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# OBSERVATION OF AURORAL SECONDARY ELECTRONS IN THE JOVIAN MAGNETOSPHERE

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*Abstract.* Localized enhancements in the flux of suprathermal electrons were observed by the Voyager 1 Plasma Science instrument near the outer boundary of the Io plasma torus between $L$ ~7.5 and $L$ ~10. This localization, which occurs within the general region of hot electrons noted by Sittler and Strobel (1987), and the spectral characteristics of the observed electrons are consistent with secondary (backscattered) electron production by intense Jovian auroral energetic particle precipitation and support the hypothesis that such electrons may contribute to the processes that heat the plasma in this region of the magnetosphere.

## Introduction

Secondary electrons (sometimes called backscattered electrons) produced during the precipitation of energetic particles into the Jovian atmosphere, have sufficient energy ($E > 10$ eV) to overcome the planet's gravitational potential. Thorne (1981) has suggested that a significant fraction of those secondaries produced above the altitude where collisions are important can flow into the magnetosphere, carrying with them cool ionospheric ions (mainly $H^+$). The presence of upflowing protons and H atoms has recently been inferred from Doppler shifted Lyman α emission in Jupiter's auroral region (Clarke et al., 1989). This ambipolar outflow should constitute an important magnetospheric plasma source over a range of $L$-shells associated with the Jovian auroral zone. Since the region of auroral particle precipitation is localized (Gehrels and Stone, 1983; Thorne, 1983), one expects a similar localization of secondary electrons. The Voyager 1 Plasma Science (PLS) electron data (presented by Scudder et al., 1981 and Sittler and Strobel, 1987) do indeed exhibit very localized enhancements in the fluxes of suprathermal electrons (extending to above ~1 keV) around the time the spacecraft crossed the auroral L-shells. Sittler and Strobel (1989) noted that the secondary electrons hypothesized by Thorne (1981) constitute one possible source for hot electrons within the torus; they also showed that, regardless of the production mechanism, the observed suprathermal electrons must be generated locally, as Coulomb collisions with the cold electrons present will thermalize them in a few days. No direct measurements of the associated thermal protons exist in this region due to the high fluxes of heavy ions originating from Io; however, in the middle magnetosphere ($12 < L < 40$) the low energy proton component varies between ~15% and ~40% (in number density).

## Plasma Measurements

Plate 1 shows data obtained on the day of closest approach to Jupiter, March 5, 1979. The color spectrograms are from 2 of the 4 sensors on the Voyager 1 PLS instrument. There is a wealth of information available from the PLS experiment during this time, but before we can extract the real variations in plasma conditions we must consider some instrumental issues. The C-sensor only measures positive ions and points toward the Earth throughout this time period. The D-sensor, mounted almost perpendicular to the C-sensor on the spacecraft, makes both electron and ion measurements. Gray areas in the L mode spectra indicate saturation due to high plasma densities in the Io torus (Bagenal (1985). It must be kept in mind that because the ions are trans-sonic the measured ion fluxes are very dependent on the orientation of the sensors with respect to the plasma flow. Conversely, since the electrons are highly subsonic the measured electron fluxes should, to first approximation, be independent of the orientation of the D-sensor. Nonetheless, there are second order couplings between the electron and ion measurements (Vasyliunas, 1971; Sitter and Strobel, 1987; McNutt, 1988). These effects have made analysis of the data obtained in this region particularly difficult.

With these caveats in mind, consider the major features of the PLS data shown in Plate 1. On the inbound pass, the dense torus stands out as the region of high ion fluxes between 0600 and 0930 SCET. The absence of thermal electrons and hot ions between 0930 and 1500 SCET corresponds to the cold inner torus region (Bagenal, 1985). The major inbound/outbound asymmetry of the ions results from the orientation of the PLS sensors with respect to the flow of corotating ions. On the inbound passage the

