Comparison of Spacecraft Charging Environments at the Earth, Jupiter, and Saturn

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Studies of the Earth with the ATS-5, ATS-6, and SCATHA spacecraft led to the development of several simple tools for predicting the potentials to be expected on a spacecraft in the space environment. These tools have been used to estimate the expected levels of worst case charging at Jupiter and Saturn for the Galileo and the Cassini missions. This paper reviews those results and puts them in the context of the design issues addressed by each mission. In the case of Galileo, spacecraft to space potentials of ~1000 V were predicted. As such levels could produce possible discharges and could effect low energy plasma measurements, the outer surface of Galileo was held to rigid conductivity requirements. Even though the surface of Galileo was not entirely conducting, after 14 orbits no adverse effects due to surface charging have been reported. The Saturnian environment, in contrast to Jupiter, results in spacecraft potentials to space of ~100 V--levels. The overall surface of the Cassini spacecraft also was not entirely conducting and grounded. Here it is shown that only in the most extreme conditions is it expected that Cassini will experience any effects of surface charging at Saturn. Those conditions are presented and the likely consequences are mentioned.

INTRODUCTION

Surface charging is not just a concern for spacecraft in geosynchronous orbit (DeForest and McIlwain, 1971), but also to a varying degree in other regions of the Earth's magnetosphere and throughout the solar system. In particular, high levels of charging (greater than a few hundred volts) are expected in the Earth's auroral zones at high latitudes (Gussenhoven, 1985) and at Jupiter (Divine and Garrett, 1983). Here a simple software tool developed for the Earth's environment is extended to predict surface potentials at Jupiter and Saturn. The results have been used by the Galileo and Cassini missions in determining the level and hence design requirements for surface potential mitigation.

In this paper, the Earth's, Jupiter's, and Saturn's environments are described. The basic assumptions of the simple tool for calculating charging will be reviewed. Estimated surface potentials for each of the environments will be presented. The results for Earth and, at least preliminarily, Jupiter and Saturn are consistent with observations demonstrating to first order the value of the tool for mission design.

THE ENVIRONMENTS

Table 1 lists the principle characteristics of the terrestrial, jovian, and saturnian magnetospheres. Jupiter and Saturn are roughly 10 times the size of the Earth while their magnetic moments are 10^5 and 10^3 larger. As the magnetic field at the equator is proportional to the magnetic moment divided by the cube of the radial distance, the terrestrial and saturnian magnetospheres relative to their planetary radii are similar. The jovian magnetic field, however, is 100 times larger. An additional consideration is that the photoelectron flux at 1 AU for the Earth is ~25 times that at Jupiter (~5 AU) and ~100 times that at Saturn (~10 AU).

Table 1. The Planets' Magnetospheres

<u>Earth</u>	
-equatorial radius (km)	$6.38x10^3$
-magnetic moment (G-cm^3)	$8.10x10^{25}$
-rotation period (hrs)	24.0
-aphelion/perihelion (au)	1.01/0.98
<u>Jupiter</u>	
-equatorial radius (km)	$7.14x10^4$
-magnetic moment (G-cm^3)	$1.59x10^{30}$
-rotation period (hrs)	10.0
-aphelion/perihelion (au)	5.45/4.95
<u>Saturn</u>	
-equatorial radius (km)	$6.00x10^4$
-magnetic moment (G-cm^3)	$4.30x10^{28}$
-rotation period (hrs)	10.23
-aphelion/perihelion (au)	10.06/9.01

The rotation rate is also an important factor. Both Jupiter and Saturn spin over twice as fast as the Earth--~10 hours versus 24 hours. Given their strong magnetic fields, this means that the cold plasma trapped in these magnetospheres is forced to corotate at velocities much higher than a spacecraft orbital velocity. This is opposite to the situation at Earth where, at low altitudes, a spacecraft orbits at ~8 km/s faster than the ionospheric plasma. Co-rotation velocities can range from 30-40 km/s near Jupiter and Saturn to over 100 km/s in their outer magnetopsheres.

As the magnetosphere is the primary controlling factor for the local plasma environments, the charging environment differs considerably for each of these planets. It is these differences that will be described in the following paragraphs.

