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ENERGY DISTRIBUTIONS AND YIELDS OF SECONDARY IONS AND ELECTRONS EMITTED BY GIOTTO DURING HALLEY ENCOUNTER

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ABSTRACT

The extreme ram velocity of the GIOTTO spacecraft with respect to the Halley environment will produce a host of surface impact phenomena not previously encountered by planetary spacecraft. This paper extends earlier efforts to model impact produced plasma at GIOTTO by investigating published data on secondary electron and ion energy distributions, including the effect of possible surface contamination. One new result is the finding that the threshold velocity for kinetic emission of secondary electrons by neutral gas is very nearly equal to the GIOTTO ram velocity. This makes it difficult to predict electron yields due to neutral gas impact.

1. INTRODUCTION

This note summarizes data on the energy distributions and yields of secondary electrons and ions which are relevant to the problems of GIOTTO spacecraft charging. The information reported here is drawn largely from a search of the literature on surface impact phenomena. It is expected that some of the GIOTTO surface materials will actually be tested in laboratory particle beams to provide more reliable data on this complex problem. The compilation of existing data and references should nonetheless prove useful, particularly with regard to anomalous surface effects seen only in space.

Efforts of the GIOTTO Plasma Environment Working Group (PEWG) have been directed toward modeling the plasma environment near the spacecraft, particularly as it relates to the problem of electrostatic charging. Thus far work has centered on identifying the relevant secondary processes and estimating their respective yields (cf. Ref. 1). Data on energy distributions and yields have been examined carefully, with the objective of specifying more precisely the boundary conditions needed for simulation models of the GIOTTO charging problem. This may also be of interest to plasma experimenters, and others with instruments on GIOTTO, whose measurements may be compromised by the high density of spurious particles induced around the spacecraft.

Figure 1 illustrates the variety of incident and emitted materials which are important in the context of the hypervelocity interaction of GIOTTO with Comet Halley. Contributors to primary radiation and particles reaching GIOTTO are solar photons, cometary electrons, ions, neutral gases, and dust. Inside the bow shock, solar wind ion and electron fluxes are negligible as Figure 2 shows. Photoelectrons and cometary electrons and ions represent a fairly small component of the current to the front surface of GIOTTO, although under normal circumstances it is these fluxes which would determine the spacecraft potential. Generally speaking, the problem of charging due to photoelectrons and ambient plasma is well understood (Refs. 3-7). This is true despite the fact that real spacecraft surfaces are seldom the pristine metallic materials preferred in laboratory experiments on secondary emission. Studies, for example by DeForest (Ref. 4) and Grard (Ref. 5), show reasonable agreement between calculations based on laboratory data and currents and potentials measured in space. Conditions on GIOTTO during Halley encounter will be more extreme than the more familiar spacecraft-plasma interaction typical of the Earth's magnetosphere, primarily because of the high ram velocity as well as the presence of dust.

2. SURFACE CHARACTERISTICS OF THE GIOTTO SHIELD

Due to thermal design considerations, the GIOTTO dust shield will not be a pure metallic surface e.g. of aluminum or gold. Instead a conducting white silicon-based paint will be used. It is emphasized that the GIOTTO spacecraft configuration, i.e., with the rocket motor pointing out through the same surface through which instruments must view, is a most undesirable, albeit necessary, situation. The painted dust shield surface will very likely be covered with one or more monolayers of rocket motor exhaust products, primarily hydrocarbons. Studies of the GEOS apogee motor, which is being used for GIOTTO, show that 7% of the weight loss of the rocket motor lining consists of materials with molecular weight $\gtrsim 50$ amu (Ref. 26) which are largely hydrocarbons (Ref. 27). Calculation of the absolute amount of material deposited is not possible, but it is known that self-scattering within the outgassing cloud as well as scattering from ambient gas and electrostatic re-attraction can produce significant amounts of surface

