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Measurement of the Charge-Exchange Plasma Flow from an Ion Thruster

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A charge-exchange plasma is produced downstream of ion thrusters by collisions between energetic ions and neutrals escaping through the ion optics. The charge-exchange ions flow radially from the thruster beam due to electric fields produced by its density gradient. The propagation of the charge-exchange plasma after it leaves the thrust beam is the subject of this paper. Under the proper conditions there is an "end-effect" of a long, cylindrical Langmuir probe which allows a significant increase in collected ion current when the probe is aligned with a flowing plasma. This effect is used to determine the charge-exchange plasma flow direction at various locations relative to the ion thruster. A portion of the charge-exchange plasma flows upstream of the ion thruster and can represent a contamination source to electrically propelled spacecraft. The ion current collected by the probe as a function of its angle with respect to the plasma flow allows determination of the plasma density and plasma flow velocity at the probe's location upstream of the ion thruster optics. The density values obtained from the ion current agree to within a factor of 2 to density values obtained by typical voltage-current Langmuir probe characteristics.

Nomenclature

a = plasma sheath thickness
e = electronic charge
I = ion current collected by "infinite" cylindrical probe
K = Boltzmann constant
L = cylindrical probe length
M_i = ion mass
N_e = plasma electron density
R_p = cylindrical probe radius
T_e = electron temperature
T_i = ion temperature
U = plasma flow velocity
V_p = probe potential relative to plasma potential
δ = slowly varying function of ψ, λ_D, R_p
θ = angle of probe with respect to plasma flow
$\theta_{1/2}$ = angular width at half-maximum of ion current vs probe angle curve
λ_D = Debye length
τ = dimensionless probe length
ψ = dimensionless potential, $(-eV_p/KT_e)$

Introduction

THE electron bombardment ion thruster has been under development for a number of years and is presently a candidate propulsion device for several space missions. Two significant differences between the ion thruster propulsion system and chemical propulsion systems are that the ion thrusters will be required to operate continuously for up to 15,000 h on some planetary missions and they produce a plasma environment that is capable of surrounding the spacecraft. It is necessary to understand the potential interactions between the thruster-produced environment and the spacecraft so that undesirable interactions can be prevented or minimized by proper spacecraft and mission design.

A cutaway view of an ion thruster is shown in Fig. 1. The ion thrusters presently developed for space application utilize mercury as the propellant. Approximately 90% of the mercury flow into the thruster discharge chamber is ionized and is accelerated through the ion optics to produce thrust. The remaining 10% leaves through the optics as neutral mercury. Charge-exchange interactions between these neutrals and the energetic ions downstream of the thruster optics form ions with only thermal energy. These ions leave the beam radially with a directed energy of a few tenths to a few electron volts due to the internal electric fields in the primary beam. These ions, with neutralizing electrons, constitute a charge-exchange plasma that can flow upstream around the spacecraft.

The propagation of the charge-exchange plasma after it leaves the influence of the primary beam has been an area of uncertainty. There are various analytical models which predict the flow of the charge-exchange plasma from an ion thruster.[1-7] The densities of the charge-exchange plasma predicted by these models at points upstream of an ion thruster vary by orders of magnitude. It is very difficult to experimentally verify such models due to the low directed energy of the ions and various effects produced by the test facility. To date, all experimental plume characterization investigations have been performed with Langmuir probes and retarding potential analyzer—Faraday cups.[3,5,8] Such techniques are useful for determining the plasma density and temperature but are insensitive to measuring the direction of flow of this low-energy plasma and cannot reliably distinguish ions which are produced by charge-exchange from those neutrals which have previously encountered the facility wall. These latter ions will not be present in space.

