Plasma Sources for Active Charge Control

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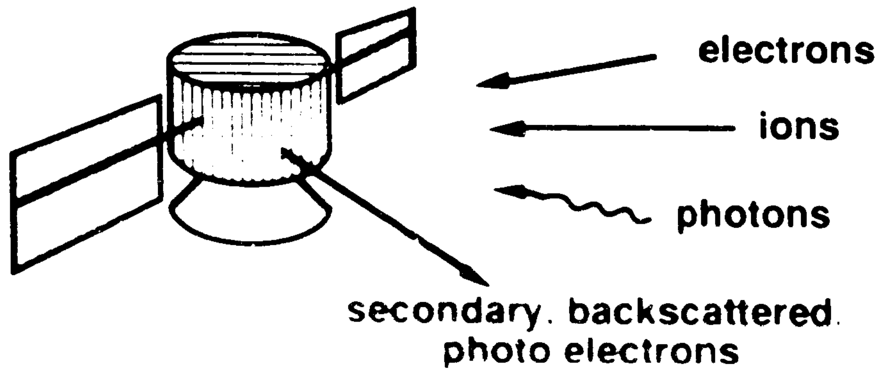
Spacecraft surfaces develop high potentials when the spacecraft is in the presence of a hot plasma or when the spacecraft is actively biased. Potential differences between the spacecraft and the surrounding plasma and between spacecraft surfaces can interfere with the mission by disturbing instrument measurements, causing surface breakdown, or enhancing surface erosion. A plasma source is an active device that reduces the potentials. The high-density, low-temperature plasma emitted by a plasma source provides the particles needed to discharge insulating surfaces. Additionally, applied potentials of tens of volts can generate ampere-level currents through the quasi-neutral plasma plume. The direction and amplitude of current flow is determined by the balance of the barometric and electric field forces on the electrons. When a plasma source operates as an electron emitter, the barometric force is stronger and the net electron current flow is opposite the electric field force. When the source is collecting electrons and the applied potential is too high for the plasma to remain quasi-neutral throughout space, a nonneutral region known as a double layer forms to separate the quasi-neutral plasma plume from the ambient plasma.

INTRODUCTION

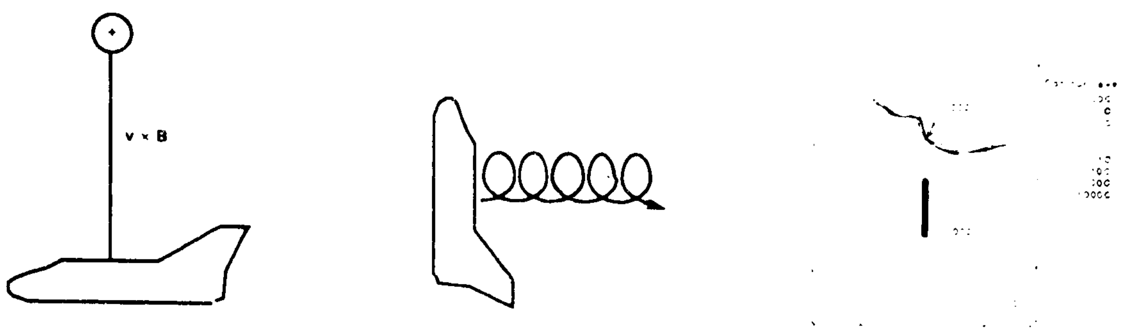
Charge can accumulate on the surfaces of a spacecraft embedded in the plasma environment of earth orbit when the spacecraft is in the presence of a hot plasma, or when the spacecraft is actively biased. Potential differences due to charge accumulation can interfere with the spacecraft mission by disturbing instrument measurements, enhancing surface erosion, or causing surface breakdown. Active control of spacecraft surface potentials can reduce or, in some cases eliminate, these problems. Plasma sources act as plasma contactors by providing a path for low-impedance current flow between spacecraft surfaces and the ambient plasma environment.