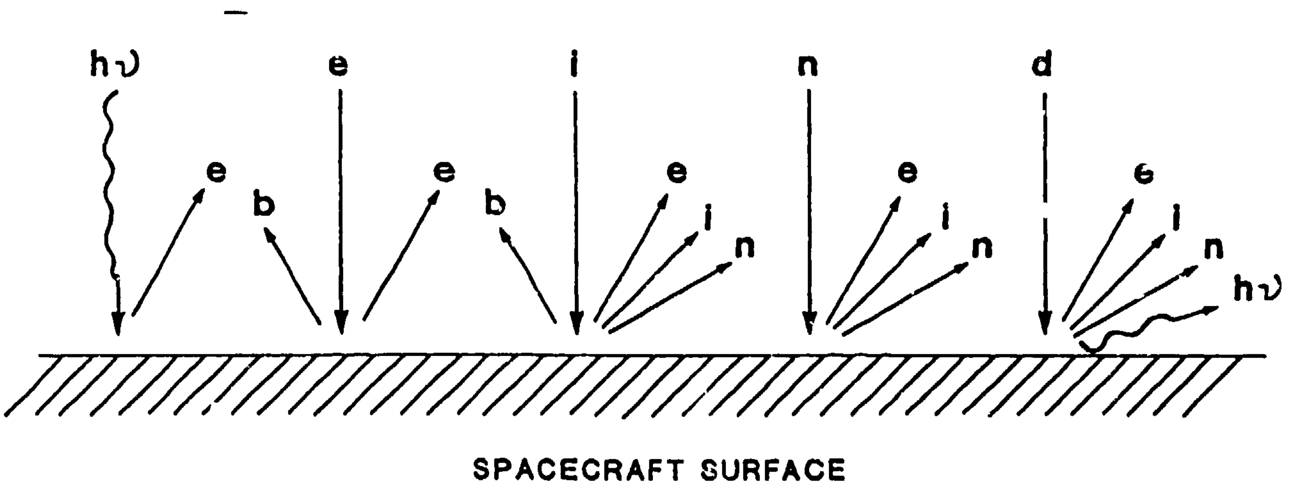

Figure 1. Incident and emitted radiation and particles on the GIOTTO dust shield surface. Abbreviations used are hv = photons, e = electrons, i = ions, n = neutral gas, d = dust, b = backscattered particles. Of the 5 types of incident material, only ions, dust, and neutral gas are incident normal to the urface.

ntamination (Ref. 28). During the 9-month uise phase, illumination of the contaminated irface by solar UV may chemically activate it, anging the effective work function and surface nding energy. Chemical activation effects are ite possibly responsible for anomalously high n sputtering yields observed on Atmospheric plorer spacecraft (Ref. 29) as well as high condary electron yields seen on OV1-18 (Ref. 30) d Pioneer Venus Orbiter (Ref. 7). Kinetic ission must clearly be involved in the case of O even though ram velocities are well below reshold. This suggests a contaminated and/or emically activated surface. These effects are arly impossible to predict beforehand, although situ plasma measurements could ease the situation as discussed below.

In summary, even without contamination, the OTTO dust shield would not be an ideal surface sofar as its physical properties are concerned. is presents those seeking to model the GIOTTO asma environment with a difficult task: to aracterize secondary charged particle emission ifficult even for a "clean" metallic surface) of ill-defined, "dirty" surface.

3. PHOTOEMISSION

Photoemission from spacecraft surfaces is nerally well understood. Moreover, in terms of condary particle currents, photoemission is not very important process within the cometary vironment (Fig. 2).

As is well known, the photoelectric effect sults in emission of electrons whose maximum kinetic energy is equal to the energy of the cident photons minus the work function of the itting surface. In fact, few electrons are und near the maximum energy and the distribution reasonably well described by a Gaussian with a an of ≈ 1.5 eV (Refs. 5,7). Provided that some all amount of ambient plasma is present to lance out the flux of the highest energy otoelectrons, it turns out that the details of e emitted electron distributions do not matter ry much. Grard (Ref. 5) found that a xwellian having a mean energy of ≈ 1.2 - 1.5 eV adequately described the emitted distributions. Electron yield and the shape of the energy distribution do depend, however, on whether a contaminating layer (e.g. an oxide or hydrocarbon coating) is present. Extensive data on photoelectron yields and spectra for a wide range of materials of interest in space are found in Ref. 9.

What is the applicability of laboratory results if the GIOTTO dust shield is contaminated by hydrocarbons from the rocket motor? Even 1-2 monolayers of such a deposit are sufficient to change the work function of the emitting surface and hence the secondary electron energy distribution (Ref. 8). Typical carbon materials have low intrinsic photoemission yields and high UV absorption coefficients (Ref. 9). Feuerbacher and Fitton (Ref. 9) noted that a 500 Å thick carbon film on gold suppressed the photo yield by a factor ~3 at photon energies <12 eV and by 30% at higher energies.

Since photoemission is fairly well understood, and since there will be opportunities for plasma instruments to be exercised during the cruise phase of the mission, it should be possible to measure the GIOTTO potential under conditions which are well-defined; viz, with solar wind plasma and photoemission the only contributors to charging. These results could then be fed back into models of GIOTTO charging in order to learn something about the secondary emission properties of the real GIOTTO surface.

