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ABSTRACT: Interaction of cometary and solar plasma components is sufficiently great to permit assumption of a common flow velocity and description of the process as a continuum. The density distribution of ions is regulated by their entrainment in the solar wind rather than by the spatial distribution of ionization probability. It is mainly the position of the shock front and the flow conditions in the low density regions remote from the head of the comet which are influenced by the variable parameters, while the position of the interface and the density and velocity of the cometary gas in the vicinity of the head of the comet are only slightly affected. The influence of the charge exchange and ionization by electron impact are considered and the results discussed.

When a comet approaches the Sun, large amounts of gas are evaporated from the conglomerate of ice and dust forming its nucleus (c.f. L. Biermann and E. Trefftz [6] and W. Huebner [8]). This gas is rendered visible in sunlight by fluorescence. Various processes ionize the effluent gas in approximately 10^6 seconds (c.f. L. Biermann and E. Trefftz[5]) and interrupt the mutual interaction with the supersonic flow of the interplanetary medium, which is also ionized. This medium constantly expands out of the outermost solar atmosphere at Mach numbers on the order of 10, and is therefore called the solar wind. Its existence was determined in 1951 by L. Biermann [1] on the basis of the accelerations which were observed in the tails of comets, and was confirmed by measurements made by the Mariner II Venus probe. As shown by L. Biermann, B. Brosowski and H.U. Schmidt [2,3,4], the mutual interaction between the cometary and solar plasma components is so strong that a common flow velocity can be assumed in good approximation and description as a continuum is permissible. /1*

The following picture was proposed in the papers discussed above: In the immediate vicinity of the nucleus, photoionization causes the formation of an expanding, purely cometary plasma of relatively high density, which deflects the solar wind out of the

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* Numbers in the margin indicate pagination in the foreign text.

path of the comet's head and streams away in the comet's tail in the direction opposite to the Sun. This purely cometary plasma is separated from the solar wind by an interface which flows around the comet's head in the direction away from the Sun and therefore continually absorbs cometary molecular ions by photoionization, charge exchange and electron impact. The associated increase in the average molecular weight tends toward Mach 1 and would produce a deflection angle in a plane flow. Hence, at a considerable distance from the head of the comet the solar wind is transformed into a subsonic flow at a shock front. The flow pattern along the Sun-comet axis was calculated for a number of solar and cometary parameters for the special case of pure photoionization in [3,4]. The positions of /2 of the interface and shock front as functions of these parameters were discussed in detail by H.U. Schmidt [9], while the numerical method used for the model calculation was discussed by B. Brosowski [7].

New model calculation took into account the influence of the charge exchange and ionization by electron impact. The results obtained are given and discussed in this paper.

In the hydrodynamic conservation theorems for a number of particles N, mass density ρ, impulse and energy of the plasma, we will use the additional source terms A, B, C and D to discuss the particle exchange with the cometary neutral gas, caused by the ionization process. We will also use the continuity equation of neutral particles with the density N_n:

$$\begin{aligned}
&\frac{\partial N}{\partial t} + \mathrm{div}\, N\vec{u} && = A(N,\rho,\vec{u},p,N_n), \\
&\frac{\partial \rho}{\partial t} + \mathrm{div}\, \rho\vec{u} && = B(N,\rho,\vec{u},p,N_n), \\
&\frac{\partial \rho\vec{u}}{\partial t} + (\vec{u}\ \mathrm{deg.})\rho\vec{u} + \rho\vec{u}\ \mathrm{div}\ \vec{u} + \mathrm{deg.}\ p && \\
& && = \vec{C}(N,\rho,\vec{u},p,N_n), \\
&\frac{\partial}{\partial t} \quad \rho\frac{\vec{u}^2}{2} + \frac{p}{\alpha-1} \quad + \mathrm{div}\ \vec{u} \left(\rho\frac{\vec{u}^2}{2} + \frac{\alpha p}{\alpha-1}\right) = D(N,\rho,\vec{u},p,N), && \\
&\frac{\partial N_n}{\partial t} + \mathrm{div}\, N_n\vec{u}_n && = A^-(N,\rho,\vec{u},p,N_n).
\end{aligned} \tag{1}$$