The potential on a spacecraft surface is determined by the net current flow to the surface. The major components of the net current are summarized in Figure 1. The floating potential of a surface in a given environment is the potential at which no net current flows to the surface. Electrons and ions impinge on any surface in a plasma. As electrons are faster than ions of equal energy, in the absence of significant photoelectron or secondary electron currents, surfaces accumulate excess negative charge. When a surface reaches a negative potential a few times the electron temperature, nearly all of the electrons are repelled so that the electron and ion currents balance. In sunlight, photoelectrons usually dominate the current. Sunlit surfaces float a few volts positive in order to retain the photoelectrons. The secondary and backscattered electron currents reduce the net current to the surface. For plasma with effective plasma temperatures below 30 keV, the secondary yield of most spacecraft materials is high enough that the surface floating potential remains near the plasma potential (Mullen, *et al.* 1986; Katz *et al.*, 1987; Katz *et al.*, 1986). Different materials have different secondary, backscatter, and photo electron yields. Some surfaces are sunlit while others are in eclipse. The thickness and conductivity of surfaces



[illegible] potential [illegible] charged [illegible]

An electrodynamic [illegible] connected to a subsatellite by a conducting tether [illegible] magnetic field generates a potential difference [illegible] with the upper body at a higher potential. If electrons are [illegible] at the upper body and emitted at the lower body, a current will flow through the tether. This current can provide electrical power to the spacecraft at the expense of orbital energy. Current can also be forced to flow in reverse in order to convert electrical energy generated on board the spacecraft, such as from solar arrays, to orbital energy. In order for a current to flow, electrons must be collected



(a) (b) (c)

Fig. 2. (a) The operation of an electrodynamic tether, (b) the emission of particle beams, and (c) the biasing of exposed spacecraft surfaces are processes that actively charge spacecraft.

from, and emitted to, the ambient plasma. A plasma source is a versatile plasma contactor as current can flow either way through the plasma cloud.

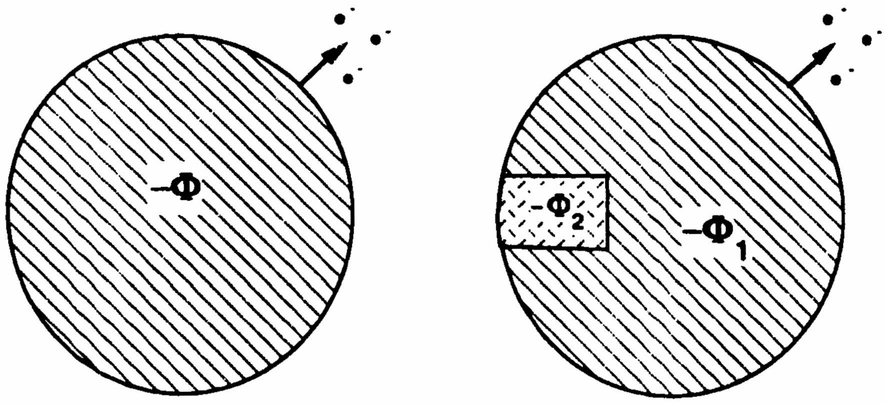
A spacecraft emitting an electron or ion beam can achieve substantial potentials. As with natural charging, the spacecraft will accumulate charge and the potential will rise until the net current is zero. The three primary contributions to the current are the emitted beam current, the collected sheath current, and the beam current that is attracted back to the spacecraft. For beam currents high compared with the sheath current at the beam potential, the potential rises to or above (Mandell and Katz, this proceedings) the beam potential and nearly all the beam current returns to the spacecraft. A plasma source provides another current to balance the beam current and can be used to maintain a beam-emitting spacecraft near plasma ground.

The ground potential on spacecraft adjusts to the potential at which no net current flows from the plasma. When a spacecraft has exposed biased surfaces, some surfaces float positive and some float negative. Complicated sheath geometries develop (Katz *et al.*, 1989), which may interfere with the desired operation of the spacecraft. A plasma source can maintain a given part of the spacecraft near plasma ground and therefore sets the spacecraft potential with respect to the plasma.

OTHER ACTIVE POTENTIAL CONTROL TECHNIQUES

The immediately obvious way to increase the flow of electrons (or ions) from a spacecraft to the environment is to use an electron (ion) source such as a hot wire or an electron (ion) gun. As shown in Figure 3a, for spacecraft entirely covered with conducting surfaces connected to a common ground, a nonneutralized charged particle source can maintain the spacecraft at plasma ground. Typically, spacecraft do not only have conducting surfaces but also have large areas of insulating surfaces, such as thermal blankets and glass coverslips over solar cells. In the presence of a hot plasma, both the conducting and insulating surfaces can accumulate a net negative charge. As an electron beam cannot discharge a negatively charged insulating surface, the conducting surfaces are near plasma ground and the insulating surfaces are at elevated potentials as illustrated in Figure 3b. When a nonneutralized charged particle source is used on an initially grounded spacecraft, such as during an electron or ion beam experiment, the insulating surfaces remain at plasma ground and the conducting surfaces are at elevated potentials. In both cases, the differential potentials can interfere with spacecraft operations.

