Current Collection by Rapidly Moving Charged Bodies in the Ionosphere: TSS-1R Results

G. Vannaroni, M. Dobrowolny, F. De Venuto, L. Iess

Istituto di Fisica dello Spazio Interplanetario – CNR – Rome, Italy

Abstract. In this paper we present an analysis of the I-V characteristics measured during the TSS-1R mission. The results strongly indicate that the electron current collection by the satellite at high potential is dominated by the space charge effects. The experimental data are compared with the characteristic predicted by a new model that considers both the space charge and the effect of the magnetic field on the attracted particles. The theoretical model provides a normalized current-voltage curve with a functional dependence in good agreement with the TSS-1R data. In particular the best agreement is obtained by applying an enhancing factor of 2.7 to the electron thermal current density. Such enhancement is likely due to effects associated to the relative velocity between the satellite and the ionospheric plasma.

1 - Introduction

The TSS-1R satellite, flown in 1996 on board the STS-75 mission, has provided a detailed set of data that are of extreme interest for understanding the physical processes associated to the current collection by a charged body in the ionosphere. In particular TSS-1R has given unexpected, and in a certain way innovative, results in that the collected currents have values not explainable in terms of the models developed in the past for an electrically biased body in a plasma medium [*Langmuir and Blodgett,* 1924; *Parker and Murphy,* 1967; *Beard and Johnson,* 1961; *Beard,* 1966; *Linson,* 1969; *Alpert and al.,* 1965].

In the TSS experimental configuration the satellite bias with respect to the ionosphere was obtained by exploiting the emf induced in the conductive tether due to the relative motion with respect to the terrestrial magnetic field. The tether length, during the mission, reached the value of 19.7 km, giving induced voltages up to 3.5 kV. The satellite potential was indirectly controlled by the current flowing in the tether that, in turn, could be set by an electron gun operating on board the orbiter. The TSS-1R allowed the study of the current-voltage (I-V) characteristics of the satellite in an extended range of potentials. In particular during the satellite deployment a total number of 18 I-V sweeps (each consisting of 16 pairs of (I,V) values) were measured; the maximum satellite potential was 1.1 kV and the maximum collected electron current was of about 0.5 A . The I-V characteristics were acquired under a large spread of plasma density conditions determined by the diurnal cycles providing additional worthwhile information to investigate the basic electrodynamics of charged bodies in plasma. A complete description of the TSS experimental configuration and the experiments operating on board the satellite and the orbiter can be found in [*Dobrowolny,* 1994].

In this paper we present an analysis of the I-V characteristics which indicates that the electron current collection by the satellite at high potential is mainly dominated by the space charge effects. In addition the results presented show that the experimental data compare quite well with the theoretical I-V characteristic derived by a new model [*Dobrowolny et al.,* 1998] which is based on space charge theory but considers also the effect of the magnetic field.

The paper is organized as follows: Sect.2 deals with an analysis of the TSS-1R experimental characteristics. This study, that was preliminarly reported in *Vannaroni et al.* [1998], shows that the current collected by the satellite, conveniently normalized to the ionospheric electron thermal current, exhibits a clear dependence from the non-dimensional satellite potential Φ_s^* given by

$$\Phi_s^* = \frac{e\Phi_s}{kT_e}\left(\frac{\lambda_D}{r_s}\right)^{4/3} \tag{1}$$

where λ_D is the Debye length ($\lambda_D = \varepsilon_0\, k\, T_e\, /\, n_0\, e^2$). As the potential Φ_s^* is typical of all the theories that analyze the current collection processes through the solution of the Poisson's equation, this dependence implies that the current collection is controlled by space charge effects. In sect.3 we introduce the general features of the theoretical model and discuss the results obtained in terms of the I-V characteristic. The theoretical curve is then compared with the experimental data. We find that the theory reproduces pretty well the experimental I-V curve if we use a multiplier factor of the order of 3 to enhance the theoretical points. We point out that an effect due to the velocity flow (suggested by several authors [*Cooke and Katz,* 1998; *Laframboise,* 1997]) may provide a plausible explanation of this enhancement factor. Sect. 4 summarizes the main results.

2 - Analysis of the TSS-1R I-V curves

A global picture of the entire set of data collected during the TSS-1R mission is shown in the Fig.1. In that figure we have shown a cumulative representation of all the current-voltage pairs of (I,V) values measured during the deployment of the satellite from the orbiter. In the figure we have shown the data plotted according to the formulations relevant to a pair of different models, *Parker and Murphy* (PM) [1967] and *Alpert* (Al) [1965] respectively.