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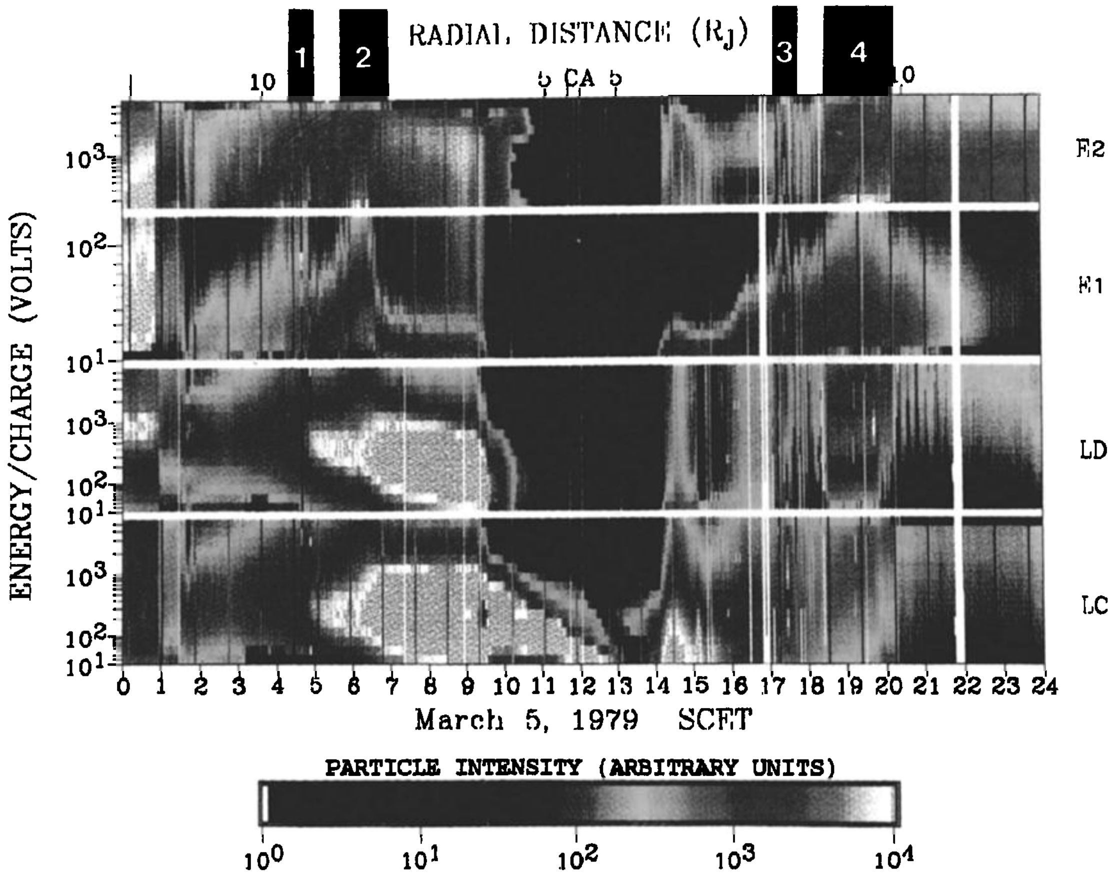

Plate 1. Color spectrograms of PLS ion and electron data from the Voyager 1 encounter with Jupiter from March 5 (day 64), 1979. Numbered arrows indicate the four events referred to in the text. The four panels (bottom to top) show data from (a) the L mode (low resolution in energy-per-charge) in the C-sensor; (b) the L mode D-sensor; (c) the E1 mode and (d) the E2 mode. The L mode measures positive ions and the E1 and E2 modes measure low energy (10 eV to 140 eV) and high energy (140 eV to 5.95 keV) electrons, respectively. Note that the four different particle intensities (LC, LD, E1, E2) are displayed with different color scales. There was a gain change in the L, E1 and E2 modes around 0100 Spacecraft Event Time (SCET).

corotating plasma initially flowed into the D-sensor and then, as the spacecraft orientation changed, moved into the C-sensor near closest approach (1204 SCET). On the outbound passage, the flow was no longer directly into any of the sensors; the spacecraft roll orientation was changed 3 times (between 1522 and 1527, between 1824 and 1835 and between 1940 and 2002 SCET) such that between 1835 and 1940 SCET the D-sensor was pointed ~40° away from corotational flow. This latter period appears as a region of larger positive ion flux in the D cup. Except for this period the component of corotational flow into all sensors was negative after ~1700 SCET. As expected, the low energy electron fluxes (E1) are symmetric about closest approach (CA). The suprathermal electrons (E2), however, suggest a marked asymmetry with significantly lower fluxes on the outbound passage through the torus (compare 0700-0900 and 1530-1700 SCET). This asymmetry was pointed out by Sittler and Strobel (1987).