When large areas of the spacecraft surface are insulating and an unneutralized charged particle source is used to maintain the spacecraft at plasma ground, potential barriers that prevent the escape of the emitted particles can form. This effect is illustrated in Figure 4. The figure shows potential contours around a "quasi-spherical" object. The calculation is a 3-dimensional NASCAP/LEO (Mandell *et al.*, 1982; Katz *et al.*, this proceedings) computation of the potentials about the 26-sided object. Most of the surfaces are at -5 kV. A conducting surface that is emitting electrons is represented by a single side of the object at -1 kV. The figure shows a slice through the grid. The gray area is the object. On the -1 kV surface, the electric field points away from the object. Electrons will be attracted back to this surface even though the entire object is negative with respect to plasma ground. Potential barriers have been observed to prevent the escape of electrons under space conditions on ATS-6 (Olsen, 1985).



(a) (b)

Fig. 3. An active electron source can discharge a negatively charged completely conducting spacecraft, but insulating surfaces are not discharged. Differential potentials are enhanced.

For some active experiments, large current flows are desired. When electrons are emitted from a positively charged spacecraft (resulting in an increase in potential), the electrons are emitted into an electron-rich sheath as illustrated in Figure 5a. For ampere-level currents, kilovolt electron guns are needed. Figure 5b shows emission of an electron beam from a negatively charged spacecraft (reducing the overall potential) into an ion-rich sheath. The positive charge within the sheath helps neutralize the beam and reduces the beam energy required. Even under these conditions, large currents require substantial voltages.

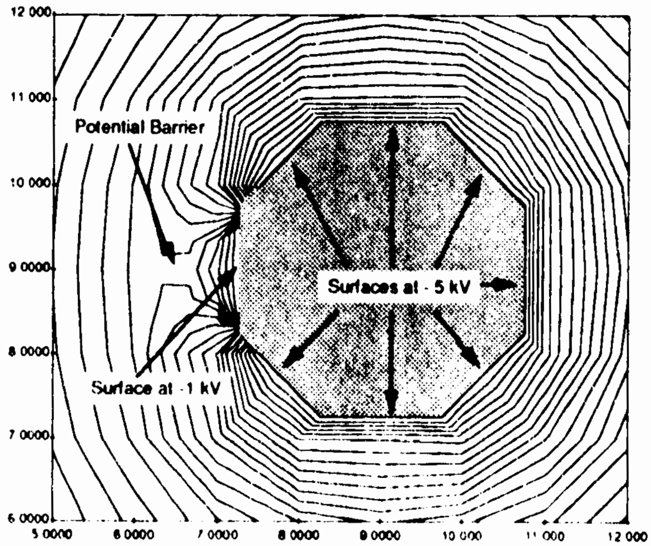


Fig. 4. Potentials around a 26-sided object. The gray area is the object. The figure shows a slice through a 3-dimensional grid. One surface is at -1 kV and the rest are at -5 kV. A 1 kV potential barrier prevents the escape of lower energy electrons from the -1 kV surface. The contour levels are drawn at 200 V intervals. A mesh unit is 0.2 m and the debye length is 1 m.

