INITIAL OBSERVATIONS OF PLASMA ELECTRONS FROM THE PIONEER 10 FLYBY OF JUPITER

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Abstract. Initial results are presented from the electron measurements made by the Ames Research Center Plasma Analyzer during the inbound passage of Pioneer 10 in the vicinity of Jupiter. The observations indicate that as in the case of the earth's magnetosheath, there is an increase in electron temperature across the Jovian bow shock. During the second extended magnetosheath traversal (~ 54 R_J to 46.5 R_J) the electron temperatures were generally higher than those observed during the first magnetosheath traversal (109 R_J to 96 R_J). These higher electron temperatures are in agreement with the measured higher magnitude of the magnetic field and ion density during this traversal. These observations are consistent with the contraction of the Jovian magnetosphere due to an increase in the solar wind dynamic pressure. In the outer Jovian magnetosphere the electron component of the thermal plasma was measured. These plasma electrons were associated with a peak in the electron counts at ~ 4 eV and do not seem to be associated with the periodic behavior observed for the energetic electrons. The dayside magnetosphere is inflated with a high beta (β ~ 1) plasma which in some respects is similar to that observed in the earth's magnetotail. The plasma electron measurements are consistent with a thick Jovian magnetosphere.

Introduction

On March 3, 1972 Pioneer 10 was successfully launched from earth on an interplanetary trajectory that was near the ecliptic plane, passing through the asteroid belt and then out beyond the orbit of Jupiter (at 5 a.u.). On December 4, 1973 Pioneer 10 arrived at its radius of closest approach to Jupiter at a distance of approximately 2.8 R_J (Jovicentric Jupiter radii). The Pioneer 10 spacecraft and trajectory details have been reported by Hall (1974).

Previously we reported (Wolfe et al., 1974a,b) that during the inbound portion of the Jovian flyby the Jovian magnetosheath was encountered for two extended time intervals: from 2031 UT (Ground Received Time) on November 26, 1973 to 2038 UT on November 27, 1973, corresponding to radial distances from Jupiter of 109 R_J and 96 R_J, respectively; and then from 0318 UT on December 1, 1973 to 1415 UT on December 1, 1973, corresponding to radial distances from Jupiter of 54 R_J and 46.5 R_J. In Wolfe et al., (1974b) we summarize the general features of the solar wind interaction with Jupiter. In this paper we summarize the plasma electron data obtained in the vicinity of Jupiter during the inbound portion of the flyby.

The thermal plasma is particularly important in the outer Jovian magnetosphere where it is evidently responsible for the large scale inflation of Jupiter's outer magnetic field as indicated by the large deviation from a dipole-like character as observed by Smith et al. (1974a). Based on these electron measurements and the magnetic field measurements (Smith et al., 1974a) and assuming thermal equilibrium between ions and electrons and a pressure balance across the magnetopause we inferred in Wolfe et al., (1974a) the existence of a high beta (β ~ 1) plasma in the outer magnetosphere.

The inbound electron data from the two extended magnetosheath traversals are also of interest since they are in general agreement with the description of the Jovian magnetosheath obtained from the ion data (Wolfe et al., 1974a,b). As in the case of the earth's bow shock there is heating of the solar wind electrons across the Jovian bow shock. The even higher electron temperatures observed during the second magnetosheath traversal are consistent with the general contraction of the Jovian magnetosphere due to the increase in the external solar wind dynamic pressure.

Magnetosheath Observations

The Ames Research Center Plasma Analyzer experiment on Pioneer 10 consists of dual, 90°, quadrispherical electrostatic analyzers, multiple charged particle detectors and attendant electronics (Wolfe et al., 1974a,b). This analyzer system is capable of determining the incident plasma distribution parameters over the energy range for ions from 100 - 18,000 eV and from approximately 1 - 500 eV for electrons. The plasma electrons are measured in fifteen logarithmically spaced energy steps with Detector B (Wolfe et al, 1974a,b). Depending on the particular operating mode of the instrument there is a 40 to 50 minute time interval between electron energy spectra during which plasma ion measurements are being made. The Detector B quadrispherical electrostatic analyzer system has five plate collectors, each having an associated electrometer amplifier. The entrance aperture of the plasma analyzer experiment is located on the Pioneer 10 spacecraft such that it views back toward the earth (and sun) through a wide slit in the back

