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Ion reflection by the TSS-1R satellite

K. Papadopoulos*, C.-L. Chang and A. Drobot

Science Application International Corporation, 1710 Goodridge Drive, McLean, VA 22102 and
*University of Maryland, College Park, MD 20742

Abstract. The results of the TSS-1R mission generated several scientific puzzles. First the current collection was much more efficient than predicted on the basis of theoretical models, and previous laboratory and rocket experiments. Second, a sharp transition in the interaction physics occurred at threshold potentials between 5–10 V. Third, a significant population of suprathermal electrons, heated ionospheric ions, and enhanced plasma waves were observed in the ram direction, following the transition. The letter contains a preliminary examination of the extent to which these phenomena are related to the interaction of the impinging ambient ram O^+ ions with the sheath surrounding the TSS satellite.

1. Introduction/Theoretical Surprises

The TSS-1R measurements generated many surprising results [*Stone and Bonifazi,* 1998]. First, for the currents commanded by the TSS circuit, the measured satellite potential was an order of magnitude lower than predicted by space charge limited, magnetically insulated flow. Furthermore, over a large current range, the observed current/voltage scaling was significantly different from theoretical models, laboratory experiments and space experiments at suborbital speeds. Figure 1 illustrates the surprising current collection efficiency of the system. It shows the value of the maximum available power, defined as $P = I\cdot(\mathcal{E} - \phi_s - \phi_{or})$ as a function of the collected current I. Here $\mathcal{E}$ is the system emf, ϕ_s the satellite potential and ϕ_{or} the orbital potential, measured during the mission. For the details of these mission measurements we refer the reader to the companion papers [*Stone and Bonifazi,* 1998; *Thomson et al.,* 1998]. The experimental results presented correspond to a day-time IV-24 cycle, with density 8.5×10^5 #/cm^3 and electron temperature 1800 K. Similar features are apparent in all of the IV-cycles and were reproduced with high reliability. The value of P is the difference between the maximum power $I\cdot\mathcal{E}$ generated and the power $I\cdot(\phi_s + \phi_{or})$ required to collect the current. It is an essential figure of merit. The experimental results are compared with the theoretical expectations based on the *Parker-Murphy* [PM] [1967] model, and the theoretical upper limit manifested by the *Beard-Johnson* [BJ] [1960] model. The results are puzzling. The applicable PM relationship would have limited the power to less than 600 W. Moreover the power would have saturated at currents of about 260 mA. The results indicate efficiencies even above the energetic upper limit given by BJ. Furthermore, no saturation was observed at the maximum current of 1.1 A which occurred during the tether break. At this point P was approximately 2 KW. The observed high efficiency is related to the low potentials that were required at the satellite to collect significant currents. Figure 2 shows the ϕ_s vs I characteristics for the above event and compares it with the expected on the basis of the PM and BJ models. The results indicate that currents between 300–500 mA were collected with potentials an order of magnitude lower than PM and factors of two or three lower than BJ.

The second surprise was related to the ϕ_s/I scaling. This is explored in Fig. 3. It shows the percentage deviations $(\phi_{PM} - \phi_s)/\phi_s$ and $(\phi_{BJ} - \phi_s)/\phi_s$ as a function of I. It is clear that within the 0.5 A range, there is no scaling consistent with the isotropic collection expected from BJ, even as modified by *Linson* [1969]. On the other hand, while large deviations are evident from the PM law, the observed scaling seems to converge towards PM for I > 300 mA but with a different coefficient of proportionality.

The third surprise was the presence of athreshold satellite voltage in the vicinity of 5–6 V. It marks a significant change in the character of the interaction physics. Related to this transition the following are observed:

(i) Ambient O^+ flowing from the forward direction of the satellite, with effective temperature larger than that of the ambient ionosphere [*Wright et al.,* 1998].
(ii) Suprathermal electrons centered around 200 eV, whose number density exhibits a four–orders of magnitude jump in population [*Winningham et al.,* 1998; *Gurgiolo et al.,* 1998].
(iii) Enhancement in wave activity in the lower hybrid (LH) range [*Iess et al.,* 1998] and evidence of turbulence in the currents measured by the BSMP in the ROPE investigation [*Wright et al.,* 1998].