In the above, u is the mass velocity, α is the ratio of the /3 specific heats, p is the plasma pressure, and u_n is the velocity of the neutral cometary particles. Since the neutral particles are exposed only to the solar radiational acceleration and have no mutual interaction with the plasma outside of the ionization processes, their velocity field u_n can be given explicity. In general, mass production is the most important source term, since the mass of cometary molecular ions is roughly equivalent to that of 30 solar protons.

We will assume rotational symmetry along the Sun-comet axis and will use cylindrical coordinates z, r and corresponding velocity components u, v and u_n, v_n for the neutral particles. By passage to the limit r → σ we obtain the following equation:

$$\begin{aligned}
&\frac{\partial N u}{\partial z} + 2N \frac{\partial v}{\partial r} &&= A(N, \rho, u, p, N_n), \\
&\frac{\partial \rho u}{\partial z} + 2\rho \frac{\partial v}{\partial r} &&= B(N, \rho, u, p, N_n), \\
&\frac{\partial}{\partial z} (\rho u^2 + p) + 2\rho u \frac{\partial v}{\partial r} &&= C_z(N, \rho, u, p, N_n), \\
&\frac{\partial}{\partial z} \left(\rho u \cdot \frac{\partial v}{\partial r}\right) + 3\rho \cdot \left(\frac{\partial v}{\partial r}\right)^2 - \frac{1}{R(z)} \frac{\partial p}{\partial z} &&= C_r(N, \rho, u, p, N_n), \\
&\frac{\partial}{\partial z} \left[u\left(\rho \frac{u^2}{2} + \frac{\alpha}{\alpha - 1} p\right)\right] = 2\left(\rho \frac{u^2}{2} + \frac{\alpha}{\alpha - 1} p\right) \frac{\partial v}{\partial r} &&= D(N, \rho, u, p, N_n), \\
&\frac{\partial}{\partial z}(N_n \cdot u_n) + 2N_n \cdot \frac{\partial v_n}{\partial z} &&= A^-(N, \rho, u, p, N_n).
\end{aligned} \tag{2}$$

Here we have replaced the trivial r-component of the impulse equation by its r-derivative and have used the radius of curvature of the isobars /4

$$R(z) = -\frac{\dfrac{\partial p}{\partial z}}{\dfrac{\partial^2 p}{\partial r^2}}.$$

We think of system (2) as a system of conventional differential equations for the functions N, ρ, u, $\frac{\partial v}{\partial r}$, p and N_n. The functions u_n, v_n, are known from the above. These functions must fulfill the following limiting conditions: at large distances from the nucleus, the undisturbed values of the solar wind must be assumed, while at the interface the velocity u must disappear and the stagnation pressure of the cometary plasma must be assumed. Moreover, the corresponding impact conditions must be fulfilled at an unknown point on the shock front. System (2) is not redundant, since the coordinates of the shock front and of the interface are among the unknowns. For the curvature of the isobars, we will assume R(z) = 2z, which corresponds to a family of confocal paraboloids whose common focus is the nucleus of the comet.

For integration of system (2), the method described in [4,7] must be considerably expanded, taking into account the charge exchange and ionization by electron impact. Figures 1-3 show the solutions for a typical comet; the solution for pure photoionization has been adopted from [4] for comparison.

A cometary gas production of 10^{30} molecules per second was assumed. With a velocity of 400 km per second and a particle density of 3 cm^{-3}, the solar wind activity corresponds exactly to the values most often measured by the Mariner II Venus probe with a quiet Sun. As in [4], we chose the following values: Mach number of the /5 undisturbed solar wind, 10; ratio of specific heats, 2; photoionization probability, 10^{-6} sec^{-1}; radiational acceleration, 0.01 cm$\cdot$$sec^{-2}$; initial velocity of the cometary molecules, 1 km$\cdot$$sec^{-1}$. The charge exchange cross section of the cometary neutral particles for a proton impact was assumed to be $3 \cdot 10^{-15}$ cm^2 and their cross section for electron impact ionization above a threshold value of 14 eV was assumed to be 10^{-16} cm^2.