4. ELECTRON IMPACT

Incident solar wind and cometary electron fluxes are small relative to other particle fluxes during most of the encounter (Fig. 2). Furthermore, maximum secondary electron yield occurs at primary electron energies of a few hundred eV. Because the typical primary electron fluxes during encounter should consist almost entirely of electrons of a few tens of eV, secondary yields will be low. According to data of Ref. 11 (Table 13-3-1, 13-3-2) we should expect yields well below 1. Therefore, taking into account both the low primary flux, and the low secondary yield, we may

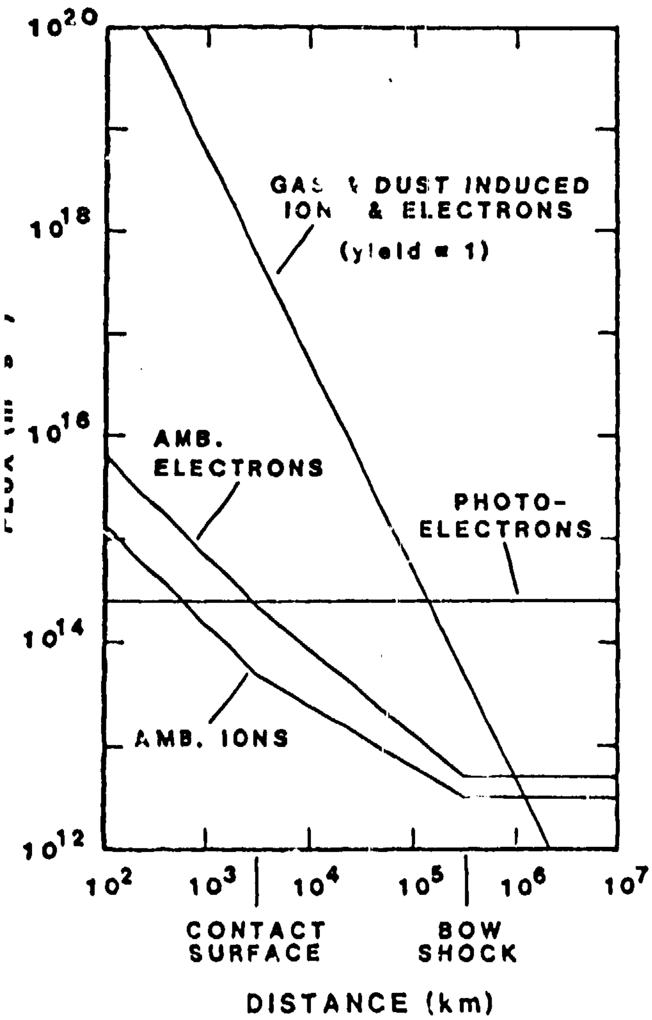

Figure 2. Approximate fluxes of ions and electrons incident on the GIOTTO dust shield (in the case of ambient ions and electrons) or created on the shield (in the case of photoelectrons, gas, and dust). The yield for gas and dust production of electrons and ions has arbitrarily been taken as 1, but in fact is ~ 50% for dust and may be <<1 for neutral gas--see text. (Adapted from Ref. 2).

exclude from further consideration secondary electron production by electron impact. Of course, if the surface is chemically activated, then electron yields may be much higher.

5. ION AND NEUTRAL IMPACT

When ions or neutrals (molecules or atoms) strike a surface three species of true secondary particles may be emitted: ions, neutrals and electrons. There also exists the possibility of backscattering of the incident particle particularly at low incident energies (few hundred eV). The subject of secondary neutrals does not concern us here, although they may dominate the total number of atomic particles emitted (cf. Ref. 1). We also note a point which is quite clear from the perspective of surface physics, but which has caused some confusion in Halley charging studies, namely that the collisional processes governing electron and ion emission are basically different. Thus secondary electron and sputtered ion yields need not be equal, nor are the emitted fluxes of these particles equal a priori. Once the effect of spacecraft charging is taken into account, then the net flux of positive ions and electrons must balance out in order for equilibrium to be reached. In one sense the surface knows nothing of charge balance, it is simply driven by the impact of ions, neutrals and dust. It is up to the spacecraft as a whole to find a charge-neutral solution to the problem.

