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THE TSS-1R ELECTRODYNAMIC TETHER EXPERIMENT: SCIENTIFIC AND TECHNOLOGICAL RESULTS

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ABSTRACT

The Tethered Satellite System program was designed to provide the opportunity to explore certain space plasma-electrodynamic processes (associated with high-voltage bodies and electrical currents in space) and the orbital mechanics of a gravity-gradient stabilized system of two satellites linked by a long conducting tether. A unique data set was obtained during the TSS-1R mission in which the tether electromotive force and current reached values in excess of 3500 volts and 1 amp, respectively. The insight this has allowed into the current collection process and the physics of high-voltage plasma sheaths is significant. Previous theoretical models of current collection were electrostatic—assuming that the orbital motion of the system, which is highly subsonic with respect to electron thermal motion, was unimportant. This may still be acceptable for the case of relatively slow-moving sounding rockets. However, the TSS-1R results show that motion relative to the plasma does affect current collection and must be accounted for in orbiting systems.

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MISSION PARAMETERS AND BACKGROUND

The Tethered Satellite System (TSS) program was a binational collaboration between NASA and the Italian space agency (ASI) with NASA providing the Shuttle-based deployer and tether and ASI providing a satellite especially designed for tethered deployment. The TSS-1R mission, which was the second flight of the TSS hardware, was launched February 22, 1996, on STS-75 into a 300 km, circular orbit at 28.5 degrees inclination. Satellite flyaway occurred at MET 3/00:27 and a unique data set was obtained over the next 5 hours as the tether was deployed to a length of 19,695 meters. At MET 3/05:11, during a day pass, the tether suddenly broke near the top of the deployer boom. The break resulted from a flaw in the tether insulation which allowed the ignition of a strong electrical discharge that melted the tether. The operations that had begun at satellite flyaway, however, allowed significant science to be accomplished. More complete treatments of the results discussed below are provided by papers in a *Geophysical Research Letters* special section on TSS-1R (Stone and Bonifazi, 1998).

INSTRUMENTATION AND MEASUREMENTS

Electrodynamic tethers convert mechanical energy into electrical energy in a classical demonstration of Faraday's law. The TSS-1R configuration was such that the satellite received a positive bias from the motional electromotive force (EMF) of the tether and collected electrons from the ionosphere. The resulting electrical current was conducted through the tether to the Orbiter where the circuit was closed back to the ionosphere (see Figure 1). There were four possible electrical configurations of the TSS: (1) open circuit with no current flow; (2) passive current closure through the collection of positive ions by conducting surfaces on the negatively charged Orbiter; (3) addition of the Shuttle Electrodynamic Tether System (SETS) experiment's fast-pulsed electron gun (FPEG) to the above circuit to discharge the Orbiter; and (4) use of the ASI-provided Core electron gun—in which case tether current flowed directly to the gun cathode (the Orbiter was not part of the electrical circuit).

TSS-1R was instrumented to diagnose the environmental space plasma properties under highly nonequilibrium conditions. Mounting arrangements for the required ensemble of instruments are shown in Figure 1. Detailed descriptions of the instrumentation, which also flew on the TSS-1 mission, are provided in a special TSS-1 issue of *Il Nuovo Cimento* (1994).