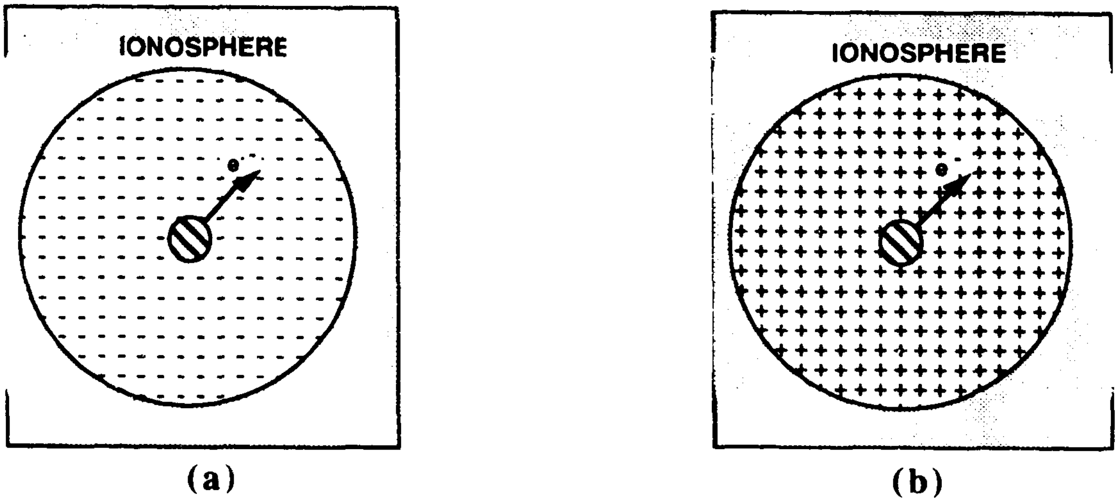


Figure 5. (a) Electrons emitted from a positively charged spacecraft are emitted into a negatively charged sheath. (b) Electrons emitted from a negatively charged spacecraft are emitted into a positively charged sheath. The sheath ions help neutralize the beam. In either case, thousands of volts are required for ampere currents.

PLASMA SOURCES - PHYSICAL MECHANISMS

Plasma sources have been observed to effectively discharge spacecraft surfaces in space. Olsen (1985) describes clear evidence for the discharging of ATS-6 by ion engines and ion engine neutralizers. ATS-6 was discharged from -3 kV to near zero in eclipse and from -45 V to less than -3 V in sunlight. Collaborating evidence has been obtained from other spacecraft.

The primary characteristic of plasma sources that makes them excellent at discharging spacecraft surfaces is the generation of a high-density ($10^{17}/m^3$), low-temperature (1 eV) plasma. As illustrated in Figure 6, the plasma provides particles of both signs to discharge the surfaces of insulators on the spacecraft. The discharging of insulating surfaces eliminates potential barriers and reduces the differential charging of surfaces. The low temperature of the high-density plasma reduces the floating potential of the surfaces.

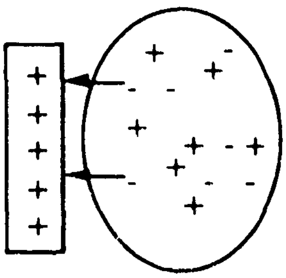


Fig. 6. The high density, low-temperature plasma generated by a plasma source discharges surfaces.

A plasma source emits both electrons and ions. Electrons carry the current between the spacecraft and the ambient plasma. The slow-moving ions neutralize the space charge so that the electrons can flow freely. As long as the potentials are not too high, the plasma cloud is quasi-neutral throughout. In a quasi-neutral argon plasma at equilibrium, the thermal electron current is 270 times the thermal ion current. If the electrons are hotter than the ions, as is the case for plasmas created by hollow cathodes, the thermal electron current is even larger. If an expanding plasma has a density of $10^{13}/m^3$ and a temperature of 1 eV at 28 cm from the source, the plasma can carry an electron current of up to 270 mA and an ion current of 1 mA or a net current of up to 269 mA toward the source through the 28 cm radius spherical surface surrounding the source (or up to 271 mA away from the source if electrons are available from the ambient plasma).

The amount of argon gas needed to sustain this plasma plume is minimal. If the process of ionization of the argon gas to create the ions is only 1 percent efficient, 30 kg/year of argon is needed to emit 270 mA of electrons. Both sources with ionization efficiencies of 50 percent and devices that allow the plasma source to be turned on only when needed have been constructed (Williamson *et al.*, this proceedings). When a high efficiency source is used, the gas needed to maintain current flow is not an important design constraint.

The mechanism for current flow through the plasma plume can be illustrated with an examination of the no current flow case. As Figure 7 shows, particles flow from regions of higher density to regions of lower density. The electrons move faster and therefore reach the regions of lower density faster. This current flow leaves an excess of positive charge, which retards the electrons. When there is no net electron current flow, the net force on the electrons is zero. Treating the electrons as a fluid, and balancing the pressure force with the electrostatic force, this criteria gives