In this paper we wish to concentrate on the relative enhancements in electron fluxes in both E1 and E2 modes which occurred as 4 separate events: (1) 0430-0500 SCET; (2) 0550-0635 SCET; (3) 1715-1740 SCET and (4) 1830-2010 SCET. We note that the enhancements (2) and (3) occur just outside the outer boundary of the torus, at the "plasma ramp" (Siscoe et al., 1981) which is between L~7 and L~8. Since event (2) shows the clearest signature we shall describe the changes in electron measurements that we regard as indications of secondary electrons for that event. Detailed examination of the PLS electron E1 spectra around 0505 through 0545 SCET indicate that the electrons have mean energies of ~15 eV as well as a suprathermal tail extending to ~150eV. At greater energies, the electron signals (in E2) are contaminated substantially by high fluxes of hot ions into the sensor. The apparent sharp drop in signal in the top channel of E2 results from secondary electrons produced *in the D-sensor* by these hot ions (see Appendix of Sittler and Strobel, 1987). The electron spectra (as presented in Sittler and Strobel, 1987) exhibited a marked change near 0550 SCET: the E1 spectra show anomalous currents in the lowest two channels which indicate an increase in temperature of the thermal component (to ~20 eV to 30 eV). The E2 spectra indicate fluxes of ~1 keV electrons sufficient to rise above the ion feedthrough signals. The presence of electrons at ~6 keV can be inferred by the higher flux levels in the top channel of the E2 mode. The sharp transition at 0635 SCET is readily apparent in the E1 spectrogram in Plate 1. The transition is characterized by a drop in electron temperature (in E1) and a disappearance of the suprathermals (in E2). Much of the E2 currents in the torus (~0700-1000 SCET) are due to ion contamination (see also Sittler and Strobel, 1987).

A second region of enhanced fluxes of suprathermal electrons can clearly be seen between ~1830 and 2015 SCET (event 4) when Voyager 1 was outbound from Jupiter. Although this event is complicated by the changes in spacecraft attitude we conclude that there was a significant enhancement of suprathermal electrons between ~1830 and 2010 SCET, but the identification of the exact time that the fluxes first increased remains a problem.

The signature of enhanced fluxes of suprathermal electrons is repeated, albeit less clearly, in the narrower events (1) and (3). The corresponding magnetic $L$-shells for these events were taken from the magnetic field model of Acuña et al. (1983) which includes an equatorial current sheet. The radial distances to the magnetic equator of the field lines crossed by Voyager 1 at the times of these events are given in Table 1. When the 2 events for each passage are combined they are found to span almost exactly the same L-shell range. Nevertheless, it remains a puzzle why this L-shell range is split into 2 events rather than just a single signature and, furthermore, why they are not symmetric inbound and outbound.

It is interesting to note that measurements of fluxes of electrons with the Low Energy Charged Particle (LECP) experiment on Voyager of ~100 keV (Krimigis et al., 1988) indicate distinct, narrow enhancements coinciding with events (1), (2) and (4). While Horanyi et al. (1988) state "the secondary electron distribution is weighted toward lower energies", it is clearly important to ascertain if signatures of secondary electrons extend above the PLS 6 keV threshold.

## Energetic Particle Precipitation

Voyager 1 was not instrumented to measure energetic particles within the loss cone; even the trapped populations were not measured over the energy range near a few keV where auroral input is expected to be dominant (e.g., Thorne, 1983; Waite et al., 1983). There is, consequently, no direct information on the auroral precipitation flux. The latter has been inferred indirectly from the estimated location and spectral characteristics of the auroral emissions in Jupiter's atmosphere (Metzger et al., 1983; Herbert et al., 1987; Waite et al., 1988) and from the observed decrease in ion phase space density of energetic ions trapped in the magnetosphere (e.g., Thorne, 1982; Cheng et al., 1983; Gehrels and Stone, 1983).