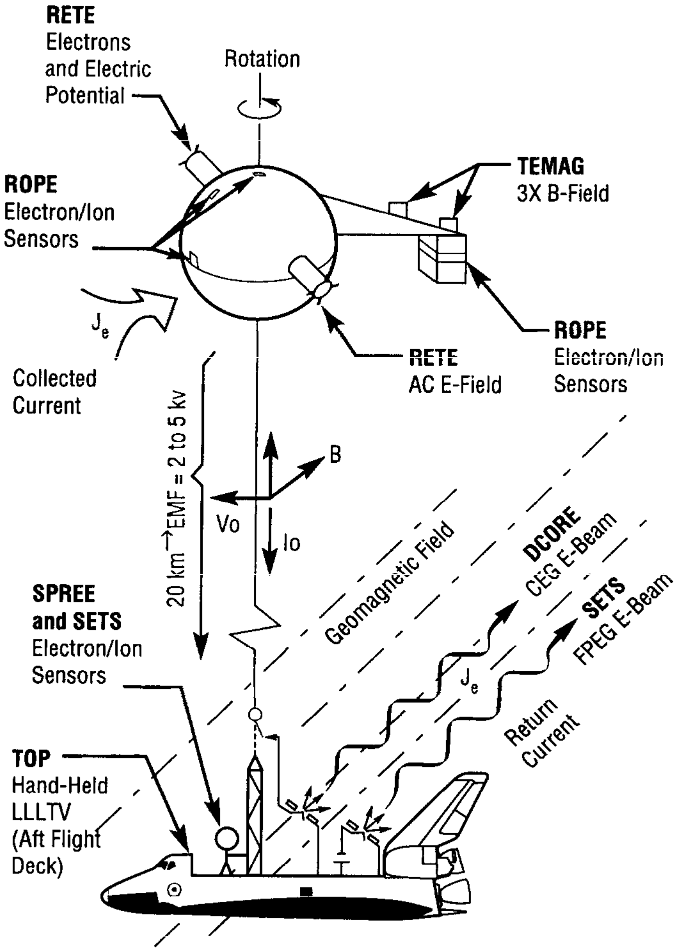

Fig. 1. Functional schematic of the TSS-1R instrumentation and hardware.

TSS-1R fell short of premission expectations in that there was no opportunity to execute the detailed experiments that had evolved over several years of planning (operations were primarily limited to calibration) and, therefore, the data set is incomplete and lacks a systematic approach. Even so, the data set obtained is unique and provides an unprecedented look at the physics of high-voltage sheaths and current collection in space plasmas.

SCIENTIFIC AND TECHNOLOGICAL RESULTS

The most fundamental scientific result from the mission to date is the discovery that the various theoretical current collection models developed over the past 70 years (e.g., Langmuir and Blodgett, 1923, 1924; Beard and Johnson, 1961; Parker and Murphy, 1967) do not include the full range of processes by which an electrically biased, mesosonic satellite (supersonic with respect to the ion sound speed but subsonic with respect to that of the electrons) interacts with its environmental space plasma. The predicted relation between the satellite potential and charge collection (the current-voltage characteristic) is, correspondingly, incorrect. Second, a variety of specific physical effects, including the creation of suprathermal charged particle populations, plasma waves, and magnetic perturbations were observed. These effects may be related to the unexpected nature of the current-voltage relationship. Third, a sharp transition in the plasma interaction process was found to occur at the relatively low spacecraft potential of +5 volts—the ram energy of the dominant atomic oxygen ions. The reflection of ionospheric ions by the satellite when its potential exceeded the ion ram energy was expected. However, a transition in the basic physical processes involved was a complete surprise.

Current Collection in Space Plasmas

The disagreement observed between the measured TSS-1R current-voltage characteristic and the predictions of the theoretical models may result in the most significant improvement to our understanding of the physics of current collection in space since the Parker-Murphy model was developed in 1967 to account for the fact that the ionospheric plasma has an embedded magnetic field which severely limits cross-field charge mobility. A review of the various contributions to the theory is given in Laframboise and Sonmor (1993). The magnetically limited model seemed to explain observations made from several relatively slow-moving sounding rocket experiments and was accepted as authoritative for the past 30 years—until the TSS-1R mission. It became immediately obvious during the mission that serious differences existed between the predictions of theoretical models and the measured results. For example, Figure 2 shows that the attractive potential on the satellite required to collect a given current is typically an order of magnitude less than that predicted by the Parker-Murphy model. This shows that current collection is far more efficient than predicted and suggests that (1) the orbital velocity has a significant effect and (2) the requirement for rather rigid adherence of electrons to magnetic field lines assumed in the magnetically limited models may be too severe—at least in the near vicinity of the satellite (Papadopolous *et al.*, 1998). New models are being developed which account for the above factors (Ma and Schunk, 1998; Singh and Leung, 1998; Cook and Katz, 1998).