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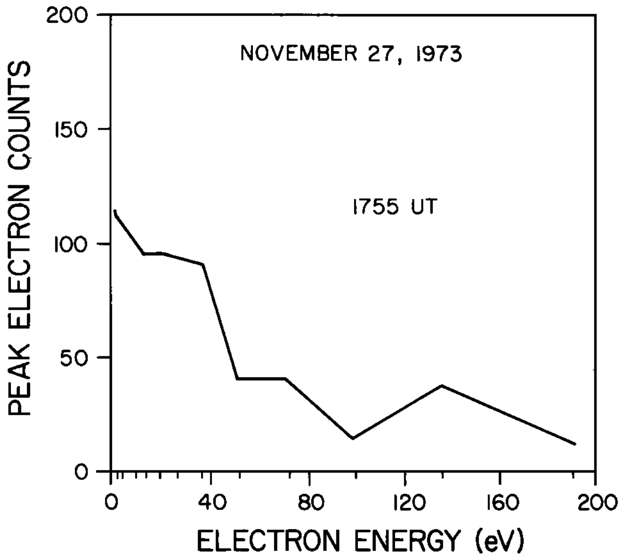

Figure 1. Electron spectrum taken in the Jovian magnetosheath during the first extended traversal by Pioneer 10. The vertical axis indicates the electron counts, the digitized output from the plasma analyzer per energy channel for the collector recording the peak (see text). Electron fluxes are digitized to nine bit accuracy (0 - 511) covering (logarithmically) the dynamic range from approximately 10^{-14} to 10^{-9} amperes cm^{-2}. The horizontal axis indicates the energy of the electrons in volts. The small vertical lines on the horizontal axis indicate the locations of the individual electron energy channels.

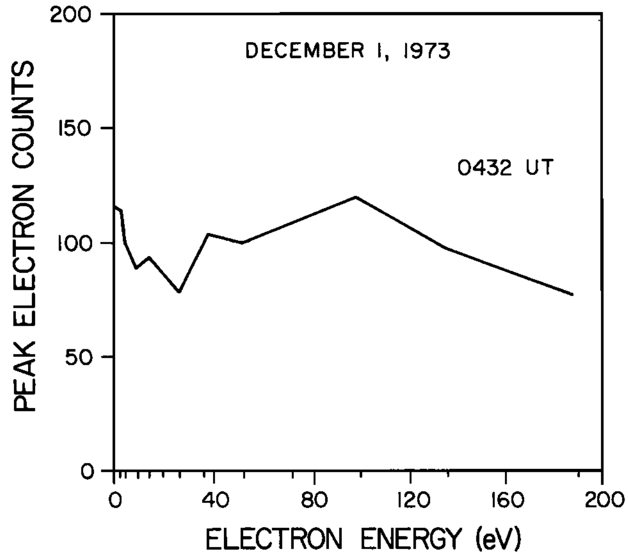

Figure 2. Electron spectrum taken during the second extended traversal of the Jovian magnetosheath.

of the spacecraft high gain antenna reflector. The entrance aperture normals are oriented parallel to the spacecraft spin axis, thereby enabling the detector to make a complete angular scan of the earthward hemisphere every half revolution of the spacecraft. The edges of the antenna reflector limit the field of view of the instrument to ± 73^{o} with respect to the spacecraft spin axis.