These results provide conclusive evidence that physical processes different than those considered previously become important and possibly dominate the interaction physics at orbital speeds. They present a challenging theoretical problem. Here we set forth some preliminary ideas for the causes of the discrepancies and define future theoretical directions.

2. Interaction Physics at Orbital Speeds – Ion Reflection

The differences between current collection in the laboratory, collection at suborbital speeds, and the TSS-1R becomes apparent by examining the interaction from a reference frame moving with the satellite. In this reference frame the O^+ ions can be viewed as a cold ion beam with energy approximately 5 eV and temperature 0.1 eV impinging on the satellite. Since the ion cyclotron frequency Ω_i is of the order of 200–300 sec^{-1}, the O^+beam ion beam can be considered as unmagnetized. The 5 eV O^+ beam impinging on the sheath introduces two effects that were, justifiably, neglected in the

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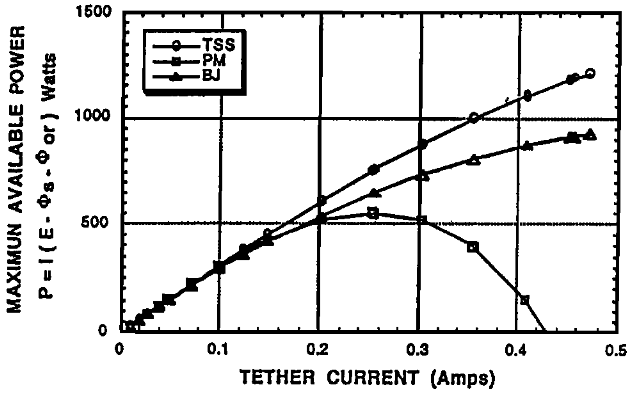

Figure 1. Maximum available power in the TSS-1R mission compared to the power expected from thhe PM and BJ models.

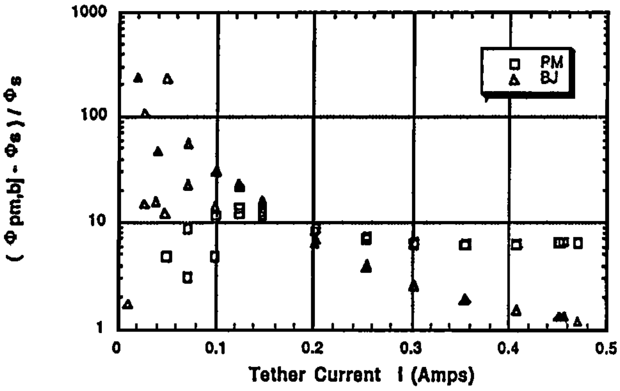

Figure 3. Comparison between the TSS-1R Φ/I scaling and those of the PM and the BJ models.

PM and BJ analysis. The first one relates to the pressure balance in the sheath and pre-sheath. In the absence of the O^+ pressure equilibrium between the expelled ions and the sheath electric field is automatically satisfied. This is not the case for large values of velocity u. Instead, the impinging ions exert on the sheath a dynamic pressure p given by $p = 1/2\, n_0 M u^2$. For $n_0 \approx 10^6$ $\#/\mathrm{cm}^3$ this corresponds to 8×10^{-7} $\mathrm{J/m^3}$, and scales linearly with the ambient density. If we introduce an electric field pressure p_E in the sheath as approximately $p_E = 1/2\, \varepsilon_0\, E^2$ we see that in order to balance 8×10^{-7} J/m^3 sheath electric fields of the order E $\approx$ 450 V/m are needed. Furthermore, the ram ions are not normal to the potential surfaces, which are determined by the projection of the collector on the magnetic field. As a result the effective ram pressure varies as $\cos^2\theta$ with maximum in the center of the tethered satellite and approaching zero at the ends of the sheath. It is unclear as to whether such an inhomogeneous equilibrium can exist in a laminar state or a dynamic or turbulent equilibrium will occur.