TABLE 1. L-SHELLS

| | INBOUND | OUTBOUND |
|---|---|---|
| $\lambda_{III}$ | 109°-131° | 60°-107° |
| PLS Electrons: | (1) 9.15-9.75 | (4) 8.62-9.71 |
| | (2) 7.63-8.30 | (3) 7.70-8.00 |
| Events combined: | 7.63-9.75 | 7.70-9.71 |
| UVS Aurora[1] | 8-12 | L<6 |
| CRS Ion Losses | 8-10 | |

[1] Herbert et al. (1987)

By scanning Jupiter's north polar region, the Voyager Ultraviolet Spectrometer indicated the auroral emissions to be confined to an oval region. However, the oval region is not aligned with the contours of magnetic L-shell from the magnetic field model of Acuña et al. (1983). This lack of agreement indicates either an unlikely strong dependence of L-shell of the precipitating particles with longitude (ranging from $L \approx 4$ at $\lambda_{III} \approx 330°$ to $L \approx 15$ at $\lambda_{III} \approx 150°$) (Herbert et al., 1987), or, more probably, problems with extrapolating the measured field to the surface of the planet (Connerney, 1981).

Gehrels and Stone (1983) have analyzed the distribution of energetic ($> 70$ MeV $\mathrm{nuc}^{-1}\ \mathrm{G}^{-1}$) oxygen and sulphur ions observed by the Voyager 1 CRS instrument and concluded that the peak auroral input at these energies occurs in the region $8 \leq L \leq 10$. Their measurements would, however, have to be extrapolated to much lower energies in order to account for the required auroral power dissipation. Cheng et al. (1983) have independently used data from the LECP experiment on Voyager to determine ion loss rates from a solution of the radial diffusion equation. They conclude that these lower energy ions (20 MeV/G $< \mu <$100 MeV/G assuming a proton composition) showed strong diffusive losses down to an $L$ value as low as 5.9. Since their technique becomes insensitive to loss at larger $L$ values, strong losses at $L \geq 8$ would also be consistent with the data (see their Fig. 3). We are therefore left with tantalizing evidence of ion loss near the region where the localized enhancements in suprathermal electrons is observed.

## Conclusions

We have reconsidered the origin of the pronounced localized enhancements in suprathermal electrons in the inner Jovian magnetosphere in the region $7.5 \leq L \leq 10$. As noted (by Sittler and Strobel (1987), for example) two theoretical models have been advanced to explain the presence of hot electrons in this region. The first is localized heating of ambient electrons by intense LHR emissions excited by ion pickup in the hot torus (Barbosa et al., 1985). Electrons heated by this mechanism should be preferentially observed in the inner portion of the torus near Io's orbit. In addition, we have found (McNutt, 1988) that the apparent tracking of the electron and hot ion fluxes in this region (including events 1, 2 and 4) is strongly biased by instrumental effects. The second model, advocated here, is that the suprathermal electrons in this region are secondary (backscattered) electrons produced by precipitating particles in the Jovian auroral zone. While no truly definitive conclusion can be drawn, we contend here that a strong body of circumstantial evidence is mounting which points to the latter model being dominant.

Specifically, (1) the locale of these events ($7.5 \leq L \leq 10$) spans the range where intense EUV auroral emissions have been observed; (2) the flux of trapped energetic ions measured on Voyager 1 by both the LECP (Cheng et al., 1983) and CRS (Geherls and Stone, 1983) experiments exhibit a sharp drop off which has been linked to precipitation loss at locations close to the suprathermal electron enhancements; (3) the energy spectra of the suprathermal electrons exhibit enhancements over the energy range (10 eV to a few keV) anticipated for auroral secondaries (Thorne et al., 1981; Horanyi et al., 1988).

While Horanyi et al. (1988) have modelled the production of secondary electrons created by ion precipitation in Jupiter's upper atmosphere, further work is needed to determine the characteristics of electrons that reach the equatorial regions of the auroral field lines. In addition to consideration of the ambipolar interaction between the escaping secondary electrons and ionospheric protons, the measured secondary electrons must have been scattered in pitchangle between leaving the ionosphere and reaching the Voyager spacecraft since the field of view of the PLS electron sensor does not include the direction parallel to the local magnetic field.

Until the Galileo spacecraft provides further evidence of the particles that are responsible for the auroral emissions, the hope for resolving the complex puzzle of the Jovian aurora lies in comparison of the limited Voyager data set with multi-spectral observations

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## References

Acuña, M. H., *et al.*, Jupiter's magnetic field and magnetosphere, Chap. 1 in *Physics of the Jovian Magnetosphere*, ed. A. J. Dessler, Cambridge University Press, New York, 1983.

