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Suprathermal electrons observed on the TSS-1R satellite

J.D.Winningham[1], N.H. Stone[2], C.A. Gurgiolo[3], K.H. Wright[4], R.A. Frahm[1], C.A. Bonifazi[5]

Abstract. Particle measurements up to 27,000 eV were made on the TSS-1R (Tethered Satellite System) satellite. The TSS satellite developed a positive bias due to the Lorentz force. It was the intent that electron measurements on the TSS satellite could be used to track the spacecraft potential and collected current. What was observed was quite different. Accelerated ionospheric electrons were observed to only ~70 eV even though larger spacecraft potentials were observed by other diagnostics on the TSS satellite. When observed they agreed with these independent measurements of the potential. In addition to the anticipated accelerated thermals, a suprathermal population of electrons was observed to be centered around 200 eV. This population exhibited a 4 orders-of-magnitude increase in intensity as the spacecraft potential exceeded the O^+ ram energy. The disappearance of the accelerated thermals is explained by the observation that the suprathermal flux becomes larger in magnitude, thus hiding the thermals. However the suprathermals cannot be the dominant current carriers if they are the result of a DC process as their calculated current magnitude exceeds that observed. These results are best explained if one assumes an AC acceleration of the suprathermal electrons whose free energy is derived from the differential ($\vec{E}x\vec{B}$ driven) drift between electrons and ions.

1. Introduction

The Soft Particle Electrostatic Spectrometer (SPES) instrument (Stone et al., 1994) was included as part of the Research on Orbital Plasma Electrodynamics (ROPE) experiment on the TSS-1 and -1R missions. It was to first order identical to the Low and High Altitude Plasma Instruments (LAPI and HAPI) instruments flown on the Dynamics Explorer Satellites (Winningham et al., 1981, Burch et al., 1981) and the Medium Energy Particle Spectrometer (MEPS) instrument (Winningham et al., 1993) flown on the Upper Atmospheric Research Satellite. The SPES electrostatic analyzers (ESAs) have parabolic deflection plates with a short path length and small deflection angle (Fig. 4 of Stone et al., 1994). This property minimizes the $\vec{E}x\vec{B}$ deflection in the analyzer and allows sub-eV electron energies to be measured. This is critical when measuring ionospheric thermal electrons. The SPES measurement range was 0.4 eV to 27 KeV. (see sensor arrangements in Figure 1 of Wright et al., 1997).

For TSS, the geometric factors and overall sensitivities (Table 1 of Stone et al., 1994) were set to allow both unaccelerated and accelerated (up to 5 KeV) thermals to be measured within the dynamic range of the channeltron detectors and associated amplifier and counters. The resulting sensitivities are thus many orders-of-magnitude less than those typical for auroral particle measurements. Since TSS deployed the spacecraft upward, away from the earth, the sign of the $\vec{V}x\vec{B}$ electric field caused a positive bias on the spacecraft with respect to the ambient plasma. This results in the ambient thermal, electron population being accelerated by the positive satellite into the SPES energy range. When the TSS satellite bias becomes large enough, the accelerated, thermal electron signature should be observed in only one of the SPES energy bins, which have a 15% energy resolution.

The TSS was flown in a 28.5° inclination orbit on the STS (Space Transportation System). Since this is well below the auroral region it was assumed that the only populations of particles present within the energy range covered by the SPESs would be ionospheric thermal electrons and ions, and atmospheric photoelectrons. However the SPES sensitivities were too low to measure atmospheric photoelectrons. Thus it was anticipated that only the ionospheric, thermal electron and accelerated (by the positive spacecraft voltage) ionospheric electrons would be observed. The goal for the SPES's was to provide the measurement of the satellite voltage (determined by observing the accelerated, thermal electron peak) and the current carried by these accelerated electrons.

Many functional objectives (FOs) (Dobrowolny and Stone, 1994) were developed to investigate the dynamic and electrodynamic properties of TSS system. FOs are procedures whereby a goal is actually carried out. The electrodynamic Fos were designed to provide a thorough understanding of current flow (and thus power) in the TSS system. As covered by other papers in this issue, multiple theories existed to explain the I-V relationship of a system such as TSS and the responsible microphysical processes. In this paper we will use results from two particular FOs (DC24 and IV24) to demonstrate that the observed electron fluxes were not what was anticipated. This will be accomplished by investigating the measured electron spectra and their dependence on spacecraft voltage. In another companion paper by Singh, et al., (1997), a theory is presented to explain these spectra and their "peculiar" angular distributions. In both cases of data discussed below, the TSS circuit was closed at the Orbiter end with the Italian-provided electron gun (see Stone and Bonifazi, 1997).