In the two axes of the plot shown in the top panel of Fig.1 we have used the normalization required by the PM model. The current is normalized to the electron thermal current I_0 that would be collected by a spherical body in a non magnetized plasma

$$I_0 = \pi r_s^{\,2}\left(\frac{8kT_e}{\pi m_e}\right)^{1/2} e n_0 \tag{2}$$

and the satellite potential Φ_s is normalized to a potential

$$\Phi_0 = \frac{e r_s^2 B^2}{2m_e} \tag{3}$$

that represents, essentially, the energy of an electron with a Larmor gyro-radius equal to the satellite radius.

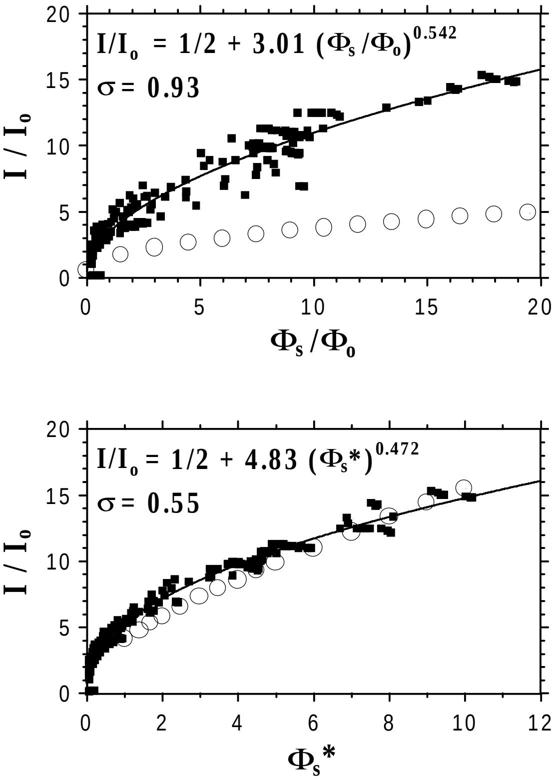

Figure 1. Cumulative representation of the I-V data obtained during the TSS-1R mission. The top panel is relevant to the PM normalization, the bottom panel to the Al formulation. The squares and open circles refer to experimental and theoretical points respectively. Solid lines represent the best fit of data to a power law.

The PM model predicts a functional dependence of the form

$$\frac{I}{I_0} = \frac{1}{2} + \left(\frac{\Phi_s}{\Phi_0}\right)^{1/2} \tag{4}$$

and assumes that the collected current is limited only by the magnetic field. It is based on the conservation of the energy and canonical angular momentum of the attracted particles and analyzes the problem under the point of view of a single particle motion neglecting therefore the space charge effect. In the figure we have also shown a set of theoretical points (open circles) expected from the PM model.

In the bottom panel we have plotted the same experimental data using the formulation relevant to the Al model. In this case the current is again normalized to the electron thermal current but the satellite potential is now normalized according to the definition of eq.(1).

The Al model solves the Poisson's equation and, therefore, considers the space charge effects neglecting, however, the magnetic field. Even in this case the theoretical points predicted by the model are shown in the plot through the open circles. The theoretical relationship I/I_0 vs. Φ_s^* can be obtained from Table XXVI of [*Alpert et al.*, 1965].

From the comparison of the two plots, we see, first of all, that the experimental points group together much better when I / I_0 is plotted vs. Φ_s^* than vs. Φ_s/Φ_0. It is true that the scatter of the points may be due to experimental errors, in particular in the plasma density and temperature, but this must hold for both cases as we are dealing with the same set of data. In addition, we notice the good agreement of the data points with the prediction of Al theory.

The dispersion of the points has been estimated in a quantitative way through regression procedures. In particular, for both normalizations, we have fitted the data to a power function, using the additional constrain that an extrapolation at zero potential must reproduce a normalized current equal to ½ as expected for electrons guided along magnetic field lines.

The results of the best fit (solid lines) are shown in the two panels of the Fig.1. As expected from the appearance of the two plots, the standard deviation is much lower in the case of the Al model (σ = 0.55) than for PM (σ = 0.93). The exponent of the power law is 0.542 for PM normalization and 0.472 for that associated to the Al model. As we can see for both models the exponents are close to 0.5, therefore in both cases the current is expected to vary, approximately, as a function of the square root of the satellite potential.