Figure 1 shows an example of a plasma electron spectrum obtained in the Jovian magnetosheath. Upstream of the Jovian bow shock, electrons were rarely observed above the instrument noise level. Although the plasma flow conditions in the Jovian magnetosheath were quite variable, the magnetosheath spectrum shown in Figure 1 is considered to be typical. Note that in this and subsequent spectra the electron counts are the digitized output from the plasma analyzer per energy channel for the collector recording the peak. For the electron measurements the electron fluxes are digitized to nine bit accuracy (0 - 511) covering (logarithmically) the dynamic range from approximately 10^{-14} to 10^{-9} amperes cm^{-2}. The electron "counts" are presented in each figure in this paper since a strict conversion of counts to flux using the instrument calibration and physical characteristics is not valid because of the changing unknown effects (as a function of energy and time) of the focusing of electrons due to the unknown spacecraft potential (as discussed below). In other words, it is not valid, for example to take the 15^{o} x 22.5^{o} field of view of the 2 cm^2 central collector and convert the counts to an omnidirectional flux since focusing due to spacecraft charge build-up can occur and give rise to an unknown changing increase in the field of view. The purpose of the figures in this paper is to indicate the change in the relative electron energy spectra. The important feature in the magnetosheath spectrum is the presence of the enhanced high energy tail of the spectrum between ~ 50 eV and 200 eV. The existence of this high energy tail in the magnetosheath electron spectrum indicates that there is heating of the solar wind electrons across the Jovian bow shock. It should be noted that if one assumes charge neutrality so that the electron number density increases across the shock by the same factor as the number density of the ions (Wolfe et al., 1974b) then if there had been no heating of the electrons across the shock the signal would still have been in the noise. This heating is similar to that observed for the ions across the Jovian bow shock (Wolfe et al., 1974b) and, of course, has been observed for the case of the earth's bow shock. As Pioneer 10 proceeded inbound the plasma ion data indicated that the spacecraft crossed the Jovian magnetopause at 96 R_J (Wolfe et al., 1974a,b) and entered the outer Jovian magnetosphere. The plasma electron observations in the outer magnetosphere are summarized later.

As previously reported (Wolfe et al., 1974a,b), the Ames Research Center Plasma Analyzer ion observations indicated that on December 1, 1973 the Pioneer 10 spacecraft reentered the Jovian magnetosheath at a radial distance of 54 R_J. The magnetosheath ion flow field persisted for approximately eleven hours and was abruptly terminated at a radial distance of 46.5 R_J. The December 1 magnetosheath plasma ion data and the magnetic field data (Smith et al., 1974b) are consistent with the second magnetosheath traversal being associated with a general contraction of the Jovian magnetosphere due to an increase in the external solar wind dynamic pressure (Wolfe et al., 1974b). Figure 2 shows a typical plasma electron spectrum obtained during this second inbound magnetosheath traversal. The greatly enhanced high energy tail in this spectrum indicates that the electron temperatures were significantly higher during the magnetosheath traversal on December 1, 1973 than during the earlier traversal. This increase in electron temperature during the December 1, 1973 magnetosheath traversal is qualitatively consistent with what one would expect for a contraction of the Jovian magnetosphere due to an increase in the solar wind dynamic pressure as has been observed for the case of the earth's bow shock (Spreiter and Alksne, 1969). Moreover, the electron temperature increase and the simultaneous changes in the plasma ions and the magnetic field during the second magnetosheath traversal all imply the importance of compressional effects due to an increase in the external solar wind dynamic pressure rather than a reorientation of a thin magnetodisk due to only a directional change in the solar wind. A quantitative analysis of the contraction of the magnetosphere must await more detailed knowledge of the topology of the Jovian magnetosphere which is impossible to ascertain based on only one flyby.

Magnetospheric Observations

At 2038 UT on November 27, 1973 Pioneer 10 crossed the Jovian magnetopause at a radial distance of 96 R_J and entered the outer Jovian magnetosphere, where the electron component of a thermal plasma was measured at an energy of a few eV. Figure 3 shows an example of an electron spectrum measured in the outer magnetosphere. This spectrum was obtained at ~ 96 R_J on November 27, 1973 after the first extended magnetosheath traversal. The peak evident here near 4 eV was consistently observed throughout the entire outer ($\gtrsim$ 15 R_J) Jovian magnetosphere. We cannot conclude the existence of a thermal plasma in the inner magnetosphere where the background due to energetic charged particles preclude their observation.