2. Data

As discussed in the introduction it was the intent that the SPESs would track the spacecraft potential (possibly as high as +5000V) as the current was varied in the tether circuit by various techniques (see Dobrowolny and Stone, 1994). This would be accomplished by observing the accelerated thermal electron spectrum. Sensitivities of the various SPES units where adjusted to track spacecraft potential through the full range from 0V to +5000V assuming the entire the entire $\vec{V}x\vec{B}$ EMF was dropped across the satellite sheath (which in reality would never occur).

[1]Southwest Research Institute, Department of Space Sciences, San Antonio, Texas;
[2]NASA/Marshall Space Flight Center ES83, Huntsville, Alabama;
[3]Bitterroot Basic Research, Hamilton, Montana;
[4]University of Alabama in Huntsville, CSPAR, Alabama;
[5]Agenzio Spaziale Italiana

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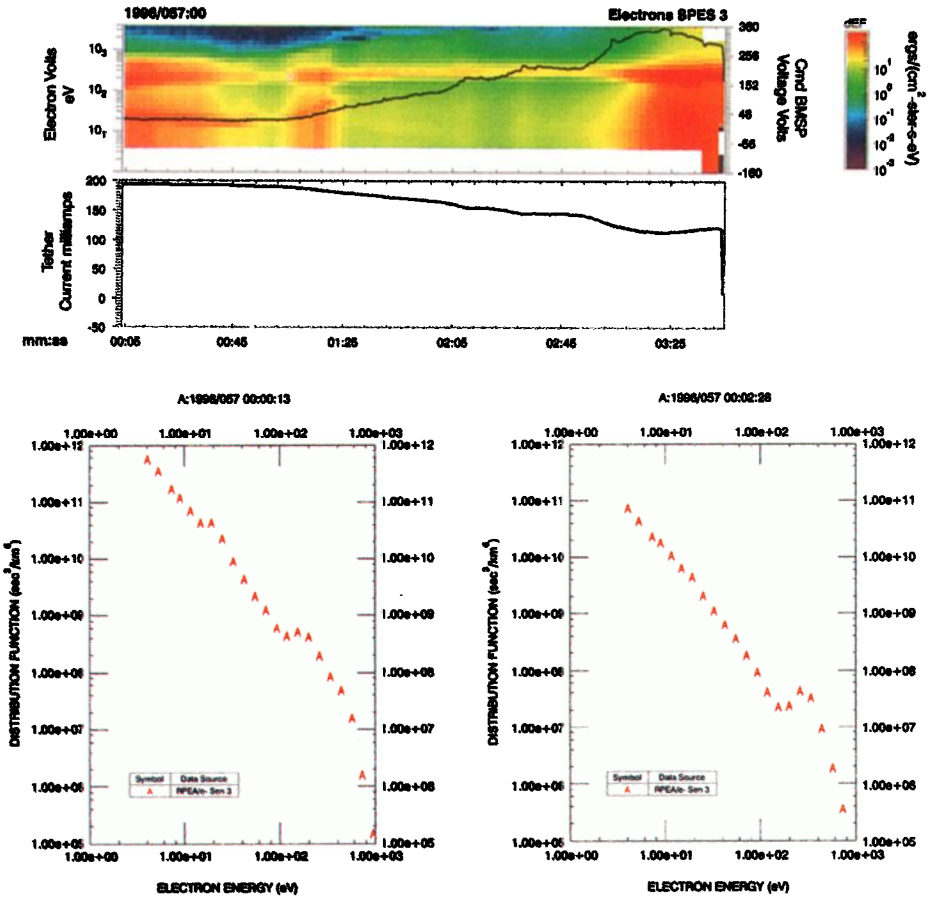

Figure 1. First 24 minute DC cycle showing accelerated thermal electrons tracking the spacecraft potential to ~70 V and no spacecraft potential dependence of the suprathermal electrons at ~200 eV.