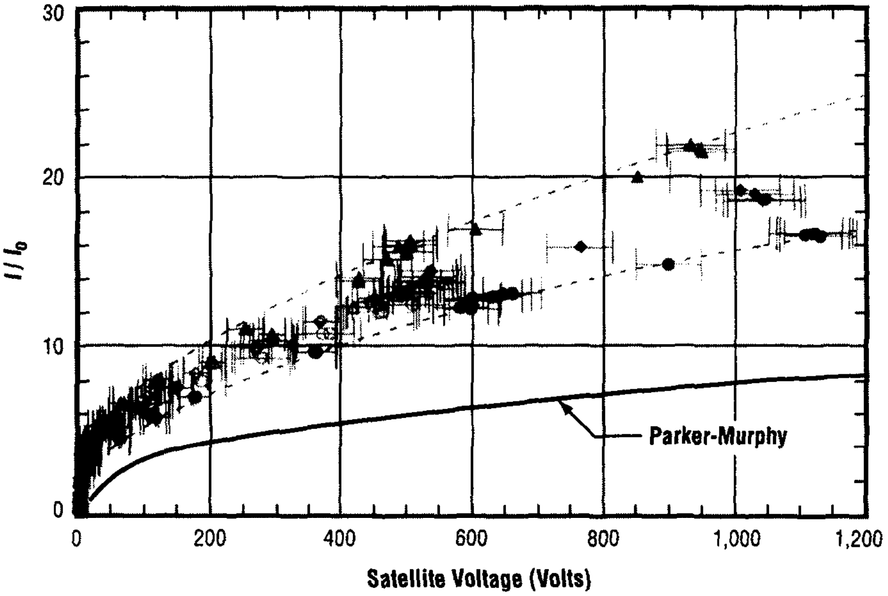

Fig. 2. TSS-1R current-voltage characteristics compared to the characteristic predicted by the Parker-Murphy theory. Data was obtained from six Core electron gun controlled sweeps in the third IV24 operations cycle at a deployed distance of approximately 18 km (after Stone and Bonifazi, 1998).

Plasma Sheath Physics

The sharp transition observed in the particle and field environment at a satellite potential of +5 volts seems to suggest an abrupt modification of the physical processes operating in the satellite's near vicinity (Winningham *et al.*, 1998). Below +5 volts, mostly accelerated ionospheric thermal electrons were observed. However, when the satellite potential exceeded the +5 volt level, a sudden onset of suprathermal (~200 eV) electrons, plasma waves, magnetic perturbations, and turbulence in the satellite sheath were observed (Winningham *et al.*, 1998; Iess *et al.*, 1998; Mariani *et al.*, 1998; and Wright *et al.*, 1998). The suprathermal flux intensity grew rapidly with increasing satellite potential and quickly swamped the ionospheric thermals. Specifically, as shown in Figure 3, a 10-volt increase in satellite potential resulted in four orders of magnitude increase in the suprathermal electron flux (Winningham *et al.*, 1998). It now appears that the conducting thermal control coating of the satellite may be the source of a large photo and/or secondary electron flux. However, their suprathermal energy remains a mystery.

In addition to the suprathermal electrons, relatively energetic ions were observed flowing out of the satellite's sheath (Wright *et al.*, 1998). The ram energy of ionospheric atomic oxygen ions is approximately 5 eV, so that the critical voltage for the transition is the level at which oxygen ions would be reflected or strongly deflected out of the sheath. It is suggested that the outflowing ions, or possibly the expulsion of ions from the plasma sheath, may provide the free energy required to generate waves and drive the energization of the suprathermal electrons (Iess *et al.*, 1998; Winningham *et al.*, 1998; Papadopoulos *et al.*, 1998). The azimuthal variation of outflowing ion flux and the correlation between its intensity and plasma noise in the satellite's sheath are shown in Figure 4.