Under the proper conditions a cylindrical Langmuir probe can be used to accurately determine the direction of flow of plasma at the probe's location; this is referred to in the literature as an "end-effect" phenomenon.[9,10] These necessary conditions are: 1) that the Debye length is greater than the probe diameter, 2) that the flow velocity is greater than the ion thermal velocity, and 3) that the probe is biased to collect an ion current. These conditions are met in the

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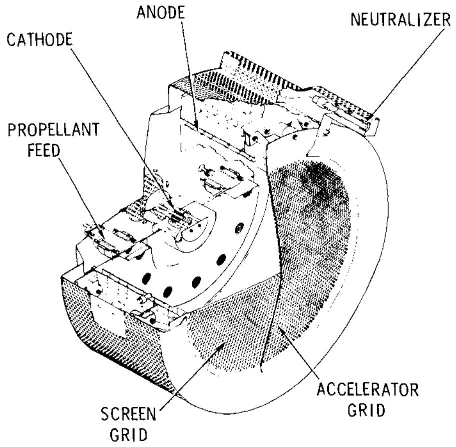

Fig. 1 Cutaway view of ion thruster.

charge-exchange plasma and this end-effect can be used to accurately determine the flow direction of that plasma at the probe location.

Langmuir Probe End-Effect

The end-effect discussed in this paper was first reported by Bettinger and Chen[9] to explain an anomalous increase in ion current observed when a cylindrical Langmuir probe on the Explorer 17 satellite was aligned with the satellite's direction of motion. The explanation for the increase in ion current is illustrated in Fig. 2. When the ion flow direction is at a large angle, θ, with respect to the probe axis, the impact parameter for collection is very small. When the probe is aligned with the plasma flow, a significant ion current can flow through the front of the sheath. The ions experience the electric field along the probe and have a much greater likelihood of being collected. By obtaining the current as a function of the probe angle with respect to the plasma flow, a current peak can be obtained whose amplitude and half-width are dependent on various plasma parameters and the ion flow velocity. The end-effect can, therefore, be used for diagnostic purposes. An obvious application is the determination of the plasma flow direction at the probe's location.

Hester and Sonin's discussion[11] of the end-effect pointed out that the Bettinger and Chen theory required a minimum-length probe. The criteria for the probe to be of sufficient length for the Bettinger and Chen theory is

$$\tau \equiv \frac{L}{\lambda_D} \frac{(KT_e/M_i)^{1/2}}{U} > 3 \tag{1}$$

Hester and Sonin presented a theory, based on numerical calculations, for the condition of the probe being smaller than this minimum length. Sanmartin later presented a more complete, closed-formula theory for the case of $\tau < 3$.[10] For $\tau > 3$ the theory of Bettinger and Chen still applies. For the plasma and probe conditions in the experiments described in this paper, τ is greater than 3. Therefore, any quantitative data other than flow direction at the probe's location requires the use of the Bettinger and Chen theory. Hester and Sonin made comments on the original theory of Bettinger and Chen, and gave a brief summary of the theory for $\tau > 3$ in an appendix to their paper.

Mott-Smith and Langmuir showed that for $KT_i \ll -eV_p$ and $KT_i \ll \frac{1}{2} M_i U^2$, the ion current collected by an "infinite" cylindrical probe, i.e., a cylindrical probe which has a length much greater than its diameter, is given by[12]

$$I = 2N_e e U R_p L (\sin^2\theta - 2eV_p/M_i U^2)^{1/2} \tag{2}$$

The current decreases to a minimum at $\theta = 0$. However, the end-effect can produce a large increase in ion current at $\theta = 0$ over that predicted by Eq. (2). The half-width, $\theta_{1/2}$, of the peak produced by plotting the probe current as a function of angle between the cylindrical probe and the plasma flow is given by

$$\theta_{1/2} = \sin^{-1} R_p (-2eV_p)^{1/2} / 0.4aUM_i^{1/2} \tag{3}$$

The half-width is the full width at half-maximum of the peak in excess of that predicted by Eq. (2). The sheath size, a, has to be obtained from a source outside the theory of Bettinger and Chen or Hester and Sonin. The sheath size is given in the theory of Sanmartin as

$$a = (2\psi\delta)^{1/2} \lambda_D \tag{4}$$

The function δ is given in graphical form by Sanmartin. It is a slowly varying function and an average value is taken so that the sheath size, a, primarily varies as a function of ψ and λ_D.