Earth

The Earth has one of the most complex and variable magnetospheres in the solar system. As will be shown, it may also have the highest charging levels. In terms of a simple schematic of the Earth's magnetosphere, there are 4 main plasma populations. Starting with the lowest latitude regime, the "ionospheric" population extends the cold ionosphere out along closed field lines to 3 to 5 R_e (typically called the plasmasphere). The plasma varies from a density of ~10^6/cm^3 (O^+ dominated) at 100 km to ~100/cm^3 (H^+) at 4 to 5 R_e. The mean energy varies from a few tenths of an eV at low altitudes to 10-100 eV at high altitude. The auroral regime is at higher latitudes and extends out to higher altitudes. This population is represented by the aurora at low altitudes and the plasmasheet at geosynchronous orbit. The plasma typically consists of an electron/H^+ composition with several 10's of keV mean energy. Superimposed on these two regimes is the Van Allen regime marked by the trapped radiation belts. These consist primarily of high energy (E>100 keV) electrons and protons. Although of small direct importance to surface charging, the high energy electrons are the primary source of internal charging. The final regime, the very high latitude regime, is characterized by low densities (0.1 cm^{-3}) and energies (200 eV) with occasional bursts of high velocity streams (800 km/s). The field lines at very high latitudes eventually couple with the interplanetary magnetic field.

Jupiter

The magnetosphere of Jupiter is dominated by three factors: the magnetic field tilt (11°) relative to its spin axis, its rapid rotation, and the jovian moon Io at 5 R_j. Io generates a vast torus of gas. The more rapid rotation of Jupiter's magnetic field forces the cold plasma associated with this torus to accelerate and expand by centrifugal force into a giant disc. The magnetic field tilt and rotation rate make this plasma disc wave up and down so that at a given location plasma parameters vary radically over a 10 hour period. Jupiter's environment can be roughly divided into three populations: the cold plasma associated with the Io torus and the plasma disc (0<E<1 keV), the intermediate plasma (1 keV<E<60 keV), and the radiation environment (E>60 keV). The cold plasma is characterized by high densities (~2000 cm^{-3}) and low energies. The plasma consists of hydrogen, oxygen (singly and doubly ionized), sulfur (singly, doubly, and triply ionized), and sodium (singly ionized) ions. Intermediate energy electrons (~1 keV) and protons (~30 keV) at Jupiter are assumed to vary exponentially from ~5 cm^{-3} for r < 10 R_j to 0.001 cm^{-3} beyond 40 R_j (Divine and Garrett, 1983). Co-rotation velocities vary from ~45 km/s at 4 R_j to ~250 km/s at 20 R_j.

Saturn

Saturn is marked by a magnificent set of rings that are its most obvious feature and set it apart from all the other planets. Aside from the rings, however, Saturn's magnetosphere resembles Jupiter's--a cold inner plasma disk giving way to a lower density, slightly higher energy plasma disk at large distances. Although there is no "Io-equivalent" moon in the inner magnetosphere, there is still a fairly dense cold plasma sheet and, at ~20 R_s, Saturn's huge moon Titan contributes a large cloud of neutral gas in the outer magnetosphere. Unlike Jupiter, Saturn's magnetic field axis is apparently aligned with the spin axis so that the plasma ring around Saturn is relatively stable compared to that of Jupiter. Plasma co-rotation velocities are similar to Jupiter though maximum velocities tend to peak a little above 100 km/s.

THE MAJOR CURRENT TERMS

A mathematical model capable of first order estimates of spacecraft surface to space plasma potential (charging potential) for a variety of conditions has been developed (e.g., Tsipouras and Garrett, 1979; Garrett, 1981). The model (or design tool) is based on current balance. Incoming electrons and ions are balanced by photoemission, backscattering, and secondary emission. The program varies the spacecraft to space potential until the total current is 0 according to the following equation:

1) $I_T(V)=I_E(V)-(I_I(V)+I_{SE}(V)+I_{SI}(V)+I_{BSE}(V)+I_{PH}(V))$

Where:

V = surface potential relative to space,
I_T= total current to spacecraft surface at V;
= 0 at equilibrium when all the current sources balance,
I_E = incident ambient electron current,
I_I = incident positive ion current,
I_{SE}= secondary emitted electron current due to I_E,
I_{SI}= secondary emitted electron current due to I_I,
I_{BSE} = backscattered electron current due to I_E,
I_{PH} = photoelectron current.