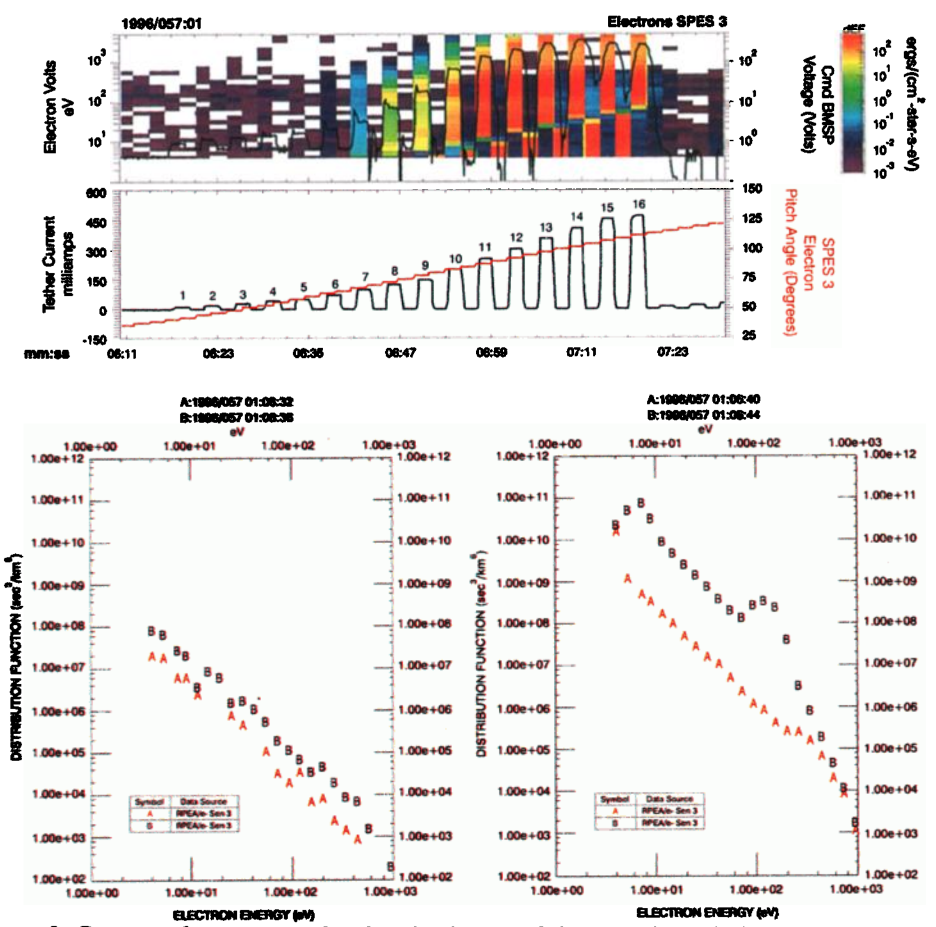

Figure 2. Current voltage survey showing dominance of the suprathermal electrons when spacecraft potential increases beyond the O^+ ram energy.

Contrary to anticipation the charging peak represented by the acceleration of thermal electrons was only observed to a maximum of ~70 eV even though the spacecraft potential increased well above 70 V. Figure 1 shows data from a section (one satellite rotation period) of the first 24 minute DC (DC24) cycle. An energy-time (E-t) spectrogram of electrons measured at the spacecraft equator is presented in the top panel. This data was accumulated on 1996 day 57 and reflects a time when the spacecraft voltage gradually increased. Accelerated thermal electrons at ~20 eV were observed from the beginning of this time period to about 0001:02 UT. During this time, the spacecraft potential was 20 V as measured by an independent means detailed later. After 0001:02 UT, the spacecraft potential increased. The accelerated thermal electron peak tracked the increase in spacecraft potential until the thermal electron peak reached ~70 eV (0001:20 UT), at which time the accelerated thermal electrons were no longer observed. The acceleration peak did not reappear through the end of the data in this panel. Spacecraft voltages were confirmed by the ROPE Boom Mounted Sensor Package (BMSP) measurement of the bias required to draw zero current to its surface (see Stone et al., 1994, for a description of the BMSP section of ROPE) and are displayed for reference on the spectrogram as a superimposed black line. The voltage scale is provided on the right hand axis. In Figure 1 another band of electrons was observed at approximately 200 eV that is at an energy not equivalent to the spacecraft voltage.