Therefore from this preliminary analysis we have drawn the conviction that the current collection in the TSS-1R satellite is actually regulated by the space charge.

3 - Space charge limited theoretical model and comparison with TSS-1R data

The theory developed by *Dobrowolny et al.* [1998] is based on the asymptotic analysis of the electron momentum equation

$$nm_e \frac{d\vec{v}_e}{dt} = -ne(-\nabla\Phi + \vec{v}_e \times \vec{B}) - \nabla p_e \tag{5}$$

It has been found that, for potentials larger than

$$\Phi_\varepsilon = \frac{kT_e}{e}\left(\frac{r_s}{a_e}\right)^2 \tag{6}$$

being a_e the electron Larmor radius ($a_e = m_e \, v_{the} / e\, B$), the inertia forces dominate the magnetic forces and the current collection takes place under the effect of a potential structure characterized by spherical symmetry. Φ_ε is for the TSS-1R conditions equal to about 40 V (notice that the definition of Φ_ε coincides approximately with the definition of the dimensionless potential Φ_0 of the PM theory).

The current collection can be qualitatively depicted as in the Fig.2. We have essentially two regions. An inner region where the potential decreases with spherical symmetry from the satellite potential Φ_s down to Φ_ε. Then we have an outer region where, instead, electron channeling along the magnetic field takes place and therefore the self-consistent potential exhibits a cylindrical symmetry. Here the velocity of the electrons is assumed parallel to *B*. The model assumes that the particle velocity, radial in the inner region, is discontinuously matched (in magnitude) to the electron velocity in the outer region with the additional assumption that, there, the electron velocity is mainly parallel to the magnetic field vector ($v_{r\varepsilon} \cong v_{z\varepsilon}$ with the z axis parallel to *B*). The external region extends up to the boundary with the quasi neutral plasma. Thus the potential in the outer region decreases from Φ_ε down to $\Phi_v \cong 5.3$ V which corresponds to the energy of the O^+ ions due to the relative motion between the satellite and ionosphere (≅ 8 km/s). The theoretical analysis examines essentially the inner region as a spherical diode by considering an external cathode at radius r_ε and an inner anode (the satellite) of radius r_s.

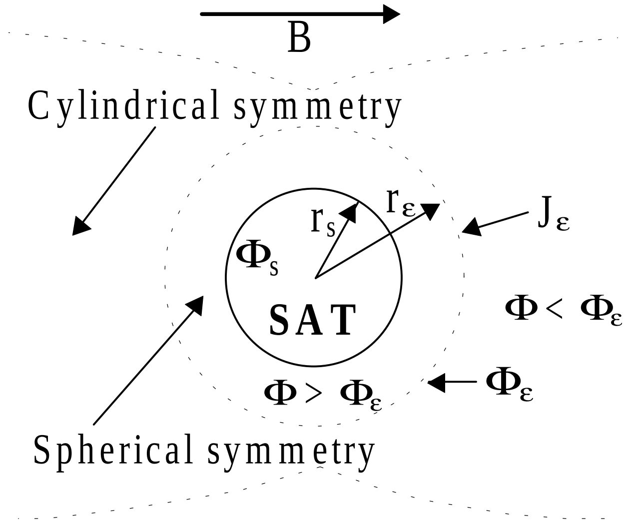

Figure 2. Schematic illustration of the perturbed region surrounding the charged satellite.

As shown in *Dobrowolny et al.* [1998], the current collection can be described by the following set of equations

$$\left(\Phi_\varepsilon^*\right)^{3/2} + \frac{9}{8\sqrt{\pi}} J'_\varepsilon \left(\frac{r_\varepsilon}{r_s}\right)^2 \alpha_{LB}^2(\gamma_s) = \left(\Phi_s^*\right)^{3/2} \qquad (7)$$

$$\frac{I}{I_0} = J'_\varepsilon \left(\frac{r_\varepsilon}{r_s}\right)^2 \qquad (8)$$

where Φ_ε^* is a normalized potential given by

$$\Phi_\varepsilon^* = \frac{e\Phi_\varepsilon}{kT_e}\left(\frac{\lambda_D}{r_s}\right)^{4/3} \qquad (9)$$

and J'_ε is the current density entering into the isotropic region normalized to the current density of the unperturbed ionosphere. The first term in the equation depends on the magnetic field and, indeed, this goes to zero if we put *B* equal to zero. Without this term we remain with the same equation of the spherical diode of the *Langmuir and Blodgett* [1924] (LB) theory. $\alpha_{LB}(\gamma_s)$ is in fact the same α calculated in that analysis.