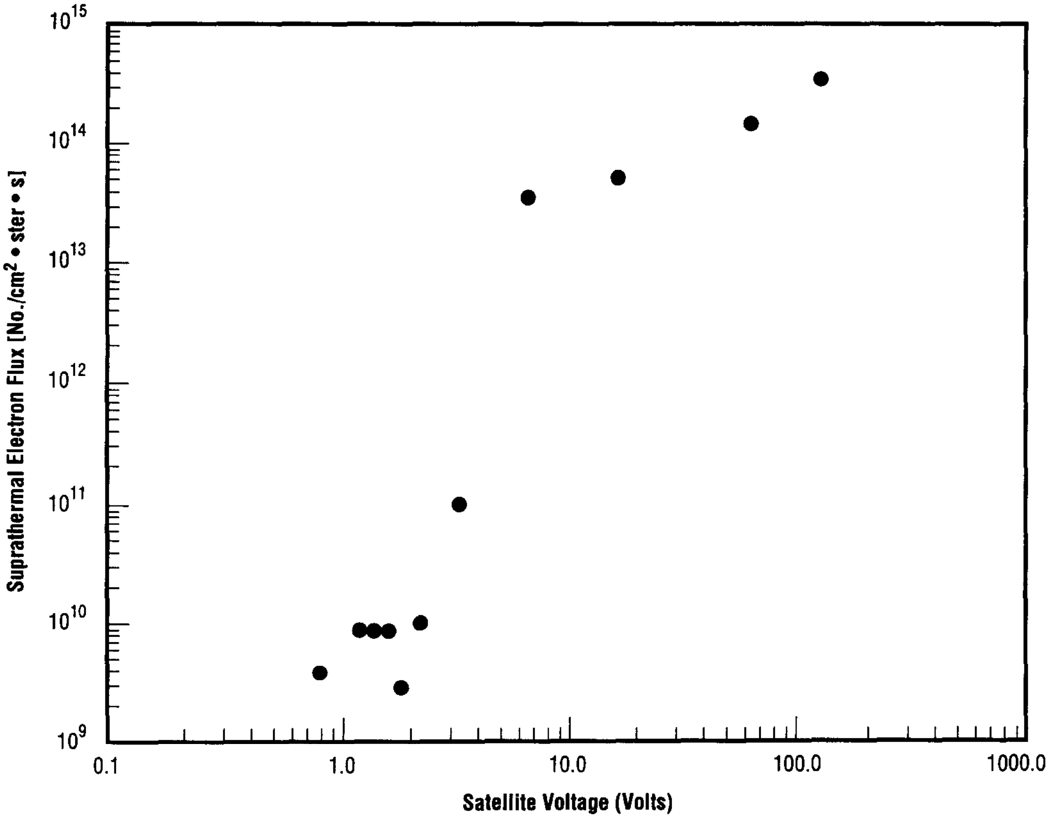

Fig. 3. Growth of the suprathermal electron flux density as a function of satellite potential.

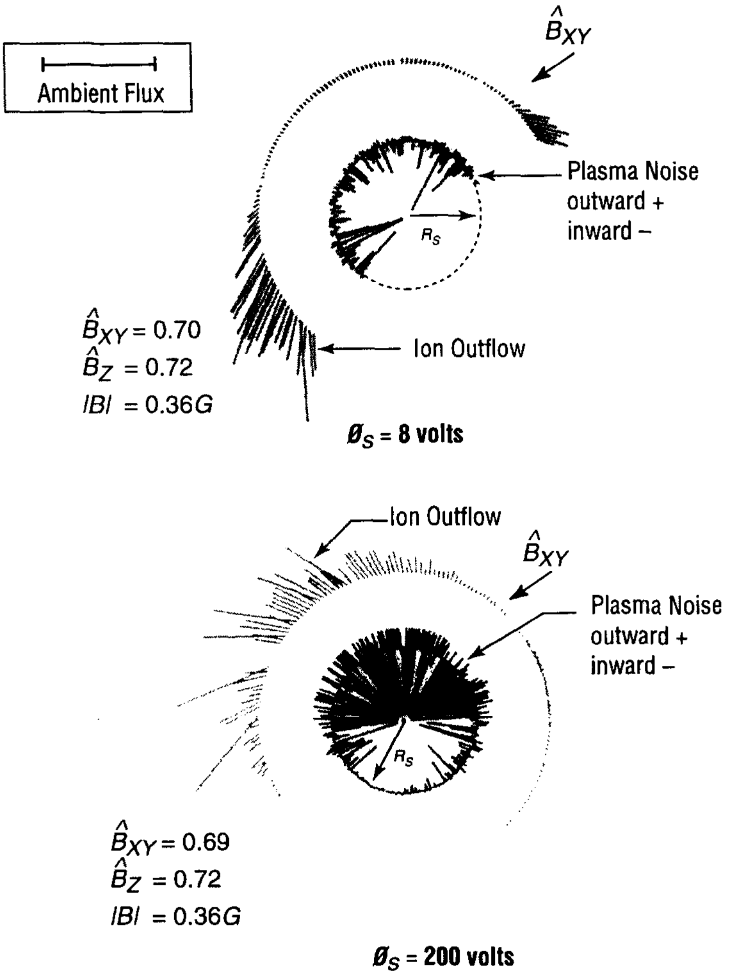

Fig. 4. Azimuthal distribution of outflowing ion flux density and the corresponding plasma noise level for satellite potentials of (a) 8 volts and (b) 200 volts.

