Observations of reflected ions and plasma turbulence for satellite potentials greater than the ion ram energy

K.H. Wright, Jr.,[1] N.H. Stone,[2] J. Sorensen,[1] J.D. Winningham[3], and C. Gurgiolo[4]

Abstract. During the TSS-1R mission, the behavior of the ions flowing from the forward hemisphere of the Tethered Satellite System (TSS) satellite was examined as the potential on the satellite was changed from below to above 5 V. The ram energy of the ambient atomic oxygen ions is ~5 eV. For satellite potentials <5 V, no ions were observed on the ram side of the satellite. When the satellite potential was raised >5 V, ions were observed to be flowing from the forward region of the satellite. In the region sampled, the ion flux was a few percent of the ambient with energies of ~5 eV. The temperature of the outflowing ions was observed to be enhanced, relative to the ambient ionosphere. The net current to the probe package became much more noisy for satellite potentials >5 V as compared with satellite potentials <5 V, indicating a more disturbed plasma environment.

1. Introduction

The deployment of a tethered satellite upward from the Orbiter results in a positive bias on the satellite which attracts electrons from the ionospheric plasma. During the latter part of the satellite deployment, various operations of the TSS were performed which allowed the satellite to charge from very low voltages to >1 kV. In this paper, observations of ions in the vicinity of the satellite as it was charged to low voltages will be reported. Emphasis will be placed on ion measurements obtained upstream from the satellite.

Various theoretical treatments of current collection by charged bodies in space plasmas have neglected the motion of the body through the plasma [e.g., *Parker and Murphy*, 1967]. The TSS experiment has motivated researchers to explicitly consider the relative motion between a body and its environmental space plasma [e.g., *Singh and Vashi*, 1990]. During the first flight of the TSS in 1992, the satellite was deployed only a short distance, was not allowed to spin, and only charged once to a potential >5 V. A 5 V potential is significant from the fact that the ram energy of ionospheric atomic oxygen (O^+), the dominant ion at the TSS altitude, is ~5 eV. Only marginal results were obtained as to mechanisms and limits of current collection during that first mission. However, the reflight of TSS in February 1996 provided an opportunity to examine the plasma behavior as a function of spin phase at both the surface of the satellite and one body radius away from its surface as satellite potential transitioned through the critical 5 V value.

[1] CSPAR, UAH, Huntsville, AL 35899
(e-mail: wrightk@cspar.uah.edu)
[2] ES83, NASA/MSFC, Huntsville, AL 35812
(e-mail: nobie.stone@msfc.nasa.gov)
[3] Space Instr. Division, SwRI, San Antonio, TX 78228
(e-mail: david@dews1.space.swri.edu)
[4] Bitterroot Basic Research Inc., Hamilton, MT 59840
(e-mail: chrisg@cybernet1.com)

Paper number 97GL02999.
0094-8534/98/97GL-02999$05.00

2. Experiment Description

The Research on Orbital Plasma Electrodynamic (ROPE) experiment contained sensors to measure the charged particle environment surrounding the satellite. These sensors were mounted on both the satellite surface and at the end of a 0.8 m fixed boom. Figure 1 shows mounting locations for the Soft Particle Energy Spectrometers (SPES) and for the Differential Ion Flux Probe (DIFP). Details of the two types of sensors are found in *Stone et al.* [1994].

The ion data presented in this paper were obtained from the DIFP and SPES-1. The DIFP detects ions by sweeping a 5° window ±60° with respect to its aperture normal in the plane containing the satellite equator (see Fig. 1(b)). Its field of view perpendicular to the satellite equatorial plane is ±45°. SPES-1 is highly collimated, having a geometric factor of only 1.24×10^{-7} cm^2 str, and uses a channel electron multiplier for amplification. Both the DIFP and SPES-1 instrument normals lie in the satellite equatorial plane. The two detectors are complimentary, as the SPES-1 is very sensitive but has a narrow field of view while the DIFP has a wide field of view but is not as sensitive as SPES-1.

The DIFP and SPES-1 are part of the Boom Mounted Sensor Package (BMSP) mounted on the end of the fixed boom (see Fig. 1(a)). The BMSP can be independently, negatively biased with respect to the satellite in order to place its surface at the local floating potential. This was accomplished by measuring the net current to the BMSP surface and then biasing the package so as to null out the current. Updates of the BMSP current and voltage occurred once every 64 ms. The range of the BMSP current monitor is from −60 to 190 μA and the range of BMSP voltage bias relative to the satellite is from 0 to −500 V. The BMSP current monitor can be used as a coarse indication of the presence and nature of disturbances in the local plasma.