The current density J'_ε consists of two terms corresponding to the possible electron velocity directions, parallel or orthogonal to the direction of *B*, respectively. In particular the perpendicular term is estimated by considering the particle drift associated to the crossed electric and magnetic fields. With reference to the results described in *Dobrowolny et al.* [1998] the expression of J'_ε is:

$$J'_\varepsilon = \frac{1}{2} + \left(\frac{r_s}{r_\varepsilon}\right)^2 \qquad (10)$$

Substituting this expression in eq.(7) we obtain an implicit equation for r_ε . Finally, the characteristic I / I_0 vs. Φ_s^* is obtained from the simultaneous solution of eqs.(7) and (8). This is shown in Fig.3 (open circles) where we have also plotted the the experimental data relevant to the TSS-1R flight (the squares).

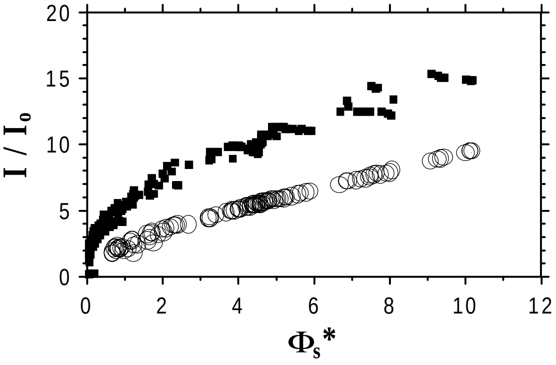

Figure 3. Comparison between TSS-1R data (squares) and theoretical points predicted by the model (open circles).

As we can see the actual values measured in flight are significantly higher than the normalized currents predicted by the model. This could be explained by considering the possible effects due to the plasma flow in our moving system. This aspect has been already analyzed by *Cooke and Katz* [1998]. In particular, they considered the possible heating due to the plasma instabilities occurring when the electrons experience, in the pre-sheath, the acceleration associated to the potential jump necessary to reflect the ions (5.3 V). The enhancement of the electron temperature, in turn, produces the increase of the thermal current at the input of the sheath. The enhancement factor for the TSS-1R conditions has been estimated of the order of 3.

As already mentioned, the outer region of the model described here extends up to the point where the local potential is $\Phi_v \cong 5.3$ V as beyond that point the presence of the ions neutralizes the space charge. This point coincides with the inner boundary of pre-sheath, therefore, it is reasonable to assume that the input thermal current of our model will be higher than that expected from the unperturbed ionosphere. We have taken such an effect into account by introducing a multiplying factor $\beta > 1$ in the definition of J'_ε. By solving the eqs. (7) and (8) for a new $J'' = \beta J'$ and varying β, we have determined the theoretical characteristic that provides the best match with the experimental points.

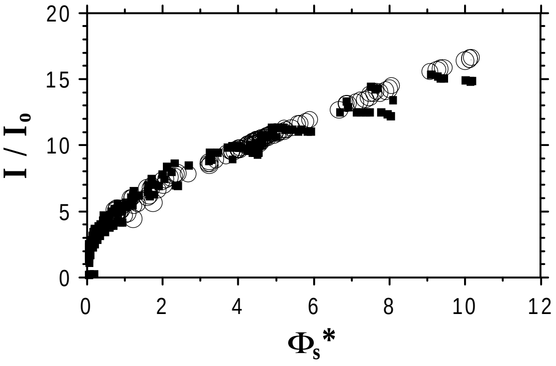

Figure 4. Comparison between TSS-1R data (squares) and theoretical points predicted by the model (open circles) when the current density *J'* is enhanced by the factor β = 2.7.

A value of β = 2.7 gives the best agreement with the data; the result is shown in the Fig.4 where the theoretical points (open circles) have been plotted along with the experimental data (squares). The agreement can be further substantiated in quantitative way by comparing the analytical functions obtained from the best fit of the experimental and theoretical points to a power law. The best fit of the theoretical points shown in Fig.4 gives:

$$\frac{I}{I_0} = \frac{1}{2} + 4.31\left(\Phi_s^*\right)^{0.551} \qquad (11)$$

This expression must be compared to that associated to the experimental points indicated in the bottom panel of Fig.1. As we can see the coefficients of the two expressions are relatively close each other so that we can conclude that the TSS-1R characteristic agrees quite well with the predictions of the theoretical model based on the space charge theory presented here.