Implications for Technological Applications

The above observations are important to all electrodynamic tether applications because their net effect is to increase the current available for any given values of the tether EMF and ionospheric conductivity. In fact, the tether break itself provided an intriguing and potentially valuable event in which large currents (in excess of 1 amp) at high satellite potentials (greater than 1 kV) began flowing approximately 10 s prior to the break and continued for about 90 s *after* separation (Gilchrist *et al.*, 1998). Efficient charge collection increases the ability of tether systems to convert orbital kinetic energy into electrical power or, conversely, electrical power into an electrodynamic propulsive force.

Figure 5 is a plot of the satellite potential required to collect a given current as a function of tether current. Note that the potential requirements of the Parker-Murphy model far exceed the actual TSS-1R data. This means that electron collection required much less work than predicted, and this, in turn, means that less of the available EMF is used to collect the tether current—leaving more usable power. Considering the collection process at the satellite and system losses, usable power is defined by:

$$P = I\,(\Phi_{EMF} - IR_T - \Phi_S - \Phi_O). \qquad (1)$$

Where P is the usable power, I is the tether current, Φ_{EMF} is the motional EMF across the tether, R_T is the tether resistance, Φ_S is the satellite potential, and Φ_O is the orbiter potential.

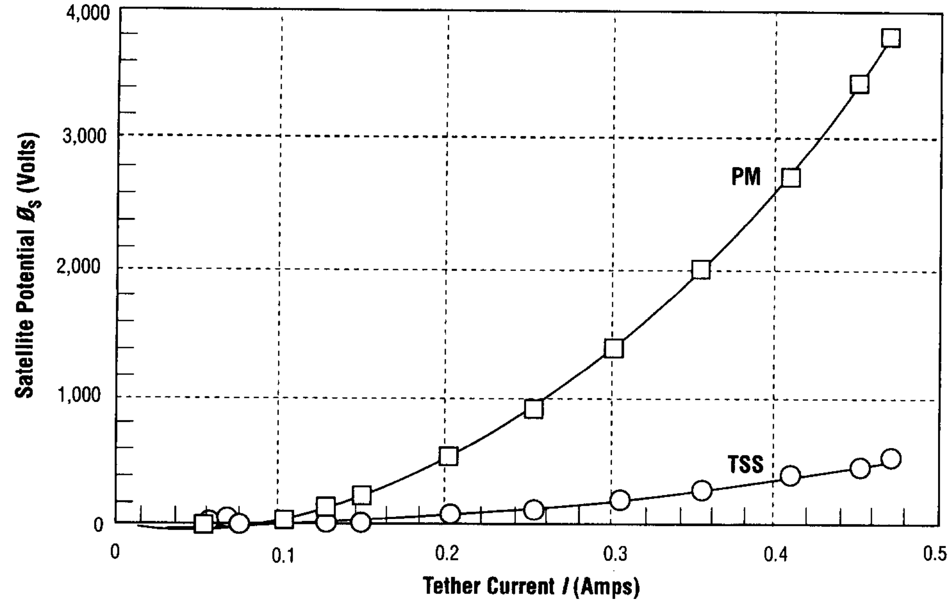

Fig. 5. Voltage-current characteristic obtained from TSS-1R data compared with characteristics predicted by the Parker-Murphy model (after Papadopoulos *et al.*, 1998).

Plotting usable power as a function of tether current in Figure 6 shows that the Parker-Murphy model predicts the usable power to increase with current to a peak at about 225 mA and then decrease to zero at about 438 mA. This is because the model predicts the collection process to become increasingly inefficient with increasing current so that eventually, all available energy is used to collect electrons and none is left to do useful work. Note, however, that this is not what actually happened. The importance of the enhanced current collection discussed earlier is apparent here because, due to the ease with which electrons are extracted from the ionosphere, the usable power developed by the TSS did not peak, but continued to increase over the range of the measurements (Papadopoulos *et al.*, 1998). The dashed curves indicate the range of improvement possible by reducing the tether resistance, which is a design parameter in tether systems.