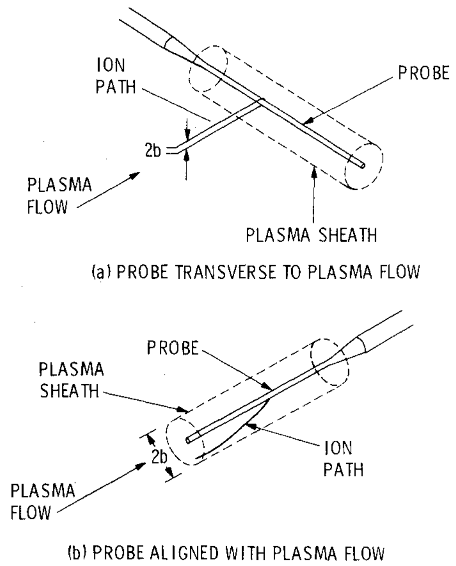

Fig. 2 Illustration of cylindrical Langmuir probe end-effect.

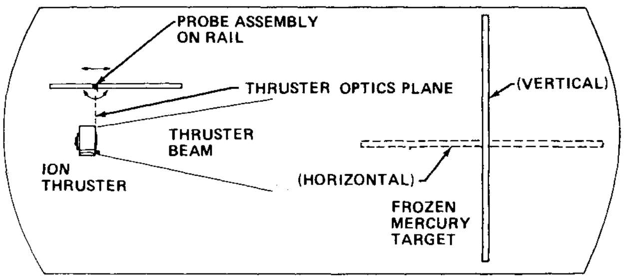

Fig. 3 Experimental arrangement.

Charge-Exchange Plasma Experiment

Experimental Arrangement

A diagram of the experimental arrangement is given in Fig. 3. A vacuum chamber, 2.1 m in diameter and 4.6 m long, was used in this experimental study. The wall of the chamber is lined with a liquid-nitrogen-cooled wall for cryopumping. A mercury ion thruster is mounted at one end of the chamber such that the thruster beam strikes a frozen mercury target at the other end of the chamber. The mercury target can be rotated so that the beam may strike the frozen mercury target or the end of the chamber. The use of the frozen mercury target prevents sputtering of the steel walls of the vacuum chamber.

The ion thruster employed in this study is a 900-series, Hughes 30-cm mercury ion thruster with SHAG (small hole accelerator grid) optics. The ion beam output of the thruster is

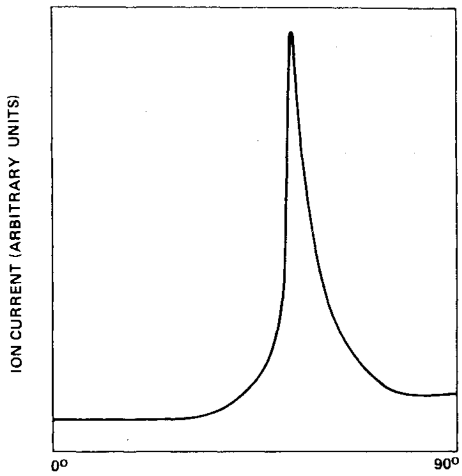

Fig. 4 Typical ion current vs probe angle curve upstream of ion thruster optics.

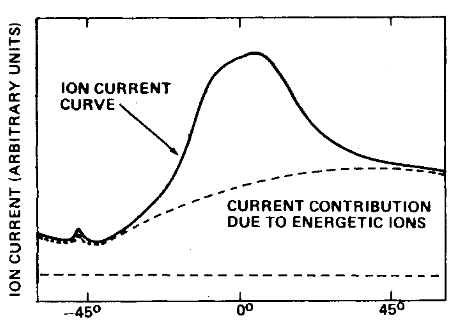

Fig. 5 Typical ion current vs probe angle curve downstream of thruster optics.

therefore equivalent to that from a J-series 30-cm ion thruster. The ion thruster was operated and throttled as recommended for a J-series thruster by NASA-LeRC.[13]