Figure 1 shows the spatial distribution of the cometary molecules along the Sun-comet axis. The particle densities are plotted as a function of the distance from the comet nucleus. The Knudsen gas of neutral particles, flowing freely out of the nucleus, is destroyed by ionization processes at large distances from the nucleus. This clearly shows the high effectiveness of the charge exchange and (especially behind the shock front) that of the electron impacts, for which our earlier assumption of thermal equilibrium between ions and electrons naturally constitutes an estimate which is somewhat on the high side. In accordance with a reduced flow of neutral molecules at large distances from the nucleus, the shock front turns inward with increasing ionization; this is in exact agreement with the equilibrium of the mass flows discussed by H. U. Schmidt [9]. On the other hand, the position of the interface is not affected, since it is determined in good approximation by the equilibrium of the dynamic pressure of the undisturbed solar wind and the cometary plasma within the interface which is produced by photoionization alone. The distribution of the molecular ions shows a still more pronounced concentration as the comet nucleus is approached; immediately in front of the interface, its density is even greater than that of the neutral molecules.

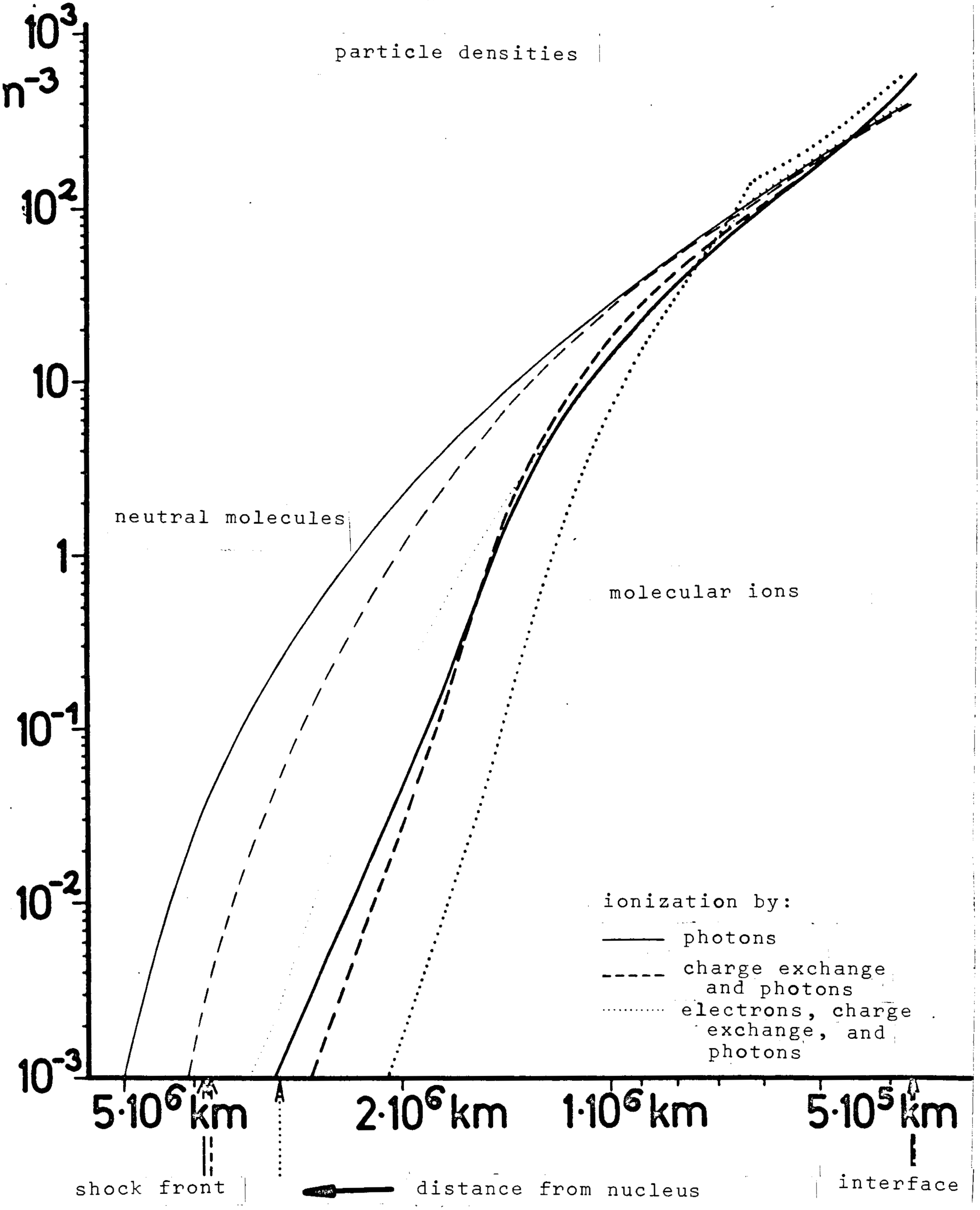
This comparison shows that the density distribution of the ions is not dependent mainly on the spatial distribution of the ionization probability. Rather, it is caused by the entrainment of ions in the solar wind, which acts like a snow plow in the zone between the shock front and the interface. These conditions suggest that the time scales observed (on the order of 10^3 seconds for the creation of ion clouds in the head of a comet) are not ionization time scales at all but rather reflect the convective exchange time scale of the "snow plow zone".