5.1 Secondary Electron Emission

For reasons that will be explained shortly, the importance of secondary electron emission to the GIOTTO mission hangs on an unusual coincidence, one that has apparently escaped notice up to now. This coincidence concerns the threshold for kinetic emission of secondary electrons. Below a certain velocity threshold, ~60-100 km/s, potential emission of electrons is the primary mechanism for secondary emission (more extensive treatments of this subject appear in Refs. 12-14). This is illustrated in Fig. 3 for argon ions and neutrals. Potential emission results primarily from Auger neutralization of the incident ion. The requirement for this process to take place is that the ionization potential of the incident ion be greater than twice the work function of the surface, i.e., $E_i > 2\phi$. Values of E_i for various cometary ions are listed in Table 1. Note that the GIOTTO surface properties, including the value of ϕ, will be largely unknown. Thus an

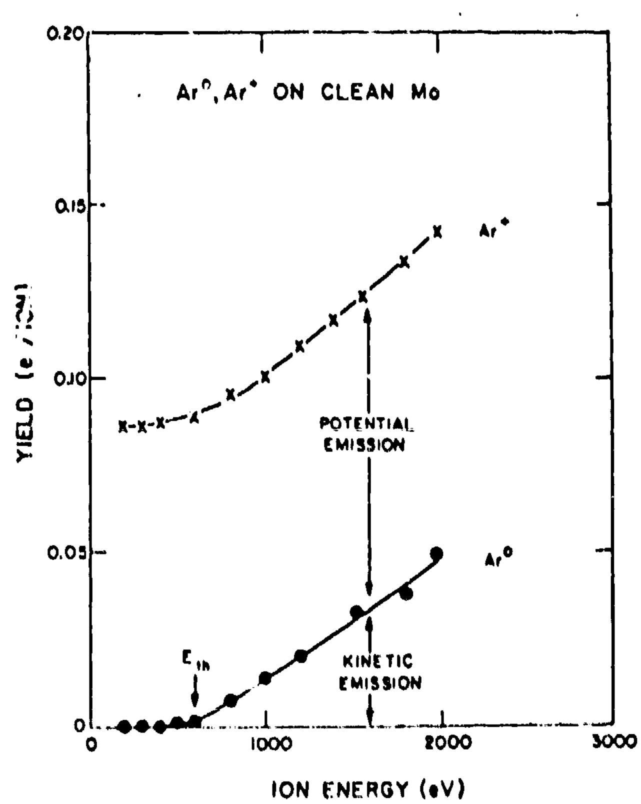

Figure 3. Secondary electron yields for argon neutrals (Ar^0) and ions (Ar^+) incident on clean, polycrystalline Mo. (Adapted from Ref. 11.).

Table 1.

...ary ...ies	First ioniz. potential (V)	Kinetic energy (eV)*	$E_i - 2\phi$ (ϕ = 5 V)**
	13.6	25	3.6
	15.6	50	5.6
	24.6	99	14.6
	13.6	398	3.6
...$_3$	11.2	423	1.2
...O	12.6	447	2.6
	14.1	696	4.1
	15.5	696	5.5
...$_2$	14.4	1094	4.4

...cted or ram energy only, based on spacecraft-...t velocity of 69 km/s.

...OTTO surface work function assumed to be 5 V.

...ate of ϕ from in-flight data, by the method ...ested in Section 4, would be most useful.

Obviously, potential emission cannot occur ...incident neutrals. However, at energies above ... the process of kinetic emission begins to ...ate. Although not understood as well as is ...ntial emission, kinetic emission is physically ...lar to collisional phenomena in gases, except ... the emitted secondaries must escape from the ...d surface in order to be observed.

The coincidence referred to above is that the ...shold energy for kinetic emission corresponds ...n incident velocity variously estimated to be ...00 km/s (Ref. 12, p. 305; Ref. 13, p. 472), a ...ow range whose lower limit coincides with the ... velocity of cometary neutrals and ions ...hing GIOTTO. The proximity of the velocity ...shold for emission to the impact velocity on ...TO suggests that it may be very difficult to ...rmine *a priori* whether a given neutral species ... eject secondary electrons. Uncertainty over ... surface work function further complicates ...ers. The kinetic emission theory of Parilis ... Kishinevskii (Ref. 15), which seems to have ...st acceptance, predicts a definite threshold ... depends on the depth of the surface's valence ..., its work function, and the ionization ...ntial of the impacting particle. More ...ntly, Baragiola et al. (Ref. 17) derive a ...shold of ~ 200 km/s dependent only on the ...ace work function. Because of this threshold ...ct the yield of secondary electrons due to ...ral impact will be critically dependent on ...ace characteristics.

Concerning secondary electron emission by ..., it is clear from Table 1 that the most ...dant cometary ion species can be expected to ...t electrons by the potential process provided ... the surface work function remains below 6-7 ...hich is likely to be the case. Again, because ... the velocity threshold, there may be little ...ribution from the kinetic process.