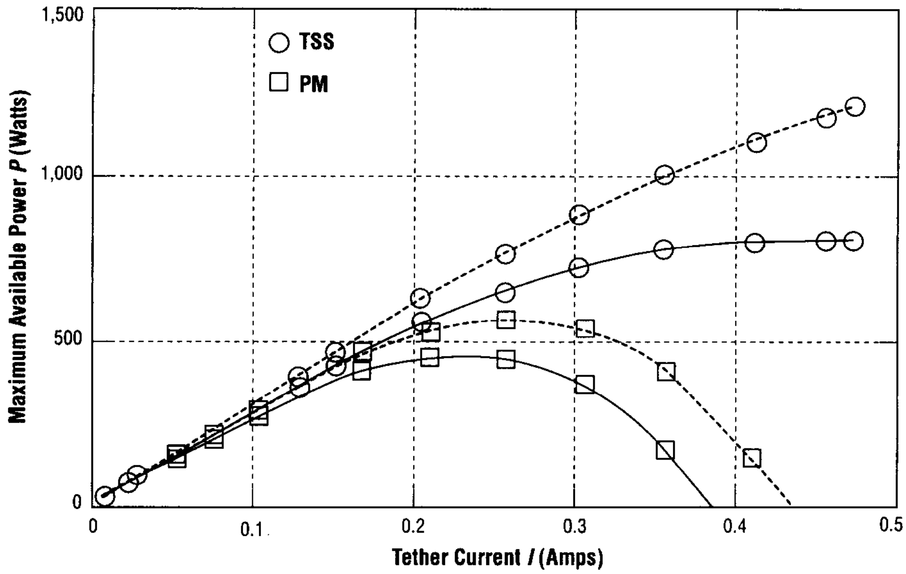

Fig. 6. Usable power available from TSS-1R compared to the usable power predicted by the Parker-Murphy model (after Papadopoulos *et al.*, 1998). Solid curves are for R_T =1,820 ohms. Dashed curves are for R_T =0 ohms.

Similarities to Geophysical and Solar System Plasma Processes

The TSS-1R data set may also have provided glimpses of important space plasma processes that occur naturally near Earth and throughout the solar system. For example:

(1) The reflection of ions by the potential barrier around the positively biased satellite created counter-streaming ion beams that, in turn, appear to have generated a spectrum of lower hybrid waves (Wright *et al.*, 1998; Iess *et al.*, 1998). Similar processes are seen in plasma double layers at the magnetopause and at the Earth's bow shock, all of which involve the basic physics of how charged particle beams couple to, and dissipate energy in, plasmas (Kindel and Kennel, 1971).

(2) The modulation of electron beams during TSS-1R operations (Gough *et al.*, 1998) may be related to the cyclotron resonant maser effect. This effect is thought to be involved in the production of auroral kilometric radiation (Wu *et al.*, 1989).

(3) There is strong evidence of pick-up ion processes at the TSS satellite. Such processes are commonly associated with solar wind interactions with planets and comets (Intriligator *et al.*, 1996).

(4) The characteristics of a high-voltage, negatively charged spacecraft and its effects on the ionospheric plasma (Gentile *et al.*, 1998; Aguero *et al.*, 1998) are important because this study—made possible for the first time by TSS-1R—can lead to improved techniques for biasing antennas in space to enhance their coupling to the magnetospheric plasma. This may have direct applications to the measurement of dc electric fields.

(5) Measurements of the magnetic field perturbations in the vicinity of the satellite, when it was highly biased, suggest the existence of a toroidal current system located approximately one radius from the surface (Mariani *et al.*, 1998). This is in agreement with numerical model predictions obtained by Singh and Leung (1998) and is suggestive of E×B driven current systems in the magnetosphere.

In addition to results already obtained, the investigation of satellite-ionospheric interactions under controlled conditions unique to the TSS-1R data set can improve our understanding of the collisionless expansion of plasma into the void region of the satellite's wake (Stone *et al.*, 1988). This process has many potential applications in space and was suggested by Samir *et al.* (1983) as a mechanism for closure of the Moon's wake in the solar wind. Recent measurements from the WIND spacecraft appear to confirm this prediction (Ogilvie *et al.*, 1996).