The incident electron and ion currents are typically estimated by integrating the appropriate Maxwellian distributions (Eq. 2) to obtain the current as a function of temperature, number density, and potential. The secondary and backscatter surface currents are then obtained by integration using the Maxwellians--the results have been parameterized by fitting them in terms of the temperature, number density, and potential (see Tsipouras and Garrett, 1979; and Garrett, 1981). Aluminum is used in this study as the surface material. The photoelectron current is similarly parameterized in terms of the potential and material.

The basic Maxwellian distribution is given by:

2) $$F_M = N(M/2\pi E_o)^{3/2} e^{-E/E_o}$$

Where:

M = Particle mass

F_M = Maxwell-Boltzmann distribution

N = Number density

E_o = Characteristic energy of plasma

E = Particle energy

Whereas Maxwellian distributions adequately represent many of the plasma environments encountered in space, they are often inadequate for explaining the complex environments at Jupiter and Saturn. For co-rotating ion plasmas, a "ram" approximation is often more appropriate:

3) $$I_R = \pi R^2 N V_S$$

Where:

I_R = "Ram" current

R = Radius of spherical spacecraft

V_S = Spacecraft velocity relative to plasma

The Jovian and Saturnian environments are characterized by a harsher radiation environment at high energies than the Earth's. As a result, a Maxwellian distribution does not join smoothly onto the high energy spectra for the protons and electrons. If the latter power law spectra are cut off at an arbitrary low energy, the resulting discontinuity causes difficulties in computing the total current density of the electrons to a satellite surface in the jovian environment.

To derive a smooth distribution function for the warm electrons and protons, the Kappa distribution function F_κ in cm^{-6}-s^3 (see Vasyliunas, 1968) was employed:

4) $$F_\kappa = N(M/2\pi E_o)^{3/2} \kappa^{-3/2} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)(1+E/\kappa E_o)^{\kappa+1}}$$

Where:

F_κ = Kappa distribution

Γ = Gamma function

κ = Kappa factor (constant)

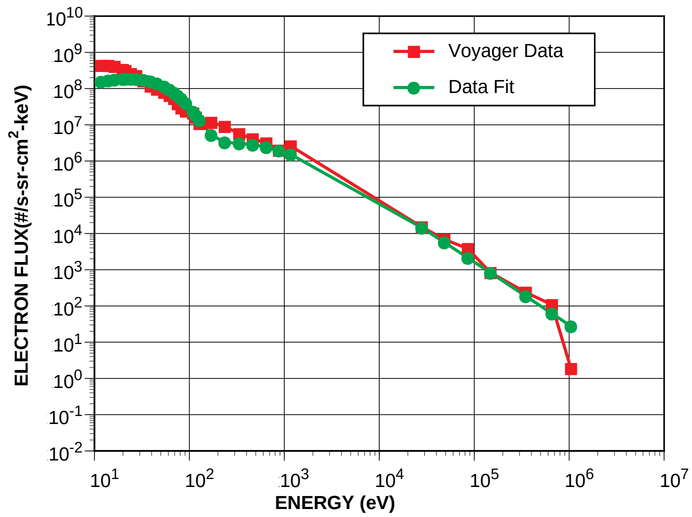

Fig. 1. Maxwellian (below 1 keV) and Kappa (above 1 keV) distribution fits to Voyager 2 inbound electron measurements for Saturn (L=11.59). The potential was estimated to be -480 V in the absence of sunlight and secondary emission for this environment.

As κ goes to infinity, Eq. 2 becomes a Maxwellian distribution. As E goes to infinity, the form of the distribution approaches a power law. A simple fitting procedure was utilized to determine the values for N, E_o, and κ. First, the omnidirectional high energy fluxes were computed and converted to values of the distribution function at two energies for electrons (36 and 360 keV) and for protons (0.6 and 6 MeV). The values of the warm electron and proton Maxwellian density and temperature were used to determine values of the distribution function at zero energy. A representative fit for Saturn is presented in Fig. 1. The resulting Kappa distributions were then integrated to give appropriate surface currents as functions of temperature, κ, number density, and potential.