Bagenal, F., Plasma conditions inside Io's orbit: Voyager measurements, *J. Geophys. Res.*, *90*, 311-324, 1985.

Barbosa, D. D., *et al.*, Voyager observations of lower hybrid noise in the Io plasma torus and anomalous plasma heating rates, *Astrophys. J.*, *289*, 392-408, 1985.

Belcher, J. W., The low-energy plasma in the Jovian magnetosphere, Chap. 3 in *Physics of the Jovian Magnetosphere*, ed. A. J. Dessler, Cambridge University Press, New York, 1983.

Cheng, A. F., *et al.*, M. T. Paonessa, and T. P. Armstrong, Energetic ion losses near Io's orbit, *J. Geophys. Res.*, *88*, 3936-3944, 1983.

Clarke, J. T., *et al.*, Doppler shifted H Ly α emission from Jupiter's aurora, *Geophys. Res. Lett.*, *16*, 587-590, 1989.

Connerney, J. E. P., The magnetic field of Jupiter: A generalized inverse approach, *J. Geophys. Res.*, *86*, 7679, 1981.

Gehrels, N., and E. C. Stone, Energetic oxygen and sulphur ions in the Jovian magnetosphere and their contribution to auroral excitation, *J. Geophys. Res.*, *88*, 5537, 1983.

Gurnett, D. A., and F. L. Scarf, Plasma waves in the Jovian magnetosphere, Chap. 8 in *Physics of the Jovian Magnetosphere*, ed. A. J. Dessler, Cambridge University Press, New York, 1983.

Herbert, F., *et al.*, Observations of the Jovian UV aurora by Voyager, *J. Geophys. Res.*, *92*, 3141, 1987.

Horanyi, M., *et al.*, The precipitation of energetic heavy ions into the upper atmosphere of Jupiter, *J. Geophys. Res.*, *93*, 7251, 1988.

Krimigis, S. M., *et al.*, Comparison of outer planets' magnetospheres with Earth's: Similarities and differences, *Third Neil Brice Memorial Symposium on the Magnetospheres of the Outer Planets (Abstracts)*, Katlenberg-Lindau, FRG, 1988.

McNutt, R. L., Jr., Net current measurements and secondary electron emission characteristics of the Voyager plasma science experiment and their impact on data interpretation, M. I. T. Center for Space Research *Technical Report CSR-TR-88-6*, Cambridge, MA, 1988.

McNutt, R. L., Jr., *et al.*, Positive ion observations in the middle magnetosphere of Jupiter, *J. Geophys. Res.*, *86*, 8319–8342, 1981.

Scudder, J. D., *et al.*, A survey of the plasma electron environment of Jupiter: a view from Voyager, *J. Geophys. Res.*, *86*, 8319, 1981.

Siscoe, G. L., *et al.*, Ring current impoundment of the Io plasma torus, *J. Geophys. Res.*, *86*, 8480, 1981.

Sittler, E. C., and D. F. Strobel, Io plasma torus electrons: Voyager 1, *J. Geophys. Res.*, *92*, 5741, 1987.

Thorne, R. M., Jovian auroral secondary electrons and their influence on the Io plasma torus, *Geophys. Res. Lett.*, *8*, 509-512, 1981.

Thorne, R. M., Injection and loss mechanisms for energetic ions in the inner Jovian magnetosphere, *J. Geophys. Res.*, *87*, 8105-8110, 1982.

Thorne, R. M., Microscopic plasma processes in the Jovian magnetosphere, Chap. 12 in *Physics of the Jovian Magnetosphere*, ed. A. J. Dessler, Cambridge University Press, New York, 1983.

Vasyliunas, V. M., Deep space plasma measurements, *Methods of Experimental Physics*, *9B*, 49-88, 1971.

Waite, J.H., *et al.*, Electron precipitation and related aeronomy of the Jovian thermosphere and ionosphere, *J. Geophys. Res.*, *88*, 6143, 1983.

Waite, J.H., *et al.*, The Jovian aurora:Electron or ion precipitation? *J. Geophys. Res.*, *93*, 7244, 1988.

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