CHARGE EXCHANGE IN SOLAR WIND–COMETARY INTERACTIONS

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ABSTRACT

In this paper we examine the effects of charge exchange between fast solar wind ions and slow cometary neutrals at the contact discontinuity separating the ionosphere of a comet from the solar wind flow. The continuity equations were solved analytically for a water-dominated cometary ionosphere, including both ionization and recombination processes. It was found that this new solution differs significantly from the one obtained by neglecting recombination. The normalized neutral and ion densities in the atmospheres of active comets were shown, using an appropriate dimensionless variable to exhibit an interesting scaling behavior. Solar wind ions have a significant probability of participating in a charge exchange interaction with a cometary neutral molecule, because the cometary neutral particle density beyond the contact discontinuity is not negligible. In this process, a fast solar wind ion and slow cometary neutral are replaced by a fast neutral particle and a slow heavy ion. The fast neutral particles originating in the solar wind have a much smaller collision frequency with the cometary constituents than the original solar wind ions; hence, they can leave the vicinity of the comet without contributing significantly to the pressure balance between the solar wind and the cometary atmosphere.

Charge exchange can effectively increase the distance of the contact discontinuity from the nucleus by removing a significant portion of the momentum from the solar wind flow. For instance, it is shown that for realistic comet Halley parameters charge exchange can possibly increase the standoff distance from a couple of hundred to a few thousand kilometers.

Subject headings: atomic processes — comets — Sun: solar wind

1. INTRODUCTION

The solar wind–cometary interaction played a historical role in space physics, prior to the first in situ solar wind measurements. Type I cometary tails were one of the few phenomena leading scientists to assume a permanent outflow of ionized gas from the Sun. A number of magnetohydrodynamic models describing the solar wind interaction with expanding cometary atmospheres were developed during the last two decades. An excellent critical review of these calculations has been recently published by Mendis and Houpis (1982) who pointed out that, in spite of the significant progress made during the last decade, these models still have a number of inconsistencies and shortcomings.

One of the open questions concerning the solar wind–cometary interactions is the role of charge exchange between cometary neutrals and solar wind ions. The importance of this process was recognized in the early 1960s, when Harwit and Hoyle (1962) concluded that charge exchange may lead to the formation of a magnetic barrier in the comet’s head. A couple of years later, Biermann and Treffitz (1964) pointed out that charge exchange is unable to transfer enough momentum from the solar wind to the cometary ions to explain the ion accelerations observed in type I ion tails. About 10 years ago, Wallis (1971) pointed out that charge exchange and photoionization, together with the resulting mass loading of the flow, may smoothly decelerate the solar wind from supersonic to subsonic velocities either without generating a shock wave at all, or creating just a weak shock ($M \approx 2$). Most of the recent multidimensional calculations also take into consideration the charge exchange effect as an additional source of heavy cometary ions. These calculations, however, do not consider another implication of the charge exchange process, namely, that because it represents a sink for solar wind particles, it plays a significant role in forming the contact discontinuity.

The solar wind–Venus interaction is the most extensively studied solar wind interaction with a nonmagnetic body, and the analogy with the cometary interaction has been explored (cf. Russell et al. 1982). In this paper a model of the effects of charge transfer on the position of the Venusian ionopause (Gombosi et al. 1980, 1981) will be modified and
applied to comets. In this model the fast neutral hydrogen created in the charge transfer process is assumed to leave the vicinity of the comet, because the probability of a collision with a cometary constituent is very small. We calculate the pressure balance surface between the weakened solar wind and the outflowing cometary ionosphere and conclude that the contact discontinuity surface separating the cometary ionosphere from the shocked solar wind is usually located at much larger distances from the nucleus than would be expected without the solar wind absorption.

The manner in which we calculate the effects of charge exchange on the solar wind-ionosphere interaction is highly simplified. Recently, Galeev, Cravens, and Gombosi (1982) investigated in more detail than we do here, the role of charge exchange and mass loading in determining the stagnation pressure of the solar wind outside the cometary contact discontinuity.