When activated during deployment, the satellite attitude control system maintained the spin rate at approximately 0.25 rpm. The spin direction is indicated in Figure 1(b). In this paper, 0° spin phase is defined as when the BMSP is directly upstream from the satellite. The pitch and roll variations experienced amounted to only a few degrees and will be ignored for the first order analysis presented here. DIFP data are reported every 1.024 s, which result in a sample every 1.5° to 2° of spin phase. SPES data are reported every 2.048 s.

3. Case 1 Data: Satellite Potential < 5 V

Several cases exist for the spinning satellite at voltages <5 V. The case for which the satellite potential approaches most closely to but remained, <5 V is shown in Figure 2. DIFP

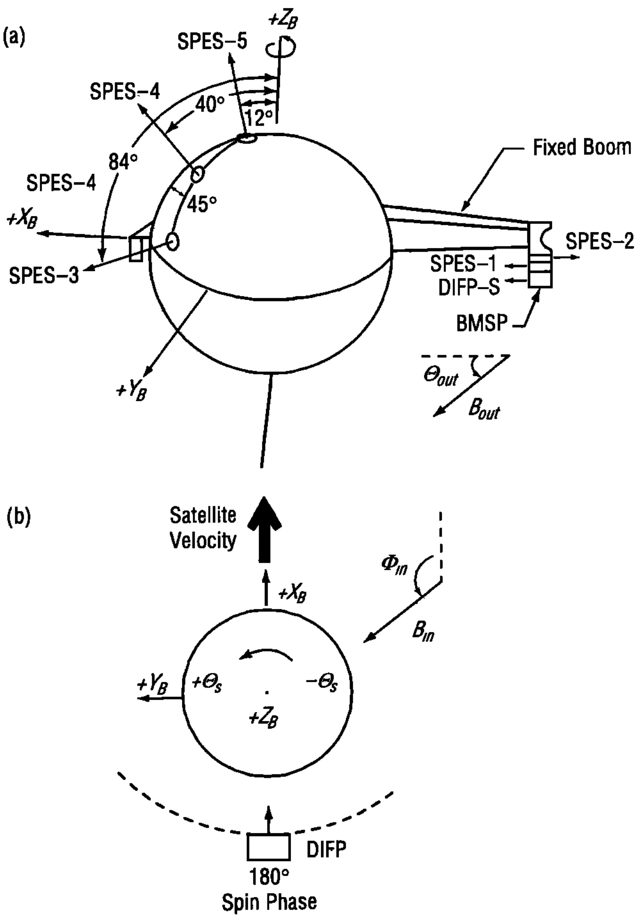

Figure 1. (a) Mounting arrangement for the ROPE experiment. The geomagnetic field orientation perpendicular to the satellite equatorial plane is given by B_{out} , Θ_{out}. (b) Top view of the satellite as it rotates counterclockwise looking down along the tether. The + symbol indicates the region of positive spin phase angles (0°–180°) while the – symbol indicates the region of negative angles. The orientation of the geomagnetic field in the spin plane is denoted by B_{in}, Φ_{in}.

ion flux, DIFP ion energy, DIFP ion temperature, BMSP bias voltage relative to the satellite, and BMSP current are shown in panels (a)–(e), respectively. The time period for this case is 1996/56/23:51:55–23:55:45 UT. The BMSP voltage can be interpreted as the charging level of the satellite. However, the SPES-2 ram ion signature and the SPES-1 and -2 electron data indicate that the BMSP is 1 to 1.5 V positive with respect to the local plasma. The satellite potential is, therefore, 1 to 1.5 V higher than the magnitude of the value shown in Figure 2(d). The BMSP current represents the net current collected by the surface with positive current values, indicating net electron collection.

The orientation of the geomagnetic field during this time period had a component in the satellite equatorial plane of about Φ_{in} = 144° and a component perpendicular to the equatorial plane of about Θ_{out} = 41° (see Fig. 1). The magnitude of the geomagnetic field was ~0.32 gauss. The tether current, as measured by the satellite ammeter, was ~57 mA and was basically constant throughout the charging event. The ambient plasma density was in the range 5–7×10^5 cm^{-3} as determined by the combined data sets from ROPE and the Research on Electrodynamic Tether Effects (RETE) experiment (J.P. Lebreton, private communication).