If one assumes that the magnetopause boundary is a tangential discontinuity then the pressure

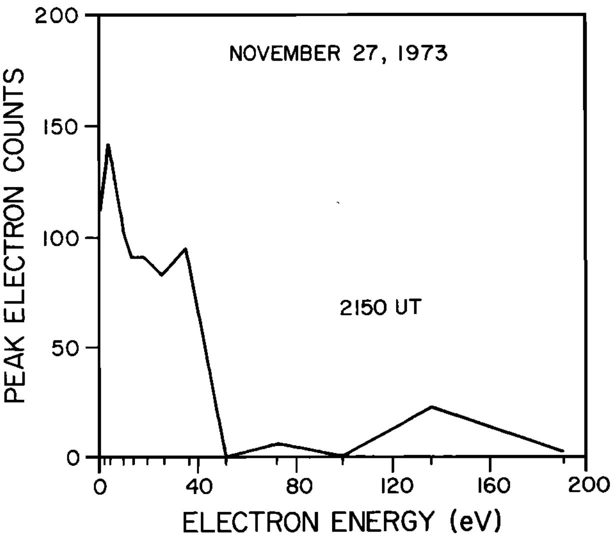

Figure 3. Electron spectrum taken in the outer Jovian magnetosphere.

balance across it can be calculated. For the inbound case the thermal component of the magnetospheric electrons was consistently observed near 4 eV and associated with a temperature of ~ 5 x 10^4 °K. Assuming T_e ~ T_i, the magnetic field values reported by Smith et al. (1974a) and the magnetosheath ion parameters (where they could be determined) reported by Wolfe et al. (1974b) imply that the dayside magnetosphere has a plasma beta near unity corresponding to a number density of a few particles cm^{-3}. It is cautioned that the above value of beta and the corresponding number density is considered to be an upper limit since the possible magnetospheric pressure contribution from the observed nonthermal plasma electrons and unobservable energetic electrons between 500 eV and ~ 50 keV have not been accounted for.

Summary

It is important to discuss the validity of the magnetospheric electron observations obtained during the Pioneer 10 Jupiter flyby. It is recognized that the measurement of low energy charged particles (of a few eV) is exceedingly difficult and subject to error primarily due to spacecraft potential effects. This is particularly true for the case of Jupiter's magnetosphere where the spacecraft is subjected to high intensities of energetic charged particles (Fillius and McIlwain, 1974; Simpson et al., 1974; Trainor et al., 1974a,b; Van Allen et al., 1974). In general, as is the case at earth, spacecraft charge build-up produces an unknown perturbing effect on these low energy electron measurements which is different for each spacecraft. At least in the outer portion of the Jovian magnetosphere, however, the consistency of the 4 eV electron peak argues in favor of the dominance of the spacecraft potential by the ambient thermal plasma and the photoelectrons since if the spacecraft potential were changing one would expect the 4 eV peak to be affected. Note that at 5 a.u. the flux of photoelectrons is below the instrument threshold. In the inner Jovian magnetosphere, however, where thermal electron measurements are obscured by high background, the possibility of spacecraft charge build-up cannot be excluded. It is argued, nevertheless, that large charge build-up probably did not occur since the effects to various spacecraft systems caused by arcing were not observed when the spacecraft passed into the Jovian shadow. This problem is complicated but one can speculate that if there had been a large charge build-up on the spacecraft before it entered the shadow of the planet then in the absence of the photoelectrons in the shadow arcing might have occurred if there were no thermal plasma present to neutralize the charge build-up. In the presence of a thermal plasma, however, the spacecraft is hit frequently by thermal plasma particles (of both positive and negative charge) and, therefore, the tendency for charge build-up is reduced. Thus, this may imply the existence of a thermal plasma in the inner Jovian magnetosphere. It is also tantalizing to speculate that the origin of the thermal plasma observed in the outer Jovian magnetosphere is likely to be the inner magnetosphere and perhaps the Jovian ionosphere.