$$\theta \nabla n - en \nabla \phi = 0 \tag{1}$$

which gives

$$n_e = n_0 e^{\phi/\theta} \tag{2}$$

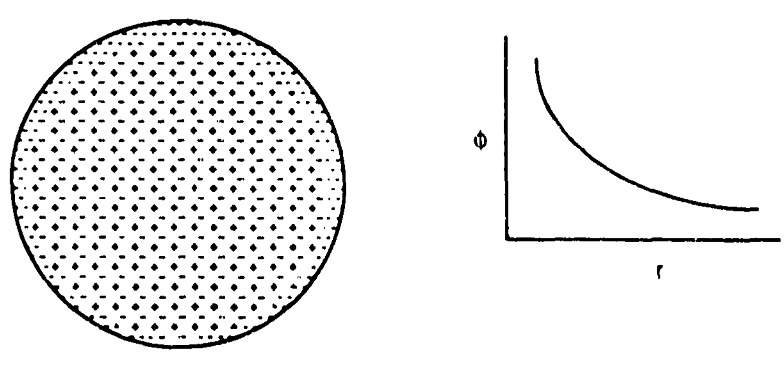
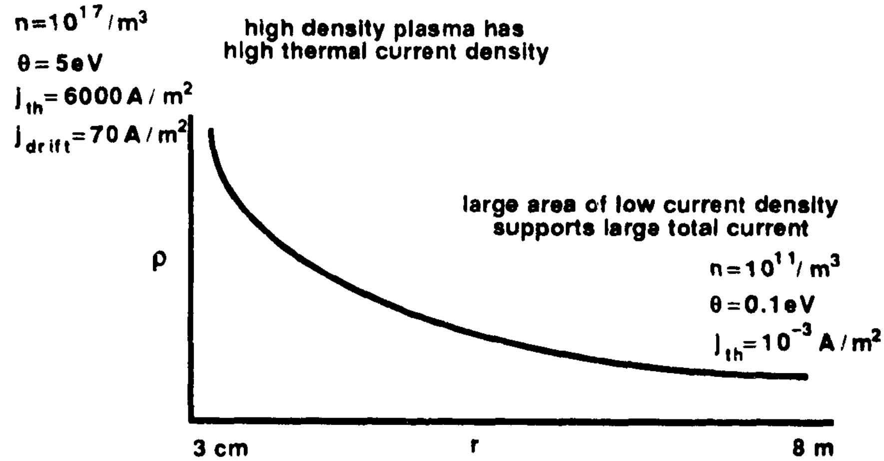


Fig. 7. Electrons flow from regions of high density to regions of low density. The resulting charge separation gives rise to the retarding barometric potential.

The variation in plasma density results in a barometric potential that is positive in regions of higher particle density. If the potential at the source is higher than the barometric potential, electron current will flow toward the source. If the potential at the source is lower than the barometric potential, electron current will flow away from the source.

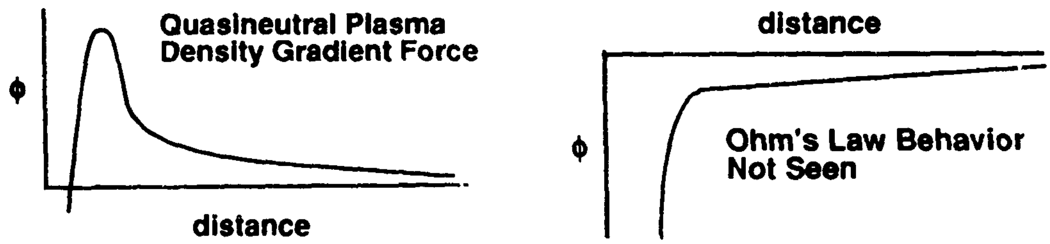
Figure 8 illustrates how small perturbations from the barometric potential generate large current flows. The source emits 800 mA of electrons into a $10^{11}/m^3$, 0.1 eV plasma. The thermal current in the ambient is 10^{-3} A/m^2. The sheath size through which the 800 mA of current will flow is 8 m in radius. The plasma density 3 cm from the source is $10^{17}/m^3$, the ion temperature is 0.1 eV, and the potential is 20 V. Ions expanding from this point have a density of $10^{11}/m^3$ 8 m away. The electron current at 3 cm for 5 eV electrons (typical near hollow cathode plasma sources) is 6000 A/m^2. For the current flow at 8 m to be 800 mA, a net current of 70 A/m^2, or 1 percent of the total thermal current, flows through the 3 cm surface.



$$\boxed{70\ A/m^2\,(0.03\,m)^2 = 10^{-3}\ A/m^2\,(8\,m)^2}$$

Fig. 8. A high-density plasma can support a high-thermal current density. After expansion, the large area of low-current density supports a high total current.