The main point to emphasize about Figure 2(a) is not where the ions exist, but rather where they do *not* exist. For the region of spin phase, Θ_s , covering the forward hemisphere(/Θ_s / <80°), no ions are observed by the DIFP or by the more sensitive SPES-1. Trace amounts of ions are observed by the DIFP near the ±90° positions, indicating some deflection (or reflection) of the ambient ion distribution by the positive potential in the sheath. The variation of the ion parameters in the satellite wake region will be discussed elsewhere. The observed energies, taking into account the local BMSP sheath, are consistent with the 5 eV ram energy for O^+ ions. It is expected that some small fraction of the O^+ ram distribution would be reflected at satellite potentials in the range of 3–4 V, but the lack of observation indicates the amount is below the detection threshold (1×10^9 #/cm^2 • s for the DIFP) and/or the ions are out of the instruments' field of view. Variations of the

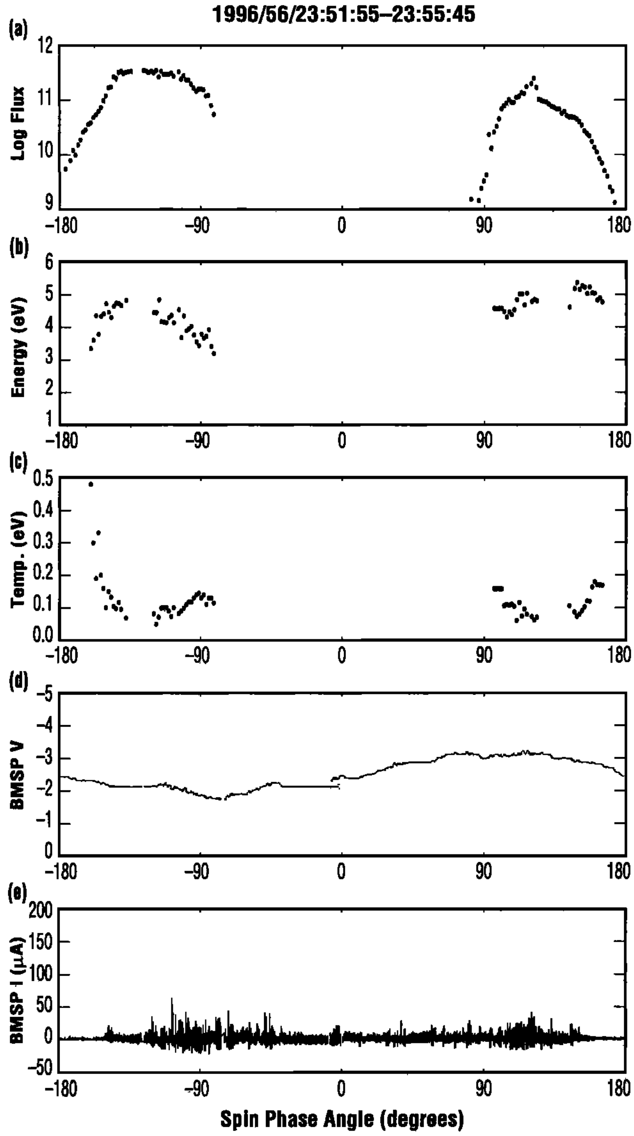

Figure 2. Measurements for 1996/56/23:51:55–23:55:45 UT. (a) Log of DIFP ion flux (#/cm^2 s); (b) DIFP ion energy; (c) DIFP ion temperature; (d) BMSP bias voltage with respect to the satellite, and; (e) BMSP net current. Positive current indicates net electron collection.

measured ion energy with spin phase can be caused by variations in the voltage of the BMSP with respect to the local plasma and/or the existence of a velocity component perpendicular to the satellite spin plane (the DIFP measurement plane).

In the forward hemisphere, the BMSP current exhibits only very small amplitude oscillations. Slightly larger amplitude oscillations appear at the $/\Theta_s/$~100° position. This angular location is in the general region of the wake boundary which can be expected to have oscillatory motions. This finding on its own is significant to wake studies.