The cylindrical probe used in this experiment is made of 5-mil-diameter tungsten wire with a length-to-diameter ratio of 450. The probe is mounted on a rail which is placed in the chamber so that the rail is parallel to the thrust beam axis. The probe can be moved linearly along the rail by means of a motor drive, and can be rotated about its midpoint from −90 deg to +90 deg, where 0 deg is defined as that position where the probe is perpendicular to the thruster beam axis. When the probe is at the −90 deg position it is parallel to the thrust beam axis and is pointed at the thruster end of the chamber. When it is at the +90 deg position it is pointed at the target end of the chamber. The ion thruster beam axis lies in the plane swept out by the probe rotation. Therefore, the probe always points at the thrust beam axis. The probe can be moved to various locations along the rail. At each location the probe can be rotated and the ion current vs probe angle obtained.

Results

As indicated by Eqs. (2-4), the shape of the ion current vs probe angle curve is dependent on the plasma density and plasma flow velocity. These curves can therefore be used to determine these quantities at various locations in the chamber. The plasma flow direction at the probe's location can be determined from the angular position of the probe where the peak ion current is obtained.

Figure 4 illustrates a typical ion current vs probe angle curve. The increase in ion current due to the end-effect is very angle-dependent and prominent. Figure 4 is an example of the curves obtained upstream of the plane of the thruster optics. Figure 5 is a typical example of the probe traces obtained downstream of the thruster.

Facility-produced effects have long been recognized as making reliable measurements of the charge-exchange plasma difficult.[1,3,8] One of the major difficulties is subtracting the facility-produced plasma from measured signals to determine true, charge-exchange plasma values. The beam strikes the target at the end of the chamber and neutral atoms are sputtered from the target. These atoms flow upstream and may be charge-exchange ionized in the beam. This produces low-energy ions which are difficult to distinguish from true charge-exchange ions, i.e., those ions which are produced by charge exchange between beam ions and neutrals escaping from the ion thruster's discharge chamber.

The end-effect will produce increased ion current when the probe is aligned with a flowing plasma. If there are a number of flowing plasmas crossing at the probe's location, an ion current peak will be produced by each one as the probe is aligned with them. If the plasma ions have a distribution of directed motions, albeit in the same general direction, the end-effect peak will be broad. With these points in mind a number of things can be said about the curves in Figs. 4 and 5.

The narrowness of the peak in Fig. 4 indicates a well-directed plasma flow at locations upstream of the ion thruster. The ion current peak is not symmetric and the ion current on either side of the peak is seen to be greater when the probe is pointed toward the frozen mercury target than when it is pointed away from the target. This increase in ion current is due to neutrals from the target flowing upstream, charge exchanging with beam ions, and continuing their motion upstream. The mercury target which is intercepting the thruster beam can be rotated so that the beam is not sputtering mercury from the target but is allowed to strike the end of the chamber. This significantly decreases the facility-produced ion production since the number of neutrals coming from the end of the chamber is lowered.

The ion current base is defined as the ion current measured on either side of the ion current peak. For a probe angle, θ, less than the angle where the peak occurs, the base current is described by Eq. (2). When $-eV_p > \frac{1}{2}M_iU^2$, the $\sin\theta$ term in Eq. (2) has very little influence, as is evident in Fig. 4 by the flat baseline. At the furthest positions upstream of the thruster the ion current base may be lowered a factor of 2 by rotating the mercury target so that the beam strikes the end of the chamber. When the probe is positioned near the thruster optics plane, the change in base current caused by rotating the mercury target is evident but much less significant. In all cases, the base values change but the angular positions at which the current peak occurs is altered only slightly. This indicates that the facility-produced ions have a distribution of velocity vectors such that no well-defined ion current peak is produced due to the end-effect. Because the facility-produced ions flow generally from the target, the base current increases when the probe is pointed toward the target. The base current here is greater than on the other side of the peak because as the probe is aligned with the facility ions the end-effect produces an increase in measured current. If the prominent current peaks are produced chiefly from the facility ions moving upstream from the target, then the plasma flow direction should, at all locations relative to the thruster, appear to come from the target. This is not the case. Therefore, the peak presents ions that are produced in the beam near the thruster and flow radially from the beam. After leaving the influence of the primary beam they then expand and flow upstream.