At the bottom of Figure 1 two spectra are presented. The left spectrum occurs at 0000:13 UT during the period when the spacecraft potential was ~20 V and the right spectrum occured at 0002:28 UT after the charging peak had disappeared. In both spectra one observes not only the charging and 200 eV peaks but particles at energies other than the peaks. Clearly these were not the anticipated spectra based on a simple DC spherical sheath that would accelerate thermal ionospheric electrons to a particular value.

The ~200 eV "suprathermal" electrons exhibited not only a sharply peaked spectrum but also a power law shape at energies lower than the peak with a slope that is $\sim E^{-2}$ in phase space. Above the peak it is roughly a Maxwellian. Due to lack of concurrent complete angular distributions one cannot produce a reduced distribution to see if the positive slope in distribution function remains.

Examination of the data shows that the suprathermal electron peak energy did not (to first order) track changes in the potential which can be seen in figure 1. The spectrogram in figure 1 displays the time history of the energy dependence of the electron population. The black line plot superimposed on the spectrogram shows the BMSP voltage varied from ~20 V to ~360 V. No one to one correlation was observed for the 200 eV suprathermal electrons with the spacecraft voltage measured by the BMSP. This same lack of dependence on spacecraft potential was typical of data from other FOs which showed a suprathermal peak.

Figure 2 presents data that demonstrates the dependence of the intensity of the suprathermal electron population with changes in the satellite potential. This was an I-V survey mode which lasts for 24 minutes. Only a fraction of the current voltage survey is presented here. In the I-V mode of TSS, the tether current was stepped through a sequence of 16 different discrete values which monotonically increased, as can be seen in the scalar plot below the E-t spectrogram near the top of figure 2. As with the previous figure the spacecraft potential, as measured by the ROPE BMSP monitor, is overlaid on the E-t spectrogram. A large increase in the intensity of the suprathermal electrons is seen from 1996/57 0106:32 to 0106:48 UT. This time encompassed current steps 5, 6, 7 and 8. The spacecraft potential corresponding to these steps were 1.6, 2, 3.2, and 6.8 volts respectively. Spectra from SPES 3 corresponding to these current steps are presented in the left and right panels at the bottom of Figure 2. The fluxes were just barely above background (counts of 1 to 4) in step 5 seen in the left panel (letter A). The overall fluxes increased in intensity by a factor of 2 to 3 for step 6 (letter B left panel) and a peak at ~200 eV is just discernable. In the right panel are shown spectra for steps 7 and 8. At step 7 (letter A) the fluxes went up a factor of 20 to 30 above that of step 5 and a knee at 300 eV develops. In step 8 (letter B) the fluxes further increased by a factor of 600 from step 7 or by ~4 orders of magnitude from step 5 and a peak at ~200 eV is clearly visible. It is clear that most of this change is between steps 7 (3.2 V at 100 ma) and step 8 (6.8V at 125 ma). During the many repetitions of this system I-V mode, the suprathermal electrons demonstrated the same dramatic change in flux intensity over this small change in satellite potential. Thus the main dependence the suprathermal electrons showed with changing spacecraft potential was a corresponding change in the intensity of the flux, not a one to one changes in spectral peak energy.

The angular distributions of the suprathermal electrons is very complex (and too long to detail in this letter). The largest flux does not peak at either of 0°, 90° or 180° pitch angle. The peak generally occurs close to 0° or 180° depending on the sign of $\vec{B}$ but is not symmetric about 0° or 180°. In addition a secondary maximum peak is seen at one 90° crossing.

3. Discussion

As mentioned in the introduction we had anticipated tracking the cold, thermal, ionospheric electron population as it was accelerated to the TSS spacecraft by the positive potential developed by the Lorentz electromotive force (i.e. $\vec{E} = -\vec{V}x\vec{B}$ actually the fraction dropped across the sheath). Sensitivities, resolutions, and ranges were set to achieve this goal. The potential that was thus determined would be used with other measurements of the partitioned total voltage to compare with predictions and to detail the TSS current-voltage relation. As with many predictions, what was actually observed was far different and more physically diverse.