The second effect relates to O^+ reflection from the sheath. For potentials lower than 5 V the O^+ ions cannot be reflected in the ram direction. Such a low potential can only deflect them setting up a quasineutral, possibly orbit limited current collection, [*Laframboise and Sonmor,* 1993]. For potentials larger than 5 V ion reflection sets in. Simulations indicate total reflection at 8–10 eV potential. In the ionospheric reference frame the reflected ions form a beam moving with speed 2u and kinetic energy of 20 eV. Ram ion reflection has two consequences. It violates charge neutrality in the ram direction. The situation resembles charge neutralization of an ion beam injected into a plasma across a magnetic field [*Chrien,* 1987]. In this case large surface polarization electric fields are driven at the interface of the beam with the plasma leading to plasma ringing and electron acceleration. It is expected that this will lead to enhanced electron collection and neutralization of the reflected ions, on a few meter length scale. Accompanying this process, is the possibility of a lower hybrid (LH) instability driven by the beam which extends over an ion gyroradius ($\approx$ 100 m). The reflected ion beam constitutes a major free energy source upstream of the interaction. For an ambient density of $n_0 \approx 10^6$ #/cm^3, the available free energy per unit volume is 2×10^{13} eV/m^3 and the available power 3×10^{17} $\mathrm{eV/m^2 sec}$.

Understanding of the physics controlling current collection at orbital speeds requires solving the above issues, each one separately as well as their interplay. This is major research endeavor, beyond the scope of this letter. In the remaining of this paper we will address in a more detailed

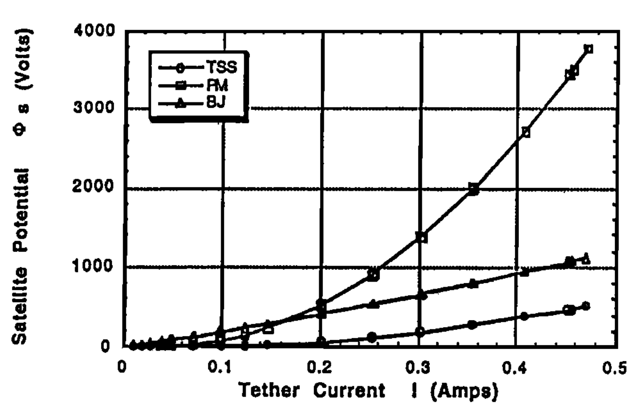

Figure 2. Voltage versus current characteristics from the TSS-1R mission, and on the basis of the PM and BJ models.

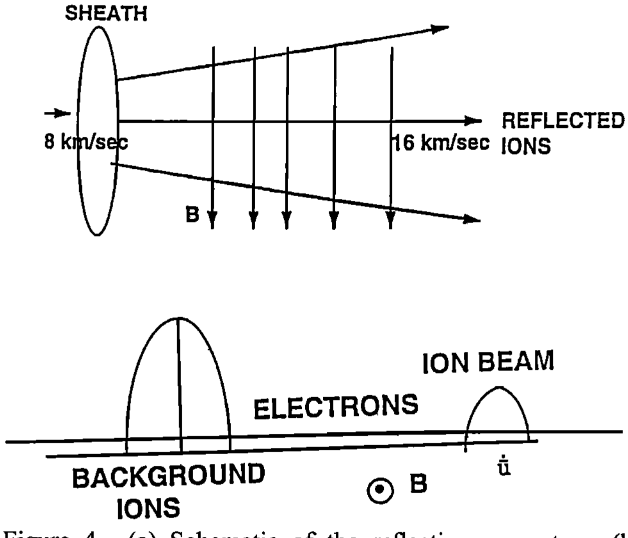

Figure 4. (a) Schematic of the reflection geometry. (b) Schematic representation of the distributions in velocity space of the background and reflected ions and the electrons.

fashion one of the above issues. The possibility that instabilities driven by ion reflection account for the ram phenomena reported by *Wright et al.* [1998], *Winningham et al.* [1998], *Gurgiolo et al.* [1998], and *Iess et al.* [1998].