4. Case 2 Data: Satellite Potential >5 V

As it turns out, only one case exists where the satellite potential was in the 5 to 10 V range and the spin phase coverage

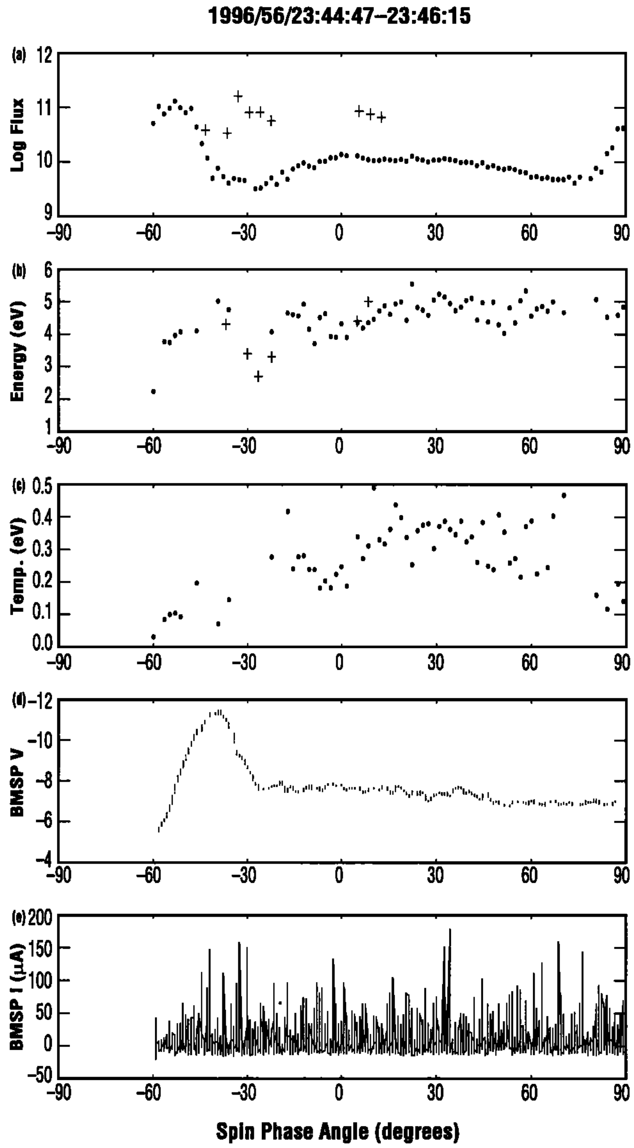

Figure 3. Measurements for 1996/56/23:44:47–23:46:15 UT. (a) Log of DIFP ion flux (#/cm^2 s) indicated by '•' and log of 100×SPES-1 number flux (#/cm^2 s str) indicated by '+'; (b) ion energy from DIFP (•) and SPES-1 (+); (c) DIFP ion temperature; (d) BMSP bias voltage with respect to the satellite, and; (e) BMSP net current.

of the BMSP passed through the ram hemisphere. Data for this case, presented in Figure 3, was obtained during the time 1996/56/23:44:47–23:46:15 UT. Ion flux from both DIFP and SPES-1, ion energy from both DIFP and SPES-1, ion temperature from the DIFP, BMSP bias voltage relative to the satellite, and BMSP current are shown in panels (a)–(e), respectively. The satellite was charged as it rotated from $\Theta_s = -61°$ to $\Theta_s = 141°$. The plots shown in Figure 3 are truncated at $\Theta_s = 90°$. The wake region contains data for both the charged and uncharged case but is not germane to the discussion here.

The orientation of the geomagnetic field during this time period, Φ_{in}=127° and Θ_{out}=48°, and its magnitude, 0.36 gauss, are similar to the previous case. The tether current was ~51 mA and was again basically constant throughout the charging event. The ambient plasma density was about 3.5×10^5 cm^{-3}.

Unlike Case 1, ions are observed to be outflowing throughout the forward hemisphere during Case 2. For the first order analysis presented here, the variation of the BMSP voltage with spin phase for $-60° < \Theta_s < -30°$ will not be discussed. For spin phase $\Theta_s > -30°$, the BMSP voltage indicates a constant satellite potential while the electron data from SPES-1 and -2 indicate that the BMSP was again 1 to 1.5 V positive with respect to the local plasma. The DIFP ion flux is observed to be fairly constant throughout the ram hemisphere, changing at most by a factor of 2, while SPES-1 only detects ions over a more limited region due to its highly collimated aperture. The SPES-1 ion number flux data, multiplied by a factor of 100 for display in Figure 3(a), consist of only a few sweeps where statistically significant counts were obtained. The value plotted in Figure 3(a) was derived by integrating the differential number flux over the range 0.5 to 10 eV. The measured energies, including the local BMSP sheath, are consistent with 5 eV.