ESTIMATED CHARGING LEVELS

Earth

Given a model of the ambient electron and ion environments in terms of Maxwellian and Kappa distributions and the density and co-rotation velocity of the cold ions, the surface potential for a spacecraft surface can be estimated using the simple spacecraft to space thick sheath model described above. Evans et al. (1989) used this method to calculate the potentials throughout the terrestrial magnetosphere for a small aluminum sphere in the Earth's shadow. Their results are presented in Fig. 2. This figure is intended to be used as a simple mission planning tool for identifying regions with high charging levels--if a spacecraft were to pass through or near a region of high charge, then appropriate mitigation methods should be considered in the design.

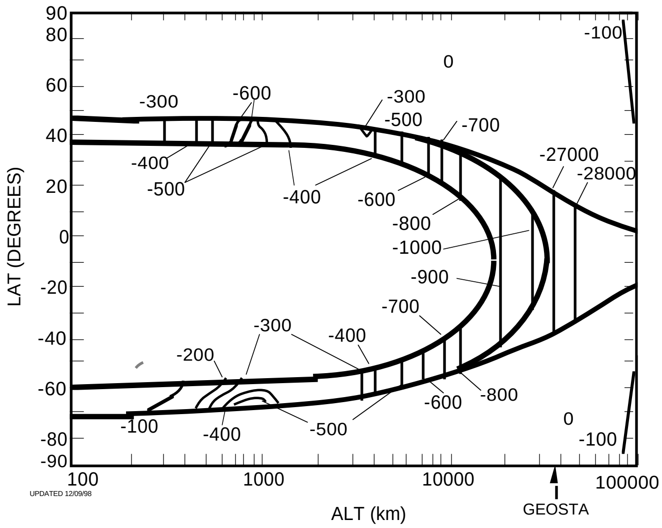

Fig. 2. Surface potential contours (in the absence of sunlight) in volts as a function of altitude and latitude for the Earth (Evans et al., 1989). Outside the "horseshoe" region charging is neglible.

<u>Jupiter</u>

Unlike the Earth, however, over a large portion of the jovian and saturnian magnetospheres warm energetic electron fluxes are the dominant current source, balancing principally with the photoelectrons. It has proven necessary to represent the 1 to 100 keV electron energy range by a kappa distribution. In Fig. 3, from Divine and Garrett (1983), the spacecraft to space potentials for the jovian magnetosphere have been estimated using the design tool. The potential contours represent the spacecraft to space potentials that would be seen for a conducting sphere in the sunlight.

These observations are in good agreement with those reported for Voyager by Scudder et al. (1981) and McNutt (1980). This latter paper implied that on one occasion a potential of -130 V might have been observed. The former paper reported potentials of a few tens of volts positive and tens of volts negative in the torus.

It should not be assumed from Fig. 3 that spacecraft charging is not a problem in the jovian environment. Under fairly restrictive conditions, secondary emissions can be suppressed over a small surface. Also, because the sunlight is a factor of 25 less than at the Earth it becomes easier for the ambient electron current to dominate and charge the spacecraft. If that surface is electrically isolated from the vehicle with secondary electron supression and in the shade so that the photoelectron flux is zero, significant charging can occur as evidenced in Fig. 4. In support of such predictions, the Voyagers may have observed tens of kV surface potentials at Jupiter (Khurana et al., 1987). However, as the Voyager and Galileo spacecraft were designed to be conductive over most of their surfaces and approached the ideal of a conducting sphere, this should not pose a threat to the spacecraft.