3. Instabilities Driven by Reflected O^+ Ions

We examine here the observables expected by instabilities driven by the reflected ions and compare with observations. We emphasize bulk plasma waves, rather than surface waves due to the charge neutralization process. The situation is shown schematically in Fig. 4. Below 5 eV there is no ion reflection, and no free energy. For larger potential ions are reflected forming an ion beam. The free energy per unit volume available is the same independently of the sheath potential and structure. Larger potential a will probably produce larger sheaths, resulting in larger total available free energy and stronger reflected O^+ – plasma interactions. The situation resembles the physics of the electron foreshock in the earth's quasi-perpendicular bow shock at supercritical Mach numbers [*Papadopoulos,* 1982]. In this case ion reflection from the magnetic overshoot results in the formation of an ion beam upstream. The subsequent interaction of the beam with the plasma generates large amplitude waves in the lower hybrid range and creates suprathermal electron tails with energy exceeding 1–2 keV.

The dispersion relation for a system such as shown in Fig. 4b has been examined by many authors [*Papadopoulos,* 1982, 1984; *Mobius et al.,* 1987]. It incorporates two types of instabilities that have the characteristic frequency

$$\omega_k^2 = \omega_{LH}^2 \left[1 + \left(M/m \cdot k_z^2/k^2\right)\right] \tag{1}$$

where M is the O^+ mass and $\mathbf{B} = \hat{e}_z B$. For a monoenergetic beam, there is a coherent hydrodynamic instability which turns quickly into the beam kinetic instability.

Papadopoulos [1992a] extended the infinite homogeneous analysis to systems where the beam is spatially limited, such as the case of critical velocity ionization experiments and the tether reflection case. His analysis included the three-dimensional electron nonlinearity [*Shapiro and Sevchenko,* 1984] which can lead to collapse and creation of localized soliton like structures. The latter effect occurs when the electron drift velocity $\tilde{E}/B$ in the presence of a low frequency fluctuating field $\tilde{E}$ exceeds the speed of sound. For values of $c_s \approx 5$ km/sec, the threshold field is about 10–20 mV/m. We refer the interested reader to *Papadopoulos* [1992a], and simply summarize the results and apply them to the tether reflection.

For a system spatially limited in the magnetic field direction (z-direction) with a length L_0 such that $L_0 < \bar{u}/\omega_{LH}\sqrt{M/m}$ where $\bar{u}$ is the transverse velocty of the reflected ions, the maximum growth occurs at the first confined mode, i.e. $\pi/k_{z_0} = L_0$. When the threshold of 10–20 mV/m is exceeded self-similar solutions indicate that in the collapsing state the wave energy W scales as [*Sotnikov et al., 1978*]

$$k_z(t) \sim \frac{W}{n_0 T}, \qquad k_\perp(t) \sim \sqrt{\frac{W}{n_0 T}}, \qquad \frac{k_z(t)}{k_\perp^2(t)} \approx \text{const.}, \quad \text{and} \quad k_z^{-1}(t) \sim \frac{1}{t-t_0}. \tag{2}$$

Equations (2) indicate that although the initial instability creates waves with strongly anisotropic polarization, the collapse tries to isotropize them.

Another profound consequence of the collapse is the suprathermal tails generated by the interaction of the electrons with collapsing wavepackets. The tail formation is described by a non-resonant Fokker-Planck equation similar to the one derived by *Morales and Lee* [1974] for Langmuir turbulence. The evolution of the distribution function of the suprathermal electron tails $f(\varepsilon)$ is given by [*Papadopoulos,* 1992a,b]

$$\frac{\partial f(\varepsilon)}{\partial t} = \frac{\partial}{\partial \varepsilon}\varepsilon D(\varepsilon)\frac{\partial f(\varepsilon)}{\partial \varepsilon} \tag{3}$$

$$D \equiv \frac{1}{2} m \frac{<\Delta v \Delta v>}{\tau} \approx 2\pi^2 \tilde{\varepsilon}\omega_{LH}\left(\frac{\varepsilon_0}{\varepsilon}\right)^{1/2} \times sech^2\left[0.12\left(\frac{\varepsilon_0}{\varepsilon}\right)^{1/2}\right] \tag{4}$$

$$\varepsilon_0 = \frac{1}{2} M\bar{u}^2, \qquad \tilde{\varepsilon} = \frac{1}{2}\frac{e^2E^2}{m\Omega_e^2} \tag{5}$$

The particular sech dependence is simply due to the selected form of solitons. Equation (3) describes a particular form of second order Fermi acceleration, in which the electrons E/B quiver according to eq. (5) and lose their energy adiabaticity if their field aligned velocity is fast enough to transit the soliton faster than $1/\omega_k$ [*Morales and Lee,* 1974; *Manheimer and Papadopoulos,* 1975; *Bingham et al.,* 1993].