One of the authors (H.U. Schmidt) has reported in detail in a /6 separate paper on the dynamics of this zone and the assumption stated above.

Figure 2 shows the curve of the average molecular weight, Mach number and pressure. The molecular weight increases when the solar wind enters the zone of effective ionization, at a faster or slower rate which depends on the ionization probability (from a value of 0.5 for the undisturbed solar wind to the cometary saturation value of 15). In this zone, the very low Mach number increases once again before reaching a value of 0 at the stagnation point. In accordance with the behavior of the Mach number, the pressure increases to the dynamic pressure value, which is practically the same as that of the undisturbed solar wind, directly behind the shock front.

Figure 3 shows the curve of the velocity, as well as the total density of the plasma and the proton density. With pure photoionization, the proton density immediately in front of the interface falls to about 1/5 of its maximum value, since the added cometary gas contributes significantly to the gas pressure and dislodges the solar protons. However, if we take the charge exchange into account, the protons will have been almost completely disintegrated beforehand.

The variations of the possible ionization processes have their principal influence only on the position of the shock front and the flow conditions in the low-density region remote from the comet's head, while the position of the interface and the density and velocity of the cometary gas in the vicinity of the comet's head are nearly independent of the details of these processes.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n^{-3}
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10^{-1}
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molecular ions
ionization by:
photons
charge exchange and photons
electrons, charge exchange, and photons
$5\cdot10^6$ km
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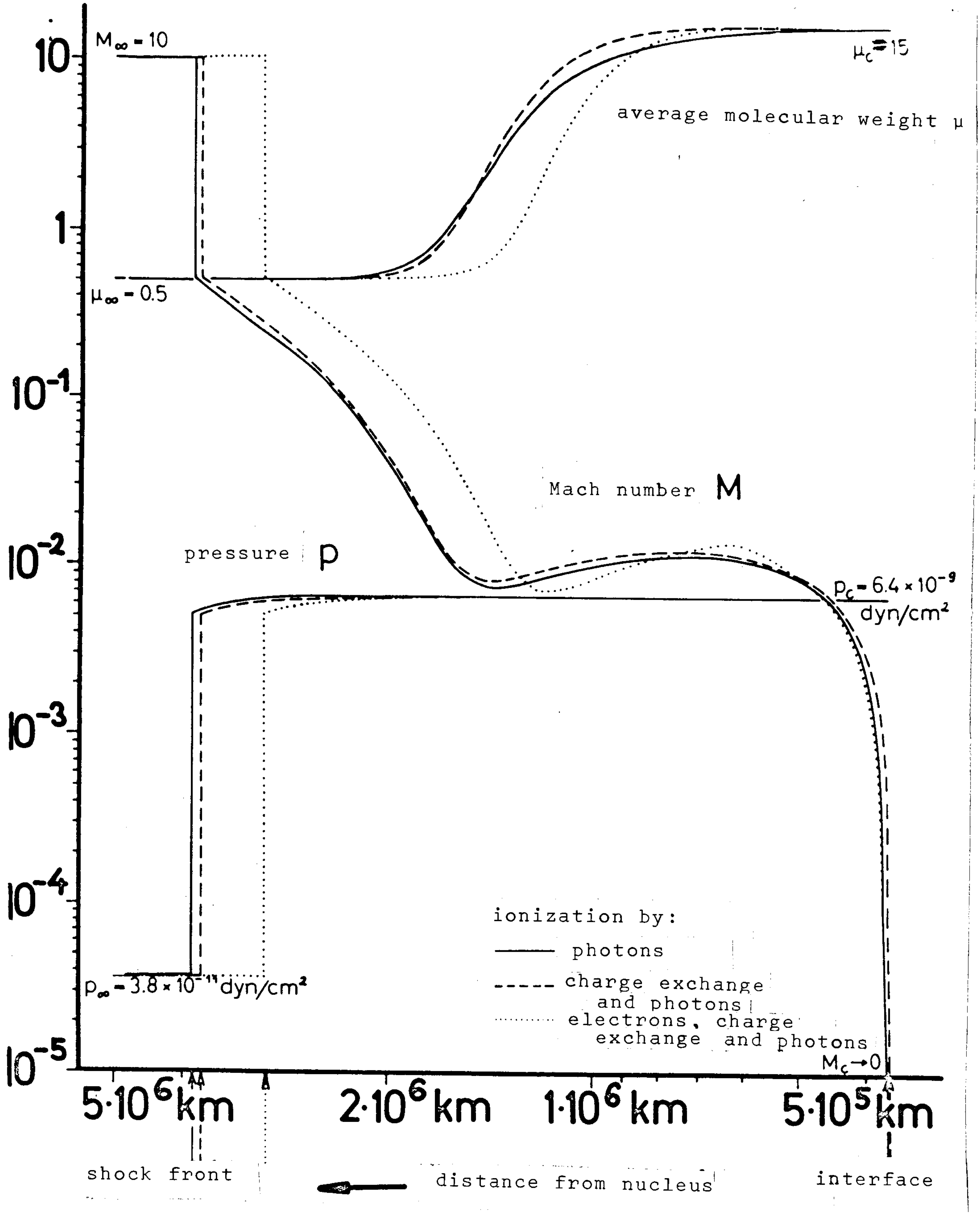
$1\cdot10^6$ km
$5\cdot10^5$ km
shock front
distance from nucleus
interface

Fig. 1.