When the barometric pressure dominates electron flow, the net electron flow is from regions of higher potential to regions of lower potential. The potential variation near a hollow cathode plasma source is shown in Figure 9a. The potential is negative near the orifice. In the vicinity of the keeper, where ionization is taking place, the plasma density is high and therefore the potential is elevated. As the plasma expands, the barometric potential drops to zero as the source plasma blends into the ambient. Early measurements of the plasma in the vicinity of electron-emitting plasma sources appeared to show a resistive force as seen in Figure 9b. Recent potential measurements show the shape shown in Figure 9a (Williams and Wilbur, 1989). The reason for the discrepancy is that potential measurements near the potential peak are difficult because emissive probe measurements can be misleading in regions of high-plasma densities (Wilbur, private communication).



(a) (b)

Fig. 9. (a) Potential variation in the vicinity of an electron-emitting plasma source. Electron motion is determined by the balance of the density gradient force and the electrostatic force. (b) The plasma does not act as a resistor.

When the potential is above the barometric potential, the net electron flow is toward the source. The ions still flow outward. When the ambient plasma is not a significant source of electrons, the maximum current available is the ion current. However, when the ambient plasma is dense enough, the ambient thermal current is attracted to the plasma source. For small potentials, quasi-neutrality can be maintained between the ions from the source and the electrons attracted from the ambient. At higher potentials, quasi-neutrality cannot be maintained everywhere and a double layer forms between the source plasma and the ambient plasma as illustrated in Figure 10 (Wei and Wilbur, 1986). A double layer is composed of two charge layers across which there is a sharp potential drop. On both sides of the double layer, the plasma is quasi-neutral and the potential varies slowly.

When the potential across the double layer exceeds the ionization potential of the gas emitted by the source, electrons attracted from the ambient plasma ionize neutral gas from the source. When enough gas is present and the potential is high enough, the sheath ionization provides the bulk of the plasma. The operation of a hollow cathode plasma source in this manner is known as the "ignited mode" (Patterson, 1987).

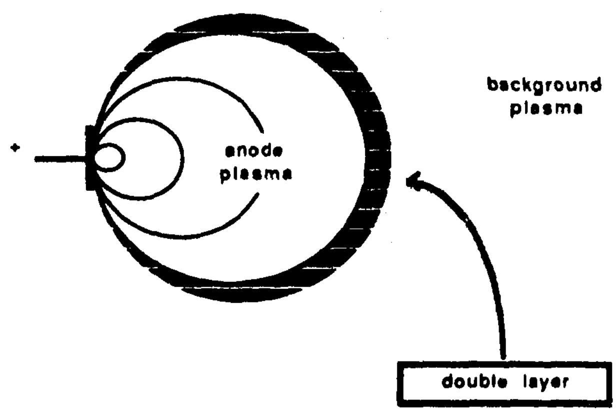


Fig. 10. When the applied potential is too high for quasi-neutrality to be maintained throughout the plasma, a localized nonneutral region known as a double layer forms. The anode plasma can be created by the plasma source or by sheath ionization.

The CHARGE-2, ECHO-7, and SPEAR I rockets all observed abrupt potential drops when thruster firings occurred during high potential operations (Neubert *et al.*, this proceedings; Raitt *et al.*, this proceedings; Malcolm *et al.*, this proceedings). It is believed that ambient electrons attracted by the high potentials (or in the case of SPEAR I, secondary electrons accelerated by the high potentials) ionized the neutral gas from the thrusters. Under these conditions, the thrusters were plasma sources that grounded the spacecraft to the ambient plasma. The amount of gas typically emitted by thrusters is orders of magnitude more than the minimum needed to sustain ampere current flows (Davis *et al.*, 1990).

CONCLUSION

The reliable operation of spacecraft sometimes requires the active control of surface potentials. Plasma sources provide a flexible means to minimize the potentials on spacecraft surfaces. The high-density, low-temperature plasma emitted provides particles that discharge the insulating surfaces of the spacecraft, eliminating potential barriers. The net current flow is toward or away from the spacecraft as needed. When the plasma source is used as an electron collector with low potentials or as an electron or ion emitter, quasi-neutrality is maintained throughout the plasma plume. The net current flow is determined by the balance of the density gradient forces and the electrostatic force. When the current flow is primarily due to electron flow away from the source, the electrons flow from a region of high potential to a region of low potential. This flow is dominated by the barometric pressure. When the potential at the source is too high to maintain quasi-neutrality throughout space, a double layer forms between the source plasma and the ambient plasma.

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