Figure 5 illustrates the curve obtained at a location downstream of the plane of the thruster optics and at some radial distance away from the thruster axis. The position of the major peak indicates that the charge-exchange plasma flows radially from the thruster beam. This is in agreement with other studies.[3,5] The width of the peak indicates that the

Table 1 Plasma flow direction at probe locations

Axial positions, cm	Probe angle, deg: Radial position = 48 cm: Charge-exchange plasma	Radial position = 48 cm: Divergent primary beam	Radial position = 66 cm: Charge-exchange plasma	Radial position = 66 cm: Divergent primary beam
-51	70			
-46	67			
-37	63		50	
-32	59		45	
-24	54		40	
-19	47		35	
-14	39		29	
-6	29		22	
0	19		14	
6	10		9	
11	4		4	
19	-2		1	
25	-5		2	
38	-2	-60		
51	4	-57	1	-45
63		-63	4	-52
76		-66	8	-56

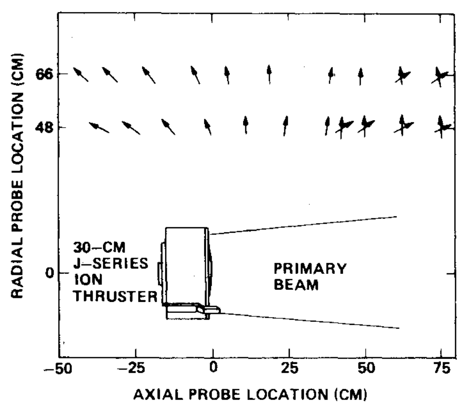

Fig. 6 Plasma flow direction at locations relative to ion thruster.

flow direction is not as well defined as at locations upstream of the thruster. It is of interest to note in Fig. 5 that for positions downstream of the thruster, a second, small, well-defined peak appears when the probe is pointed toward the edge of the thruster optics. It is known that the outer beamlets of the thruster optics produce the most divergent ions in the thruster beam.[14] This peak is produced by those ions. Because these thruster beam ions are very energetic, $\frac{1}{2}M_iU^2 \gg -eV_p$ so that the $\sin\theta$ term in Eq. (2) is prominent. The contribution to the total ion current by the energetic beam ions is illustrated by the dashed envelope in Fig. 5.

Data were obtained with the probe at various locations along the rail and with the rail at two different radial distances from the thrust beam axis. The data were also obtained at different beam currents. The flow directions upstream of the thruster do not change as a function of beam current, which was varied from 1.0 to 1.8 A, and altered only a few degrees in the downstream positions. Table 1 gives the probe angle at which the current peak occurs (average for all beam currents) for various axial and radial positions relative to the thruster. For the axial positions given, the negative (−) numbers are upstream of the plane of the thruster optics. The radial position is the distance from the thrust beam axis to the probe location. The probe angle has been previously defined.

The plasma flow can more easily be seen in Fig. 6 which illustrates the plasma propagation for a 1.8-A beam current. One can observe that the flow seems to originate just downstream of the thruster. Near the thruster the plasma flow is primarily radial. The plasma flow can be seen to be bending both upstream and downstream as it propagates outward. Internal electric fields in the plasma due to variations in plasma density act on the ions. This produces the added component of velocity parallel to the thruster axis.[1-3,8] It should be noted that increased experimental uncertainty exists for the flow directions given in Table 1 and Fig. 6 for positions greater than approximately 50 cm downstream. This is due to the broadness in the charge-exchange ion current peak, as compared to upstream positions, and by the varying magnitude of the primary beam contribution with probe angle.