The observations of the electron component of the thermal plasma and the inferred ion component are consistent with this thermal plasma being the primary controlling factor causing the inflation of Jupiter's outer magnetosphere. It is interesting to note that the Pioneer 10 observations made in the daylight hemisphere for Jupiter's magnetosphere are more reminiscent of the case in the earth's magnetotail. That is, in the outer ($\gtrsim$ 15 R_J) Jovian dayside hemisphere the magnetic field lines are stretched out away from the planet (Smith et al., 1974a) and there is a high beta plasma so that in this respect it is similar to the earth's magnetotail (Wolfe and Intriligator, 1970). It is also important to recognize that these thermal electrons were observed everywhere in the outer Jovian magnetosphere and not simply confined to the disc-like configuration observed for the energetic (> 1 MeV) electrons (Fillius and McIlwain, 1974; Simpson et al., 1974; Trainor et al., 1974a,b; Van Allen et al., 1974). The energetic electrons observed in the outer magnetosphere appear to be modulated by the planet's period of rotation (Fillius and McIlwain, 1974, Simpson et al., 1974; Trainor et al., 1974a,b; Van Allen et al., 1974). Trainor et al.,(1974b) reported, however, that the ~ 10 hour periodicity in the outer magnetosphere was not nearly as significant for the lower energy electrons (< 1 MeV) or for the protons. Since the plasma electrons do not seem to be associated with the periodic behavior observed for the energetic (> 1 MeV) electrons this supports arguments in favor of a thick magnetosphere as opposed to a "magnetodisk" implied by observations of the energetic electrons alone.

The thick magnetosphere, the large inflation of the magnetosphere, and the increase in the electron temperatures observed throughout the second magnetosheath traversal all imply the importance of compressional effects and the ease with which Jupiter's magnetosphere responds to relatively minor changes in the solar wind dynamic pressure.

The origin and dynamics of the more energetic plasma electrons are not understood. It is not clear whether these observations are consistent with local acceleration, radial diffusion, temporal effects of dynamic changes in the entire magnetosphere (e.g., its moving in and out), or possibly loss from the inner magnetosphere. Further analysis of the Pioneer 10 data and comparisons with the data obtained during the Pioneer 11 flyby of Jupiter in December 1974 may shed some light on these questions.

Finally, the electrons observed in the Jovian magnetosheath are completely consistent with the ion observations of a high Alfvén Mach number bow shock and magnetosheath flow field. These observations are strikingly similar to observations of the solar wind interaction with the earth and only differ in terms of the scale size of the interaction.

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References

Fillius, R. W., and C. E. McIlwain, Radiation belts of Jupiter, Science, 183, 314, 1974.

Hall, Charles F., Pioneer 10, Science, 183, 301, 1974.

Smith, E. J., L. Davis, Jr., D. E. Jones, D. S. Colburn, P. J. Coleman, Jr., P. Dyal, and C. P. Sonett, Magnetic field of Jupiter and its interaction with the solar wind, Science, 183, 305, 1974a.

Smith, E. J., L. Davis, Jr., D. E. Jones, D. S. Colburn, P. J. Coleman, Jr., 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, 1974b.

Simpson, J. A., D. Hamilton, G. Lentz, R. B. McKibben, A. Mogro-Campero, M. Perkins, K. R. Pyle, A. J. Tuzzolino, and J. J. O'Gallagher, Protons and electrons in Jupiter's magnetic field: Results from the University of Chicago experiment on Pioneer 10, Science, 183, 306, 1974.

Spreiter, J. R., and A. Y. Alksne, Plasma flow around the magnetosphere, in Magnetospheric Physics, edited by Donald J. Williams and Gilbert D. Mead, p. 11, American Geophysical Union, Washington, D.C. 1969.

Trainor, J. H., B. J. Teegarden, D. E. Stilwell, F. B. McDonald, E. C. Roelof, and W. R. Webber, Energetic particle population in the Jovian magnetosphere: A preliminary note, Science, 183, 311, 1974a.

Trainor, J. H., F. B. McDonald, J. H. Teegarden, W. R. Webber, and E. C. Roelof, Energetic particles in the Jovian magnetosphere, J. Geophys. Res., 79, 3600, 1974b.

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, 183, 309, 1974.

Wolfe, John H., and Devrie S. Intriligator, The solar wind interaction with the geomagnetic field, Space Sci. Rev., 10, 511, 1970.

Wolfe, John H., H. R. Collard, J. D. Mihalov, and D. S. Intriligator, Preliminary Pioneer 10 encounter results from the Ames Research Center plasma analyzer experiment, Science, 183, 303, 1974a.

Wolfe, J. H., J. D. Mihalov. H. R. Collard, D. D. McKibbin, L. A. Frank, and D. S. Intriligator, Pioneer 10 observations of the solar wind interaction with Jupiter, J. Geophys. Res., 79, 3489, 1974b.

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