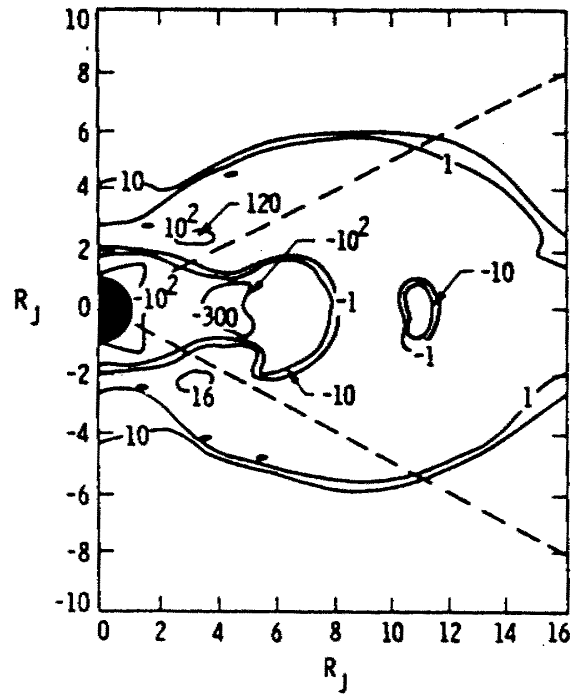

Fig. 3. Spacecraft charging potential contours in volts for the thick sheath approximation in the 110°W sunlit meridian at Jupiter (Divine and Garrett, 1983). The horizontal axis represents distance along the rotational equator. Photoelectron and secondary electron currents are included. The dashed lines bracket the region of applicability (observations).

<u>Saturn</u>

The charging environment at Saturn resembles that at Jupiter. To date, however, a comprehensive plasma model such as developed for Jupiter has not been completed. Instead, a set of 16 electron and ion spectra covering the L-shell range from ~4 to ~21 have been reconstructed from the Voyager 1 and 2 flybys (Krimigis et al., 1983; Richardson and Sitler, 1990; Maurice et al., 1996) for the purpose of estimating the expected potentials. A representative electron spectrum is presented in Fig 1. Each set of electron spectra were fit by a Maxwellian at low energies (~10 to 1000 eV) and a Kappa distribution from 1 keV to 100 keV. The cold plasma populations (hydrogen and oxygen ions) were fit by either a Maxwellian or co-rotation velocity. The proton population above 1 keV was fit by a Kappa distribution.

Fig. 5 gives the potentials calculated by the tool for sunlit and shadowed conditions. Two cases are shown for the cold ions--thick sheath and ram. The thick sheath case, as described in Garrett (1981), assumes the cold ions are best described by a Maxwellian plasma. The ram case assumes the cold ion current is best represented by a co-rotating flow (see Eq. 3). In reality, the actual current lies between these two limits but closer to the thick sheath limit. Fig. 5 basically shows that even though the photoelectron flux is very low at Saturn (100 times lower than at the Earth), the plasma charging environment is relatively benign. Surface potentials might reach a few tens to a hundred volts negative only in the outer magnetosphere.

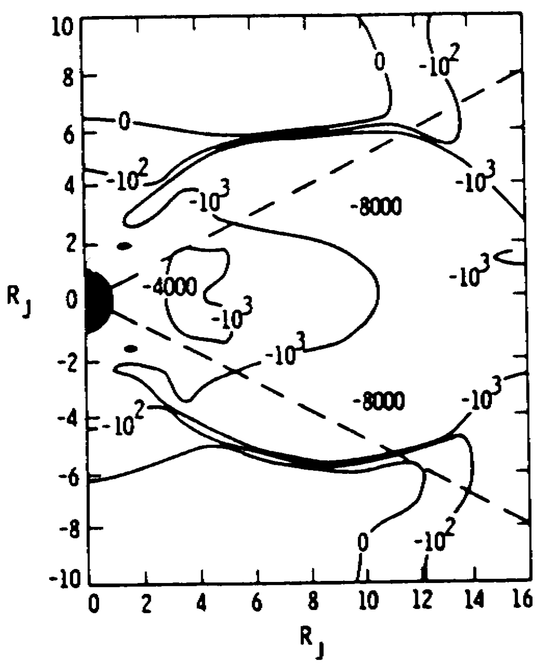

Fig. 4. Spacecraft to space potential contours for the thick sheath approximation (Divine and Garrett, 1983) as in Fig. 3. No photoelectron or secondary currents are included.

Again, however, this is not the whole story. In Fig. 6, the potentials were estimated assuming that the spacecraft was in shadow and that either the cold ions (as when they are shadowed on one side of the spacecraft) or the secondary electrons were suppressed. For those cases (and either ram or thick sheath), the potential can reach several hundred volts negative between 8 and 18 L (note: the assumption here that the ion ram current is the only current is strictly a worst case and not realistic as there is usually an ion thermal "thick sheath" current also present). Although Cassini was designed to be conductive on the outside, this wasn't entirely successful. There may be some areas on Cassini that can charge. However, as all areas where charging or arcing might be a concern were covered with conducting materials before launch, charging will not likely impact the mission.

