational effect to show up even in hot plasma. That being so, our measurements of plasma sheet density and thickness are in very good agreement with those inferred by Kivelson et al. (1978).

Acknowledgements. The research at the University of Iowa was supported by NASA through Contract 954013 with the Jet Propulsion Laboratory and through NASA Grant NGL-16-001-043. The research at TRW was supported by NASA through contract 954012 with the Jet Propulsion Laboratory.

References

Bridge, H. S., J. W. Belcher, A. J. Lazarus, J. D. Sullivan, R. L. McNutt, F. Bogenal, J. D. Scudder, E. C. Sittler, G. L. Siscoe, V. N. Vasyliunas, C. K. Goertz and C. M. Yeates, Plasma observations near Jupiter: Initial results from Voyager 1, *Science, 204,* 987, 1979.

Goertz, C. K., The current sheet in Jupiter's magnetosphere, *J. Geophys. Res., 81,* 3368, 1976.

Goertz, C. K., D. E. Jones, B. A. Randall, E. J. Smith and M. F. Thomsen, Evidence for open field lines in Jupiter's magnetosphere, *J. Geophys. Res., 81,* 3393, 1976.

Goertz, C. K., A. W. Schardt, J. A. Van Allen and J. L. Parish. Plasma in the Jovian current sheet, *Geophys. Res. Lett., 6,* 495, 1979.

Gurnett, D. A., The Earth as a radio source: The non-thermal continuum, *J. Geophys. Res., 80,* 2751, 1975.

Kivelson, M. G., P. J. Coleman, Jr., L. Froidevaux and R. L. Rosenberg, A time dependent model of the Jovian current sheet, *J. Geophys. Res., 83,* 4823, 1978.

Krimigis, S. M., T. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, G. Gloeckler, L. J. Lanzerotti, E. P. Keath, R. D. Zwickl, K. F. Carbary and D. C. Hamilton, Low-energy charged particle environment at Jupiter: A first look, *Science, 204,* 998, 1979.

Michel, F. C. and P. A. Sturrock, Centrifugal instability of the Jovian magnetosphere and its interaction with the solar wind, *Planet. Space Sci., 22,* 1501, 1974.

Ness, N. F., M. H. Acuna, R. P. Lepping, L. F. Burlaga, K. W. Behannon and F. N. Neubauer, Magnetic field studies at Jupiter by Voyager 1: Preliminary results, *Science, 204,* 982, 1979.

Northrop, T. G., C. K. Goertz and M. F. Thomsen, The magnetosphere of Jupiter as observed with Pioneer 10. 2. Nonrigid rotation of the magnetodisc, *J. Geophys. Res., 79,* 3579, 1974.

Scarf, F. L. and D. A. Gurnett, A plasma wave investigation for the Voyager mission, *Space Sci. Revs., 21,* 289, 1977.

Scarf, F. L., D. A. Gurnett and W. S. Kurth, Jupiter plasma wave observations: An initial Voyager 1 overview, *Science, 204,* 991, 1979.

Schardt, A. W., F. B. McDonald and J. H. Trainor, Acceleration of protons at 32 Jovian radii in the outer magnetosphere of Jupiter, *J. Geophys. Res., 83,* 1104, 1978.

Sentman, D. D., J. A. Van Allen and C. K. Goertz, Recirculation of energetic particles in Jupiter's magnetosphere, *Geophys. Res. Lett., 2,* 465, 1975.

Sentman, D. D., J. A. Van Allen and C. K. Goertz, Correction to "Recirculation of energetic particles in Jupiter's magnetosphere," *Geophys. Res. Lett., 5,* 621, 1978.

Simpson, J. A. and R. B. McKibben, Dynamics of the Jovian magnetosphere and energetic particle radiation, in *Jupiter,* ed. by T. Gehrels, Univ. of Arizona Press, Tucson, 1976.

Smith, E. J., L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, C. P. Sonett and A. M. A. Frandsen, The planetary magnetic field and magnetosphere of Jupiter: Pioneer 10, *J. Geophys. Res., 79,* 3501, 1974.

Smith, E. J., L. Davis, Jr. and D. E. Jones, Jupiter's magnetic field and magnetosphere, in *Jupiter,* ed. by T. Gehrels, Univ. of Arizona Press, Tucson, 1976.

Van Allen, J. A., Energetic electrons in Jupiter's dawn magnetodisc, *Geophys. Res. Lett., 6,* 309, 1979.

Van Allen, J. A., D. N. Baker, B. A. Randall, M. F. Thomsen, D. D. Sentman and H. R. Flindt, Energetic electrons in the magnetosphere of Jupiter, *Science, 184,* 309, 1974.

Walker, R. J., M. G. Kivelson and A. W. Schardt, High β plasma in the dynamic Jovian current sheet, *Geophys. Res. Lett., 5,* 799, 1978.

(Received July 25, 1979;
accepted August 23, 1979.)