First, we did observe the accelerated thermal electrons but only to a maximum of ~70 V even through larger potentials (up to ~1500 V) were observed by other diagnostics. As long as they were present, the peak energy of the energized thermals agreed with the other independent measurements of satellite potential. After extensive examination of the ROPE results the most plausible explanation of the "loss of observability" of the thermal electrons lies with the suprathermal electrons. As the voltage and current increase, the suprathermal electron flux also grows, although not in a linear fashion. Within the measurement capabilities of the SPESs the accelerated thermal electrons simply "submerge" beneath the suprathermal electron population. It should be noted that this doesn't imply that the suprathermals are thus the dominate current carrier. In fact, calculations based on a spherical DC model show that when one can observe them, the accelerated electrons can account for most of the observed current in the TSS circuit; whereas in nearly all cases, the suprathermals appear to carry a current far in excess of what is actually observed. This seems paradoxical in a DC picture. However if the suprathermal electrons are due to an AC process contained within the expanded sheath, then on a time averaged basis they would contribute much less and possibly zero current. Also if they are created within and never exit the sheath and are "recollected" then they would be nearly neutral in effect. The BMSP current shows significant fluctuations when suprathermal electrons are present.

The paper by Iess et al., 1997 (this issue) provide evidence for large amplitude waves in the LHR region in association with these suprathermal fluxes which further supports an AC dominated processes. This wave acceleration possibility is theoretically explored in the companion paper by Singh et al., 1997 (this issue).

The results presented here show that the most dramatic dependence of the suprathermal electrons on the spacecraft potential is in the few volts range. Steps 5, 6, 7, and 8 of the I-V cycle presented in this paper are 1.6, 2, 3.2, and 6.8 volts with the most dramatic increase in flux occuring between steps 7 and 8 (3.2 and 6.8 V). The orbital velocity of the STS gives a ram energy for the dominant O^+ ions of ~4.8 eV. Thus between step 7 and 8 the O^+ ions become "totally" reflected. Due to the finite temperature of O^+ ions there are ions at energies both above and below the "ram energy". The ram energy is really the energy of the centroid of the O^+ distribution in the satellite reference frame. The reflected ions are thus counterstreaming relative to those incoming and represent a large source of free energy which can drive plasma instabilities. Wright, et al., 1997 (this issue) presents observations of reflected ions. These instabilities could give rise to AC electrostatic or electromagnetic waves that could accelerate the observed suprathermal electrons. In the paper by Singh, et al., 1997, (this issue) a wave based theory is developed to explain the suprathermal electrons. This theory is based on the drift of magnetized electrons in the $\vec{E}x\vec{B}$ field of the sheath relative to the fixed, non-magnetized ions. This relative drift also generates LH waves. Singh et al. compares this to the ion two stream instability and concludes the electron-ion drift model to be much more effective and could accelerate electrons to a few hundred volts. In addition it predicts that the electrons will not be symmetric in flow around $\vec{B}$ due to the $\vec{E}x\vec{B}$ induced drift. The flux instead will arrive at the satellite surface at an angle close to $\vec{B}$ and on only one side in this model (see Singh, et al. this issue). The ram energy sensitivity in this model is due to a shift in the $\vec{E}x\vec{B}$ induced pattern towards the ram side of the spacecraft when the ion ram energy is passed. Thus the Singh et al. model to first order agrees well with the observations.

4. Conclusions

In summary the observations made by the ROPE experiment on TSS do not agree with the picture of a static DC sheath surrounding the satellite through which ionospheric electrons simply "fall" to the satellite surface. Even voltages in the few volts range produce dramatic departures from this simple picture. Intense, suprathermal electron fluxes are observed that are likely due to wave-particle interactions in the TSS sheath. The papers by Stone and Bonifazi, 1997; Thompson et al., 1997, Chang et al., and Vannaroni et al., 1997, detailing the I-V characteristics of the TSS circuit also show a significant difference between extant theories of current collection and what is actually observed. These results also show their maximum differences in the voltage region around the O+ ram energy. The environment around the TSS satellite is a very dynamic environment, one that contains sheath effects combined with wave-particle interactions. The result is a significantly different current collection scenario than previously predicted. The source of free energy to accelerate the observed suprathermal electrons can be derived from the $\vec{E}x\vec{B}$ motion of the electrons relative to ions in the sheath.

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J.D. Winningham, Instrumentation and Space Research Division, Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228

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