4 - Conclusions

In this paper we have analyzed the current-voltage characteristic measured during the TSS-1R mission. First of all the experimental curves have been compared with the characteristics predicted by two different models. The first one is the *Parker and Murphy* [1967] model that considers a current collection process only limited by the magnetic field effect. The second is the *Alpert et al.* [1965] model. This model is based on the solution of the Poisson's equation and considers only the limiting effect of the space charge. From this analysis we have shown that the normalized current I / I_0 exhibits a functional dependence on Φ_s^* . This feature gives a strong indication of the fact that the current collection in the TSS-1R conditions is controlled by the space charge.

Then we have presented the main points of a recent model developed by *Dobrowolny et al.* [1998]. This model is mainly based on the space charge theory but considers also the effect of the magnetic field. We have shown that this model provides a normalized current-voltage curve with a functional dependence (currents vs. potentials) in very good agreement with the TSS-1R data. The best agreement with the experimental points is obtained, however, if we consider a multiplying factor of 2.7 to enhance the electron thermal current density above the value determined by the unperturbed plasma parameters. We point out that such enhancement could be due to effects associated to the relative flow between the satellite and ionosphere and observe that the factor of 2.7 is, in fact, very close to the enhancement factor determined by *Cooke and Katz* [1998].

References

Alpert, Y. L., A. V. Gurevic, L. P. Pitaewskii, Disturbance of the plasma and the electric field in the vicinity of a charged body at rest, in *Space Physics with Artificial Satellites,* p. 186, Consult. Bur., New York, 1965.

Beard D. B., F. S. Johnson, Ionospheric Limitations on Attainable Satellite Potential, *J. Geophys. Res.,66,* 4113, 1961.

Beard, D. B., Correction to Paper by David B. Beard and Francis S. Johnson, "Ionospheric Limitations on Attainable Satellite Potential", *J. Geophyis Res., 71,* 4707, 1966.

Cooke, D. L., I. Katz, TSS-1R electron currents: Magnetic limited collection from a heated presheath, *Geophys. Res. Lett., 25,* 753, 1998.

Dobrowolny, M., (Editor), *Special TSS-1 Issue,* pp. 1-141, *Il Nuovo Cimento, Soc. Ital. Fis. C 17,* 1, 1994.

Dobrowolny, M., G. Vannaroni, F. De Venuto, Electron collection by a charged satellite in the ionospheric plasma, Internal Report IFSI-CNR, IFSI-98-6, 1998, submitted to *Il Nuovo Cimento C,* (1998).

Laframboise, J. G., Current collection by a positively charged spacecraft: Effects of its magnetic presheath, *J. Geophys Res., 102,* 2417, 1997.

Langmuir, I., K. Blodgett, Currents limited by space charge flow between concentric spheres, *Phys. Rev., 24,* 49, 1924.

Linson, L. M., Current-Voltage Characteristics of an Electron-Emitting Satellite in the Ionosphere, *J. Geophys, Res., 74,* 2368, 1969.

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

Vannaroni G., M. Dobrowolny, J. P. Lebreton, E. Melchioni, F. De Venuto, C.C. Harvey, L. Iess, U. Guidoni, C. Bonifazi, F. Mariani, Current-voltage characteristic of the TSS-1R satellite: Comparison with isotropic and anisotropic models, *Geophys. Res. Lett., 25,* 749, 1998.

G. Vannaroni, Istituto di Fisica dello Spazio Interplanetario – CNR, via del Fosso del Cavaliere 100, 00133 Rome, Italy. (e-mail: vannaro@ifsi.rm.cnr.it)

M. Dobrowolny, Istituto di Fisica dello Spazio Interplanetario – CNR, via del Fosso del Cavaliere 100, 00133 Rome, Italy. (e-mail: dobrowolny@asi.it)

F. De Venuto, Istituto di Fisica dello Spazio Interplanetario – CNR, via del Fosso del Cavaliere 100, 00133 Rome, Italy. (e-mail: devenuto@ifsi.rm.cnr.it)

L. Iess, Istituto di Fisica dello Spazio Interplanetario – CNR, via del Fosso del Cavaliere 100, 00133 Rome, Italy. (e-mail: iess@nero.ing.uniroma1.it