Secondary Electron Energy Distributions

Where potential emission is possible, as in ... case of most ion species impacting GIOTTO, the ...mum electron energy is given simply by ... 2ϕ. Values of this parameter are given in ... last column of Table 1 under the assumption ... ϕ = 5 V. From Table 1 (He^+ may be neglected) and with reference to secondary electron spectra of Hagstrum (Fig. 4), secondary electrons will have mean energies of ≈ 2 eV (i.e. ≈ $\frac{1}{2}(E_i - 2\phi)$) with maximum values of ≈5 eV. For heavier, and therefore more energetic, ions the high energy tail should extend a bit farther than the estimate in Table 1. This is illustrated in Fig. 5 for Kr^+

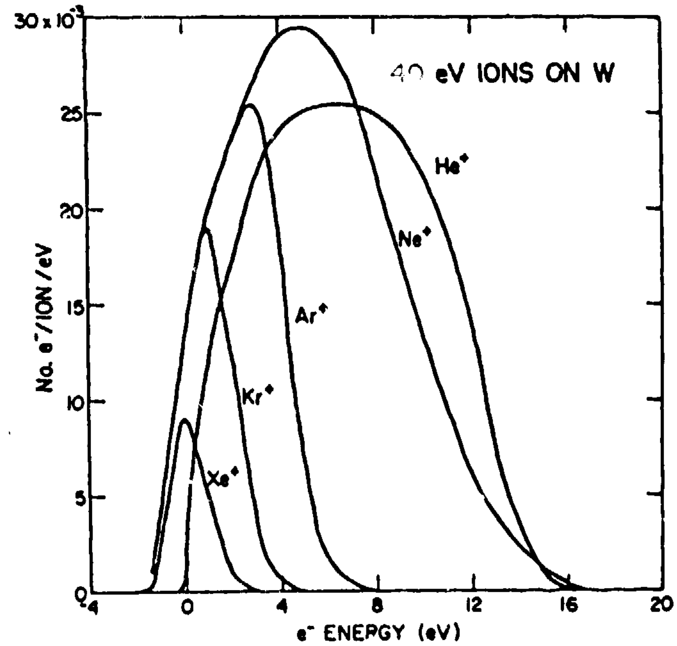

Figure 4. Energy spectra of secondary electrons produced by the process of potential ejection. (From Ref. 16).

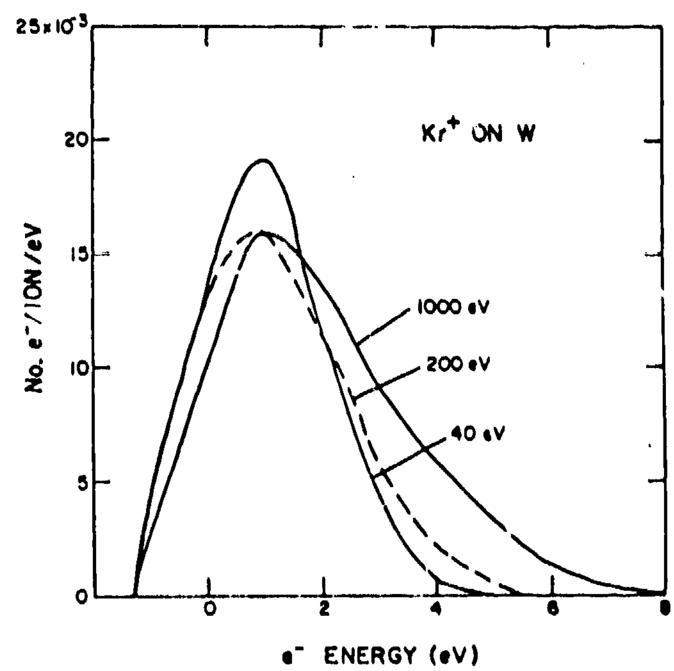

Figure 5. Effect of varying ion energy on energy distribution of secondary electrons ejected by the Auger process. (From Ref. 16).

from which we may estimate that heavy ions such as CO_2^+ will produce electrons up to ≈ 10 eV.

In kinetic emission (Fig. 6) the energetic tail of the electron distribution becomes more important with increasing ion energy. However because GIOTTO is just at the threshold for emission, the distributions will be rather "soft", e.g., similar to that of Cs^+ in Fig. 6. This stems from the fact that near threshold the ions have low energy and are stopped relatively near the surface where a greater percentage of low energy electrons escape. Moreover, there is little ion kinetic energy to transfer to the electrons which are ejected.