It is of interest to look at the density distribution upstream of an ion thruster. As previously mentioned, the major flow direction appears to be independent of the facility-produced plasma. However, the base ion current is dependent on the facility-produced ions. With this in mind, the plasma density and flow velocity are determined using Eqs. (2) and (3). Both equations are dependent on the plasma density, N_e, and the flow velocity, U. Equation (3) is a result of the end-effect theory while Eq. (2) gives the ion current collected by an infinite probe in a flowing plasma. The position, $\theta = 90$ deg, is chosen to evaluate the data curves using Eq. (2) since the end-effect prevents using $\theta = 0$. The half-width of the peak on each curve is used to evaluate Eq. (3). Only those peaks upstream of the thruster are evaluated because the broadening of the current peak at downstream positions introduces additional error. To reduce facility effects the curves obtained with the target horizontal are used. The probe is biased −5 V relative to ground. By typical Langmuir probe methods, the plasma potential in all cases was found to average 1-2 V above ground. Therefore, V_p is taken as −6.5 V in the calculations. The results for a 1.8-A beam current are given in Table 2.

Independent density measurements were made at some locations. At each location the cylindrical probe was pointed into the plasma flow and a typical voltage-current Langmuir probe characteristic obtained. Each characteristic was analyzed, using the method outlined by Chen,[15] to obtain the plasma density. The values obtained with thij method and those shown in Table 2 agree within a factor of 2, although the density values in Table 2 are higher than those obtained with probe voltage-current characteristics. No additional attempts have been made to assess the degree the facility-produced plasma contributes to the density. Therefore, the

Table 2 Plasma density and directed energy of plasma ions

	Radial position = 48 cm		Radial position = 66 cm	
Axial position, cm	Density, m^{-3}	Energy, eV	Density, m^{-3}	Energy, eV
−51	3.8×10^{12}	1.9		
−44	4.6×10^{12}	1.78	3.9×10^{12}	1.2
−38	6.9×10^{12}	0.9	4.8×10^{12}	2.0
−32	8.5×10^{12}	1.0	5.6×10^{12}	1.6
−25	1.2×10^{13}	1.1	8.3×10^{12}	2.01
−19	1.7×10^{13}	2.3	1.3×10^{13}	2.7
−13	2.8×10^{13}	2.7	1.7×10^{13}	2.8
−6	4.2×10^{13}	3.3	2.4×10^{13}	1.9

density values in Table 2 are higher than the density due to true ion thruster charge-exchange plasma. Based on previous studies, the error in density introduced by existence of facility ions is small near the thruster plane but can increase an uncertain amount for positions upstream of the thruster optics.[2,3,8] Therefore, the values given in Table 2 are considered accurate to within a factor of 2 near the thruster, but may be less accurate for positions farther upstream.

Concluding Remarks

A cylindrical, Langmuir probe end-effect has been used to determine the direction of flow of the charge-exchange plasma produced by a 30-cm J-series ion thruster. The flow direction is independent of the facility-produced ions. The flow direction is also independent of the beam current at which the ion thruster is operated. The angular position of the ion current peak is reproducible to within a couple of degrees at each probe location.

Two well-defined peaks occur in the ion current vs probe angle curves at positions downstream of the thruster optics plane. The most prominent peak is produced by the charge-exchange plasma and the additional, smaller peak is caused by ions coming from the edge of the thruster optics. These ions represent the very divergent part of the primary beam. This indicates that the end-effect might be useful in studies involving such divergent beam ions.

Ion current measurements were also used to determine the density and flow velocity at various locations upstream of the thruster. Due to the lack of a unique flow direction at positions downstream of the thruster, as required by Eq. (2), no density calculations were performed at these positions. Independent measurements of density obtained from typical voltage-current probe characteristics agreed with the densities obtained from the ion current measurements upstream to within a factor of 2. No attempt was made to make correction for the facility-produced ions. As already stated, these ions do not affect charge-exchange plasma flow direction but do affect local density. The density values given in this paper are probably high for true charge-exchange ions due to the presence of facility ions. The error introduced is expected to be small near the thruster but can increase an uncertain amount for positions farther upstream. To obtain the density upstream due to genuine charge-exchange ions the facility effects have to be accounted for. In the past this has been done but the accuracy of such corrections are uncertain.[1-3,8]

Acknowledgments

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