The observed ion flux is in the range of 2%–4% of the ambient O$^+$ flux. This appears too low, since for an 8-V positive satellite, all of the ionospheric O$^+$ ions should be reflected. Note, however, that even with the rotation of the DIFP about the satellite, measurements were made in a very limited region of the forward hemisphere (i.e., only in the equatorial plane). The low ion flux observed implies that the reflected ions may have substantial velocity components normal to the satellite equatorial plane.

The temperature of the outflowing ions exhibits a surprising behavior. Temperatures are greater than ambient over most of the ram region, reaching a maximum of approximately 5 times ambient at a spin phase of 32°. (The ambient ion temperature is 0.08 to 0.09 eV.) This places the temperature maximum in a plane containing the center of the satellite and the normal to the geomagnetic field. Ion temperature is determined by the energy analysis section of the DIFP, which is a standard planar RPA. Very good fits of the data were obtained using the equation of *Whipple* [1959], which assumed a Maxwellian distribution. Whether this apparent temperature enhancement represents a real heating or shows how a thermal distribution of ions scatters from a positive potential structure is under study.

The current collected by the BMSP in Case 2 has considerably larger amplitude oscillations than in Case 1. Figure 4 shows the results from applying an FFT to the BMSP current over the range $-60° < \Theta_s < 90°$ for each case. Recall that the sample time for the BMSP current is once every 64 ms, which gives a Nyquist frequency of 8 Hz. In Figure 4(a), two peaks are seen in the 2–4 Hz range. This represents a beating in the

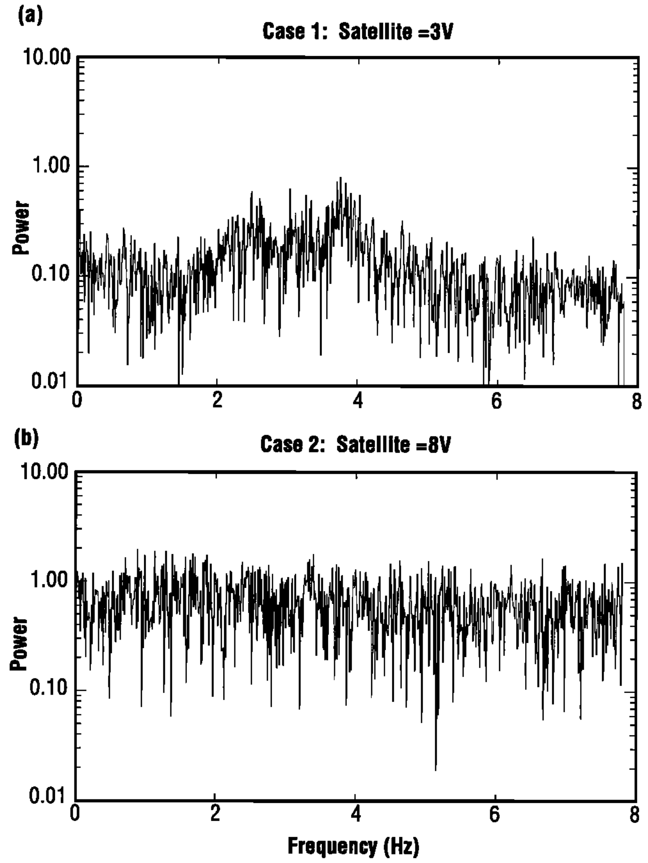

Figure 4. FFT of the BMSP current from (a) Figure 2(e) of Case 1; (b) Figure 3(e) of Case 2.

interactive hardware/software control of the BMSP bias and current. Most of the spectrum shows basically white noise of relatively low power. The Case 2 spectrum shown in Figure 4(b) is approximately an order of magnitude greater in power than for Case 1. The range and sample period of the BMSP current was not specifically designed to examine plasma turbulence, but semiquantitatively, the BMSP current behavior indicates a dramatically more disturbed plasma state in Case 2 than in Case 1. Moreover, this increased "turbulence" is the result of a small change of only a few volts in satellite potential. Apparently, the presence of ions flowing away from the satellite plays a role in contributing to this disturbed state. A detailed, quantitative examination of the spectra of electric field oscillations in the vicinity of the satellite has been performed by *Iess et al.* [1997].