10
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μ∞ = 0.5
μc = 15
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pressure p
pc = 6.4 × 10^-9 dyn/cm²
p∞ = 3.8 × 10^-11 dyn/cm²
ionization by:
photons
charge exchange and photons
electrons, charge exchange and photons
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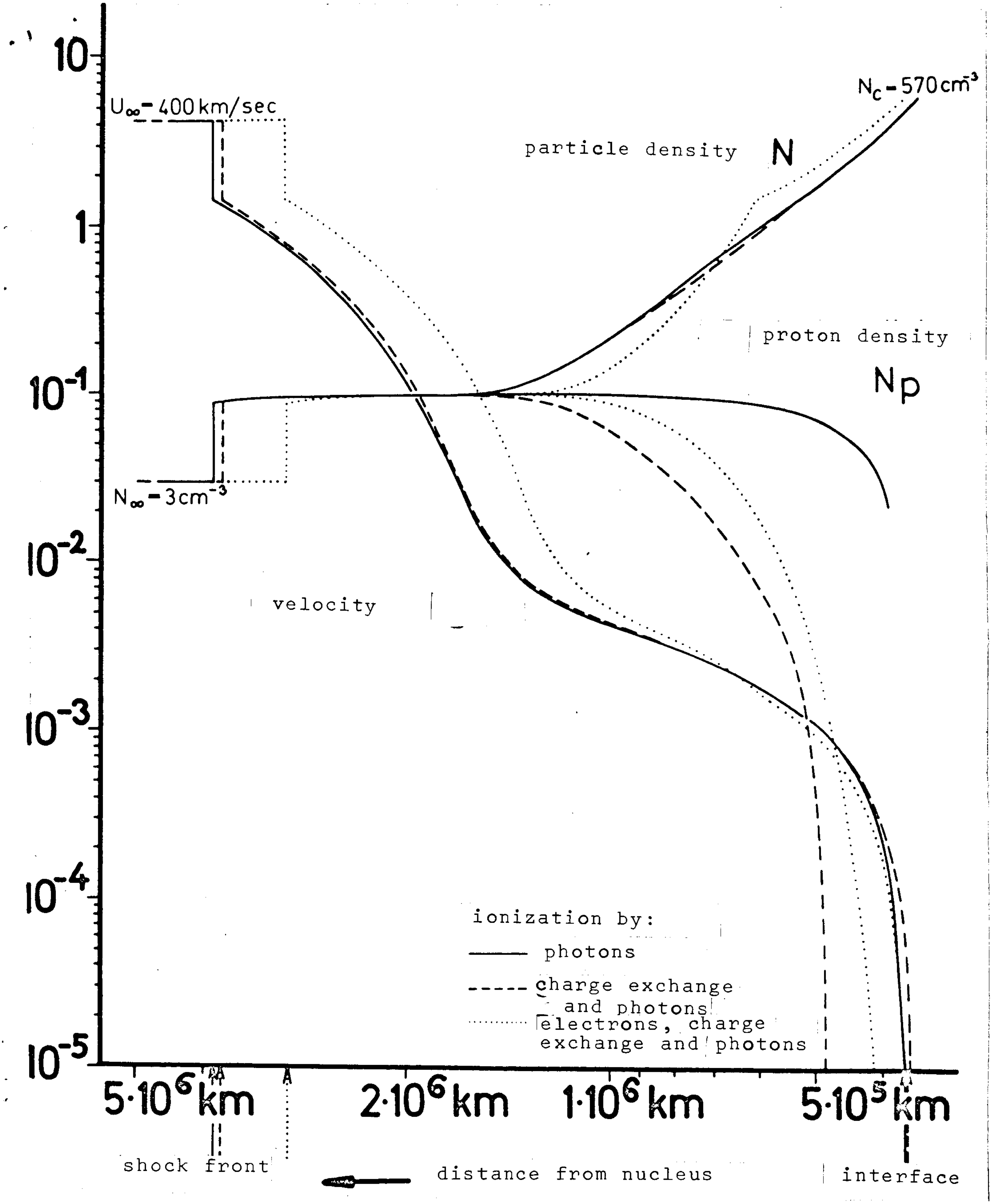
shock front
distance from nucleus
interface

Fig. 2.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10^{-3}
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U_∞ - 400 km/sec
N_c - 570 cm^{-3}
particle density N
proton density N_p
N_∞ - 3 cm^{-3}
velocity
ionization by:
photons
charge exchange and photons
electrons, charge exchange and photons
$5 \cdot 10^6$ km
$2 \cdot 10^6$ km
$1 \cdot 10^6$ km
$5 \cdot 10^5$ km
shock front
distance from nucleus
interface

Fig. 3.

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