5.3 Sputtered Ion Distributions

Despite the emergence of secondary ion mass spectrometry (SIMS) as a tool in surface and materials sciences, there is not a great deal of information available which is relevant to GIOTTO. The currently favored theory of ion sputtering is that of particle ejection by a localized heating process in which sputtered atoms, molecules, ions and electrons are all in local thermal equilibrium (LTE) so that a modified form of the Saha ionization equation may be applied (Ref. 17). One failure of this theory, which is of some importance here, is the appearance of long, non-Maxwellian high energy tails on sputtered ion distributions. Examples are given in Figs. 7-9 for several systems and energy ranges. Appreciable numbers of ions are present out to several tens of eV in all 3 cases. Note also that mean ion energies are ~5 eV, about twice the value for secondary electrons.

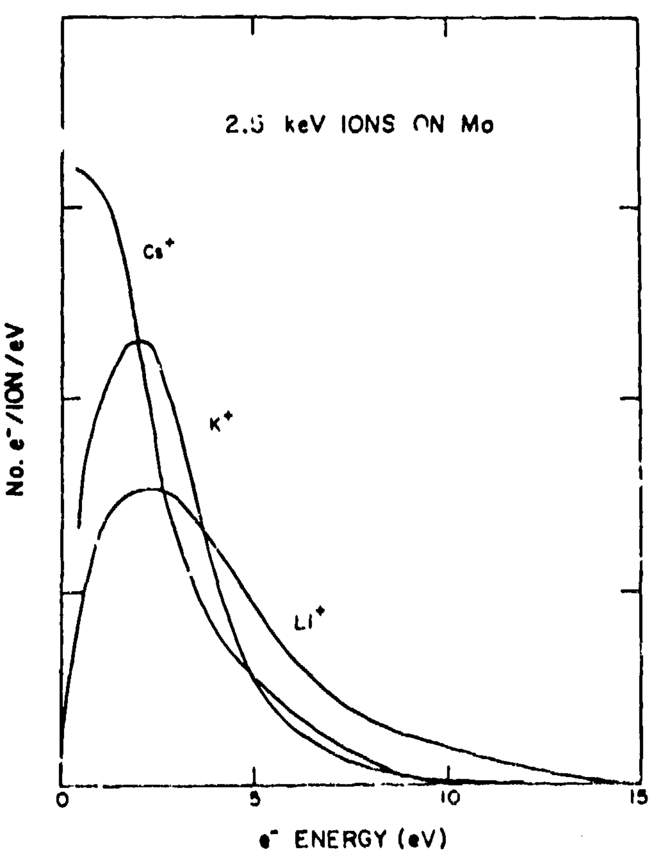

Figure 6. Effect of varying ion velocity on energy distribution of secondary electrons ejected by the kinetic process. Ion masses (amu) and velocities (km/s) are Li^+ (6.94, 263), K^+ (39.1, 111), and Cs^+ (132.9, 60). Cs^+ is very near the threshold velocity for kinetic emission. (Adapted from Ref. 11).

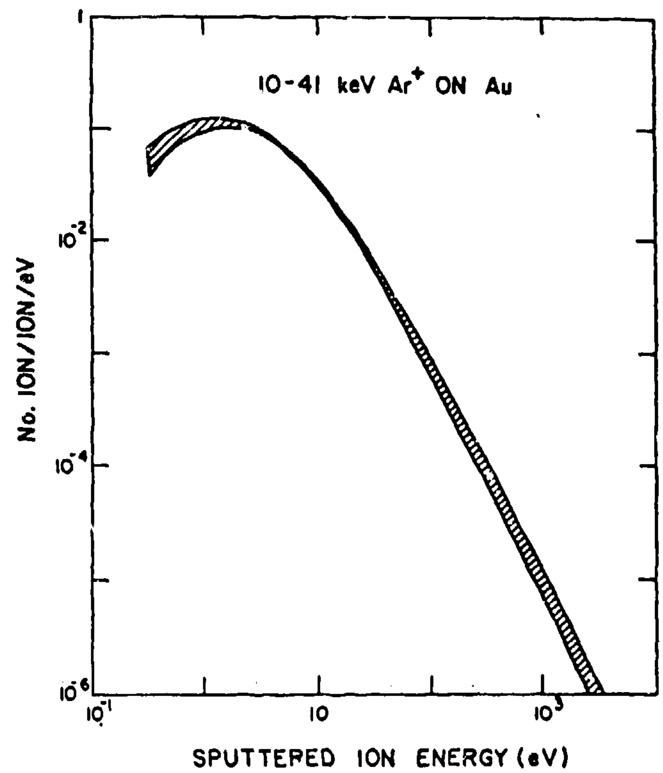

Figure 7. Energy spectrum of atoms sputtered from a polycrystalline Au target bombarded by Ar^+ ions. (Adapted from Ref. 18).