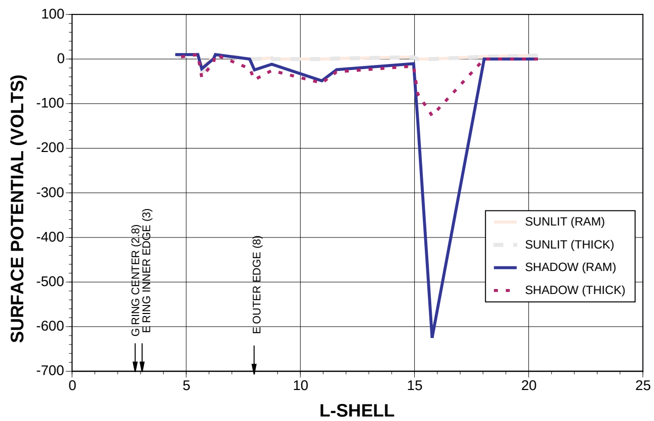

Fig. 5. Spacecraft to space potentials in sunlight and shadow for Saturn as a function of L-shell. For one curve, the ion current is assumed proportional to its thermal (thick sheath) value. For the other, it is set equal to the ram current (Eq. 3).

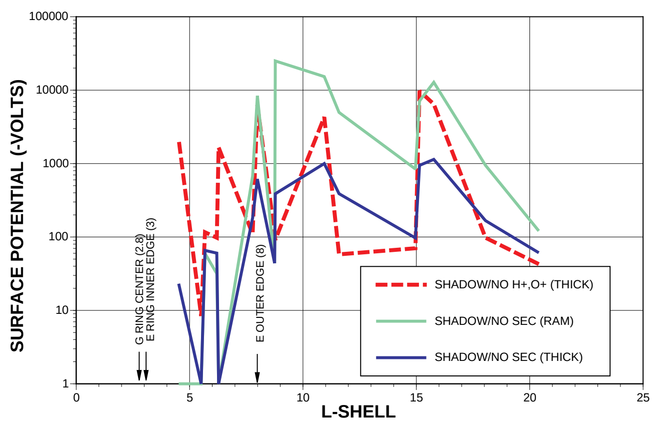

Fig. 6. Spacecraft to space potentials (negative) in shadow for Saturn as a function of L-shell. For two of the estimates, the secondary current has been set equal to 0. As in Fig 5, for one, the co-rotating ion current is assumed proportional to its thermal (thick sheath) value while in the other, it is set equal to the ram current (Eq. 3). For the third set, the co-rotating ions have been set equal to 0.

CONCLUSIONS

A simple design tool based on current balance and on the Earth's, Jupiter's, and Saturn's plasma environments has been used to estimate the spacecraft to space potentials for missions to these planets. The results of this tool for a spherical spacecraft with aluminum surfaces are presented in

Table 2 for several different situations. Based on this table, the Earth clearly represents the worst threat to spacecraft. Negative potentials as high as 28,000 V are predicted near geosynchronous orbit in eclipse and, indeed, potentials in excess of -20,000 V have apparently been observed. At Jupiter, potentials are more moderate. Large potentials are only observed if secondary emissions can be suppressed--unlikely but possible for some surface configurations. Conditions at Saturn are similar to those at Jupiter, though somewhat lower in general. Even so, spacecraft surface charging is still a concern for spacecraft survivability at these planets. Indeed, as potentials of even a few 10's of volts can seriously affect low energy plasma measurements, and therefore spacecraft charging must be considered for most missions to these planets.

Table 2. Representative Charging levels at the Earth, Jupiter, and Saturn based on the simple charging design tool.

	V_c(km/s)	Potential(V)	
		Sun	No Sun/Sec
Earth			
-ionosphere	8	-0.7	-4.4
-plasmasphere	3.7	-1.6	-3.8
-auroral zone	8	-0.7	-500
-geosynchronous	3	2.0	-28,000
Jupiter			
-cold torus	44	-.59	-1.2
-hot torus	100	-60	-70
-plasma sheet	150	-94	-130
-outer mag-sph	250	9.5	-8,000
Saturn			
-inner plasma sheet	100	~5	-30
-outer plasma sheet	100	~5	-500
-hot outer mag-sph	100	~5	-10,000

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