5. Discussion

The "macroscopic view" of current collection by the TSS satellite is given by the current-voltage characteristic discussed by *Thompson et al.* [1997]. The low voltage region of the curve indicates the existence of a "knee" occurring at ~5 V. In this paper, a piece of the "microscopic view" of the collection process has been examined about this critical value. Specifically, observations in the upstream region of the satellite have been performed as its voltage transitioned from below to above 5V. When the satellite potential is <5 V, the plasma behavior is fairly quiescent, as indicated by the measurements presented here. However, as the satellite potential becomes >5 V, a significant change occurs in the upstream environment. For the area of the ram hemisphere covered by the measurements, ions are observed to reflect from the satellite sheath in quantities of 2% – 4% of ambient and exhibit an apparent heating. These effects are seen in numerical simulations (particle-in-cell technique) [N. Singh, personal communication, 1997]. Upstreaming ions, counter-streaming with respect to the ram ion flow, can provide a source of free energy to excite lower hybrid waves [*Papadopolous,* 1992]. The upstreaming ions are one part of a complex of processes that ignites as the satellite sheath becomes >5 V; i.e., dramatic increase in a suprathermal electron population [*Winningham et al.,* 1997]; increase in the power spectral density of the wave spectrum [*Iess et al.,* 1997]; and sheet structure of the local current distribution [*Mariani et al.,* 1997]. This information should be examined in more detail in conjunction with the behavior ahead of a planetary magnetopause.

Acknowledgments. KHW acknowledges NASA for support under contract NAS–37107. The authors thank the engineering team at Alenia Spazio (Turin, Italy) for providing information on satellite attitude. Magnetic field measurements are provided by F. Mariani (TEMAG) and tether current measurements are provided by C. Bonifazi (CORE).

References

Iess, L., C. Harvey, G. Vannaroni, J.P. Lebreton, M. Dobrowolny, R. Manning, A. Onelli, and F. De Venuto, Plasma waves in the sheath of the TSS-1R satellite, *Geophys. Res. Lett.*, this issue, 1997.

Mariani, F., M. Candidi, S. Orsini, R. Terenzi, R. Agresti, G. Musmann, M. Ram, N.F. Ness, M. Acuna, P. Panetta, and F. Neubauer, High voltage sheath structure as observed by the TEMAG magnetic field experiment on TSS-1R, *Geophys. Res. Lett.*, this issue, 1997.

Papadopoulos, K., The CIV process in the CRIT experiment, *Geophys. Res. Lett.*, *19*, 605, 1992.

Parker, L.W., and B.L. Murphy, Potential buildup on an electron-emitting ionospheric satellite, *J. Geophys. Res.*, *72*, 1631, 1967.

Singh, N., and B.I. Vashi, Current collection in a flowing magnetoplasma, in *Current Collection from Space Plasmas*, eds. N. Singh, K.H. Wright, Jr., and N.H. Stone, *NASA CP-3089*, Dec. 1990.

Stone, N.H., K.H. Wright, Jr., J.D. Winningham, J. Biard, and C. Gurgiolo, A technical description of the ROPE investigation, *Il Nuovo Cimento*, *17*, 85, 1994.

Thompson, D.C., C. Bonifazi, B.E. Gilchrist, S.D. Williams, W.J. Raitt, J.P. Lebreton, W.J. Burke, and N.H. Stone, The current-voltage characteristics of a large probe in low-Earth orbit: TSS-1R results, *Geophys. Res. Lett.*, this issue, 1997.

Whipple, E.C., The ion-trap results in "Exploration of the upper atmosphere with the help of the third Soviet sputnik," *Proceedings of the IRE*, *47*, 2023, 1959.

Winningham, J.D., N.H. Stone, C. A. Gurgiolo, K.H. Wright, and R.A. Frahm, Suprathermal electrons observed on the TSS-1R satellite, *Geophys. Res. Lett.*, this issue, 1997.

(Received January 21, 1997; revised September 25, 1997; accepted October 15, 1997.)