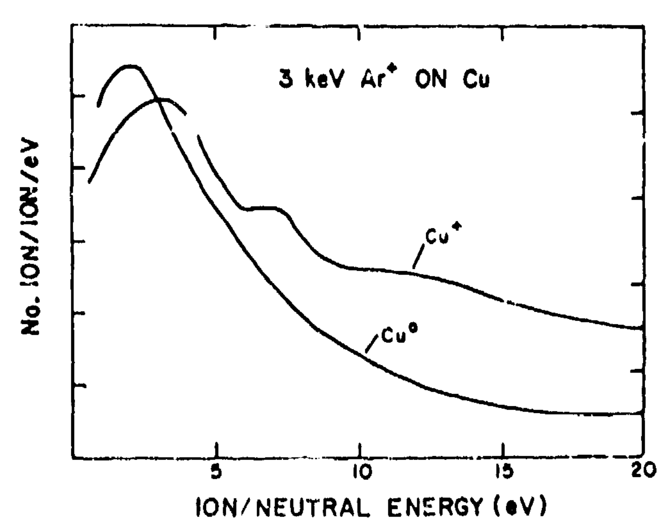

Figure 8. Energy spectra of sputtered Cu atoms and ions plotted on an arbitrary scale. Note the more intense high energy tail of the ion distribution relative to that of the neutrals. (Adapted from Ref. 19).

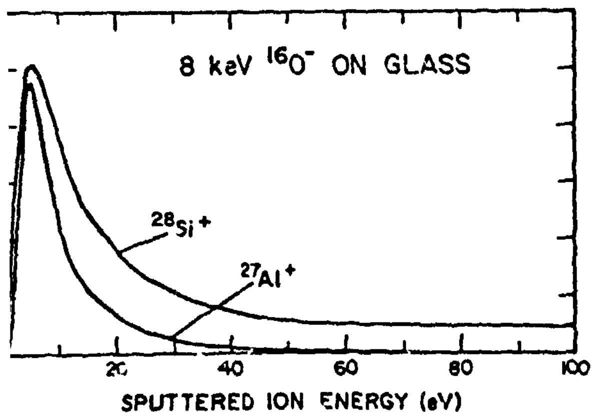

Figure 9. Energy spectra of ions sputtered a glass surface bombarded by 8 keV $^{16}O^-$. for the two species are offset by ≈ 1/2 unit he (arbitrary) linear scale. Note that the energy tail extends to ~50 eV although the are fit reasonably well by a maxwellian out 10 eV. (Adapted from Ref. 15).

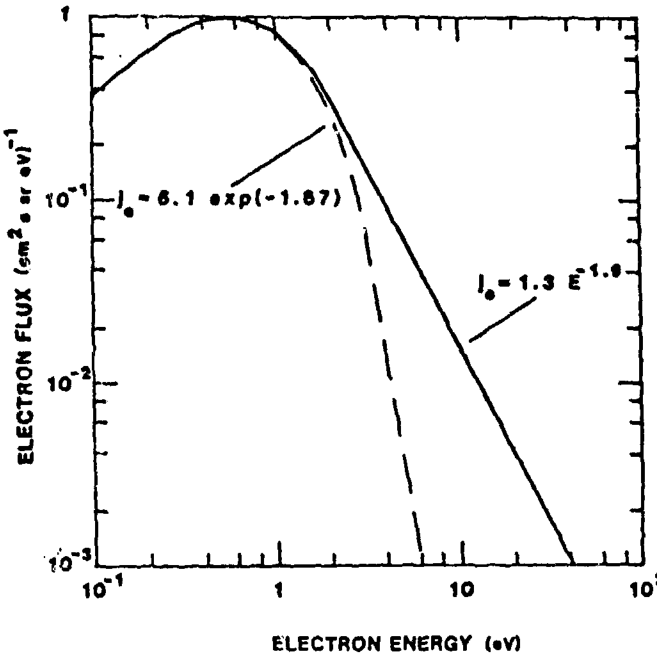

Figure 10. Electron energy spectrum expected from dust impact on the GIOTTO shield. Dashed line represents a maxwellian with kT_e = 0.6 eV.