CONCLUSIONS

It is apparent from the TSS-1R data set that (1) a sharp transition in the physics of the interaction between the TSS and the ionosphere occurs, when the satellite potential exceeds +5 volts, in which electron flux to the satellite changes from being primarily accelerated ionospheric thermals, to being dominated by suprathermal electrons; and (2) the current-voltage characteristic, possibly as a result of the above transition, is in disagreement with the Parker-Murphy model—which requires an order of magnitude higher satellite potential to collect a given current. (The effects observed at the satellite are shown schematically in Figure 7.) Current extraction from the ionosphere was surprisingly efficient—to the extent, in fact, that the TSS never pushed the ionospheric plasma's limits of conductivity.

These results are extremely encouraging for scientific and technological applications of electrodynamic tethers, such as the generation and study of current systems, electromagnetic waves, or plasma disturbances in the ionosphere; the generation of electrical power or electrodynamic thrust, and the use of tethers as very low frequency/ultra low frequency (VLF/ULF) antennas. As the physics contained in the TSS-1R observations become more clear, this mission may well serve to elucidate certain plasma-electrodynamic processes commonly found to operate in the Earth's near space environment, as well as the physical properties of this environment.

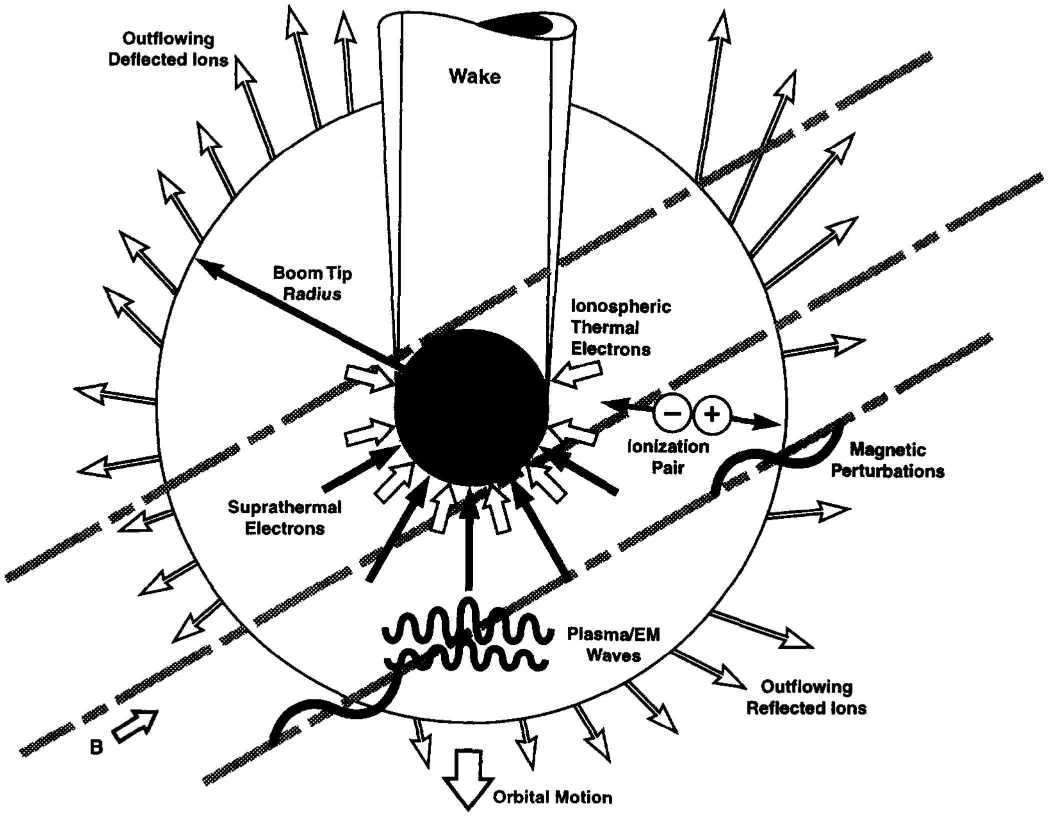

Fig. 7. A composite schematic of the complex array of physical effects and characteristics observed in the near environment of the TSS-1R satellite (after Stone and Bonifazi, 1998).

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