4. Comparison with Experimental Data

We compare next the TSS-1R measurements with the above theoretical estimates. The wave measurements [*Iess et al.,* 1998] indicate wave amplitudes of up to 12 V/m for satellite potentials of the order of 10 V/m, when ion reflection is expected. The waves have broadband frequency with maximum spectral density between 2–3 kHz, below the LH frequency which is 6.4 kHz. This exceeds by far the collapse threshold. For $E \sim 12$ V/m, $n_0 \approx 8 \times 10^5$ #/cm^3 and .1 eV temperature, $W/n_0T \approx 6 \times 10^{-2}$. On the basis of eqs. (2), we expect that the LH cavities will have dimensions of the order of 20 cm in the transverse direction and 4–6 m in the parallel direction. From *Papadopoulos* [1992; eq. (17)] the observed frequency ω_0 will be given by $\omega_0 \approx 2\omega_{LH}\sqrt{\frac{W}{n_0 T}}$which for $W/n_0T \approx 6 \times 10^{-2}$ corresponds to 2–3 kHz, consistent with the observations by *Iess* et al.[1998].

Consider next the transit time acceleration of electrons. Since the parallel scalelength of the wavepackets is of the order of $\ell \approx 6$m, only electrons with parallel velocity $v >> \ell\omega_{LH} \approx 3 \times 10^7$ cm/sec can be accelerated. From eqs. (3–5) [see also *Papadopoulos, 1992b*], the time required for acceleration to energy ϵ is given by

$$\tau_0(\varepsilon) = \frac{\varepsilon}{D} = 5 \times 10^{-2}\left(\frac{\varepsilon}{\tilde{\varepsilon}}\right)\left(\frac{\varepsilon}{\varepsilon_0}\right)^{1/2}\omega_{LH}^{-1} \tag{6}$$

For $\varepsilon \approx 200$ eV, the time required for acceleration to 200 eV is 8×10^{-3} sec. For the TSS case it requires that the turbulence extends to 60 m ahead of the probe.

The expected distribution function can be found by considering a stationary process so that, eq. (3) gives

$$\varepsilon D(\varepsilon)\frac{\partial f}{\partial \varepsilon} = \text{const} \tag{7}$$

and using eq. (4) for $D(\varepsilon)$, we find $\partial f/\partial \varepsilon \sim 1/\varepsilon^{3/2}$ which is also consistent with the dependence reported by *Winningham et al.* (1998).

We finally examine heating of the reflected ions. In the presence of $E \approx 12$ V/m at the LH range the sloshing of the beam ions is $\Delta v = eE/M\omega_{LH} \approx 2 \times 10^3$ m/sec which corresponds to an effective reflected ion temperature $\frac{1}{2}M(\Delta v)^2 \simeq .3 - .4$ eV consistent with the one reported by *Wright et al.* [1998].

5. Concluding Remarks

This letter is an attempt to explore and list the factors responsible for the theoretical puzzles observed in TSS-1R. The preliminary analysis indicates that the main reason for the discrepancies is associated with ion reflection from the sheath and the required dynamic pressure balance between the impinging ions and the electric fields in the sheath. From the three factors associated with reflection – pressure equilibrium, violation of charge neutrality, and ion reflection driven instabilities – we concentrated on the last. The observed 5 V threshold behavior, the enhanced wave activity and frequency, the presence of suprathermal electron tails, and the observed heating of the reflected ions are, at least to zero order, consistent with theoretical expectations instability. How and to what extent reflection, coupled with sheath equilibrium and non-neutrality produces the high current collection efficiency is a major theoretical challenge not yet resolved.

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K. Papadopoulos, C.-L. Chang and A. Drobot, Science Application International Corporation, 1710 Goodridge Drive, McLean, VA 22101. (e-mail: kp@astro.umd.edu)

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