6. DUST IMPACT

Dust particles with masses $\lesssim 3 \times 10^{-7}$ g will penetrate the front "bumper" shield of GIOTTO. he impact velocity of 69 km/s these small par-es are vaporized and to a large degree ionized -100% depending on particle mass), thereby ucing a plasma composed of dust material, , C, Si, Fe, Mg (Ref. 20). Discussion of the TO dust impact ionization phenomenon is found Refs. 21-23. The dust plasma cloud formed by impact of a single particle rebounds away from shield surface with a bulk velocity ≈ 40 km/s a cloud expansion velocity of somewhat less . 22). Maassberg (Ref. 24) considered a le, analytical model of plasma cloud expansion found, in the worst case, that dust impacts i induce short ($\lesssim 10^{-3}$ s) negative excursions spacecraft potential of 10-20 volts. This ction is supported by plasma wave instrumenta-on Voyager 2 which observed an intense noise t during crossing of the G ring (Ref. 25). ger data were interpreted in terms of an iding dust plasma cloud that enveloped the ma wave experiment antennas. Pulse duration $\lesssim 10^{-3}$ s and amplitudes (which depend very on coupling of the antenna to the induced ma cloud) were above the instrument saturation l of 0.25 V.

Modeling of the dust plasma component is tly important in view of its large contribu-to total charged particle fluxes (Fig. 2). rtunately the high impact velocity of 69 km/s ludes direct laboratory measurement of emitted ged particles. We may conclude from the ious discussion that ions will form a drifted illian distribution with speeds divided about lly between drift and expansion motions. trons are carried along by the demands of ge neutrality in the expanding plasma cloud. are subsonic because even at low temperatures eV) their thermal speed is much higher than cloud's drift rate. Electron temperatures may estimated from the Saha formula for the iding cloud (Ref. 22). Smaller dust particles ice higher electron temperatures because the electron-ion relaxation time becomes shorter for smaller particles and electrons lose thermal contact with ions earlier in the expansion. Using data in Ref. 22 we find that kT_e ≈ 0.5, 1.0, and 4.0 eV respectively for electrons originating from the impact of 100, 10, and 1 μ dust particles. This information, together with a model of the dust size distribution (Ref. 26) and the degree of ionization (Ref. 21), has been used to construct the model electron distribution shown in Fig. 10. The solid line indicates the approximate envelope of the combined electron distributions of varying temperatures. For comparison, the dashed line is the tail of a maxwellian having kT_e = 0.6 eV.

7. SUMMARY AND CONCLUSIONS

Tables 2 and 3 provide a summary of the distributions discussed in the preceding sections. Note that in Table 2 the yield for secondary electron emission by ion and neutral impact is not given. These are dependent on whether the respective thresholds are met as discussed above. The yield for shock ionization of dust particles is given as 0.5 because this is roughly the mean when averaged over the dust size distribution.

The GIOTTO mission is almost certain to present plasma experimenters with complex and challenging problems in the area of spacecraft interactions with planetary environments. Basically, the ram velocity of the spacecraft is so great that a considerable amount of free energy is available to drive physical and chemical processes which will result in charged particle emissions orders of magnitude greater than any previously encountered. At the same time, the peculiar spacecraft configuration of a rocket motor protruding through the forward (ram-direction) surface, sets the stage for self-contamination as well as chemical-activation problems. Under this set of circumstances it is doubtful that

Table 2. Secondary Electron Emission

Source	Mechanism	Yield	Energy Distribution	Mean Thermal Energy (eV)
Photoabsorption	Photoelectric effect	---	Max.	1-2
Electron impact	Collisions	<< 1	Max. Backscatter	1-2 E_o
Ion impact	Potential ejection Kinetic ejection	0 for $E_i < 2\phi$ 0 for $V_o < V_{th}$	Max. Max.	2-5 1-2
Neutral impact	Kinetic ejection	0 for $V_o < V_{th}$	Max.	1-2
Dust impact	Shock ionization	0.5	Non-max.	0.3-1*

* Distribution has high-energy tail.

Table 3. Secondary Ion Emission

Source	Mechanism	Yield	Energy Distribution	Mean Thermal Energy (eV)	Drift Energy (eV)
Ion impact	Sputtering	0.1-1	Non-max.	5	---
Neutral impact	Sputtering	0.1-1	Non-max.	5	---
Dust impact	Shock ionization	0.5	Drifted max.	$\lesssim$9 eV/amu	9 eV/amu

predictions of secondary particle fluxes are very accurate. Charging calculations based on these estimations are nonetheless useful, provided a fairly wide range of input distributions can be considered. Modeling of the spacecraft plasma environment will very likely be an important aspect of post-encounter data analysis.

8. ACKNOWLEDGEMENTS

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