When calculating the solar wind interaction with the comet, we used a new solution to the coupled neutral and ionospheric continuity equations for the cometary atmosphere. This solution was obtained by including both ionization of neutrals and recombination of ions in the coma, thus significantly decreasing the ion densities within the cometary ionosphere.

For the parameters estimated for comet Halley (Newburn and Reinhard 1981) we predict a standoff distance of a few thousand km or less at 0.9 AU, which seems to be reasonable in the light of the very limited observational data on cometary contact discontinuity surfaces (Combi and Delsemme 1980).

II. THE MODEL ATMOSPHERE AND IONOSPHERE

In this section, we consider a two-component (neutrals and ions) uniformly expanding spherically symmetric cometary atmosphere, where only two physical processes can take place: ionization and recombination. In this spherically symmetric model of the cometary atmosphere the continuity equations are the following:

\[
\frac{1}{r^2} \frac{d}{dr} \left[ r^2 V n_n(r) \right] = - \frac{n_n(r)}{\tau} + an_i^2(r) \tag{1a}
\]

\[
\frac{1}{r^2} \frac{d}{dr} \left[ r^2 V n_i(r) \right] = \frac{n_n(r)}{\tau} - an_i^2(r), \tag{1b}
\]

where we used the following notations: \( r \), distance from the center of nucleus; \( n_n \), neutral density; \( n_i \), ion density; \( V \), uniform expansion velocity; \( \tau \), average neutral particle lifetime against ionization; and \( a \), recombination rate coefficient.

The electron density is assumed to be equal to the ion density because of charge neutrality. Adding the two continuity equations one obtains the obvious result that:

\[
\frac{d}{dr} \left( r^2 V [n_i(r) + n_n(r)] \right) = 0. \tag{2}
\]

One boundary condition is that at the surface of the nucleus all particles are neutrals:

\[
n_n(R_n) = \frac{Q}{4\pi VR_n^2}, \quad n_i(R_n) = 0, \tag{3}
\]

where \( R_n \) is the radius of nucleus and \( Q \) is the production rate. Combining (2) and (3) one obtains the conservation of the total number of particles:

\[
n_i(r) + n_n(r) = \frac{Q}{4\pi Vr^2}. \tag{4}
\]

Substituting equation (4) into equation (1b) one obtains the governing differential equation for this simplified two-component model:

\[
\frac{1}{r^2} \frac{d}{dr} \left[ r^2 V n_i(r) \right] = \frac{Q}{4\pi Vr^2} \frac{1}{\tau} - \frac{n_i(r)}{\tau} - an_i^2(r). \tag{5}
\]
No. 2, 1983  
SOLAR WIND–COMETARY INTERACTIONS  

Let us introduce a new, dimensionless variable:

\[ s = \frac{r}{V_\tau} \]  

(6)

and also a new function, \( u(s) \), defined by the following expression:

\[ \alpha\tau n_0(s) + \frac{1}{s} + \frac{1}{2} = \frac{1}{u(s)} \frac{du(s)}{ds}. \]  

(7)

After some algebraic manipulation one can obtain a second order differential equation for \( u(s) \):

\[ u''(s) - \left( \frac{G}{s^2} + \frac{1}{s} + \frac{1}{4} \right) u(s) = 0, \]  

(8)

where the dimensionless \( G \) is defined by:

\[ G = -\frac{\alpha Q}{4\pi V^3_\tau}. \]  

(9)

Equation (8) is essentially the Whittaker equation:

\[ W''(s) + \left( \frac{0.25 - \mu^2}{s^2} + \frac{\lambda}{s} - \frac{1}{4} \right) W(s) = 0, \]  

(10)

which is well known in nuclear physics. The solution of equation (10) is (see Slater 1965):

\[ W(s) = M_{\lambda, \mu}(s) + \beta M_{\lambda, -\mu}(s), \]  

(11)

where \( M_{\lambda, \mu} \) is the Whittaker function:

\[ M_{\lambda, \mu}(s) = e^{-s/2} s^{1/2} \phi \left( \mu - \lambda + \frac{1}{2}, 2\mu + 1, s \right). \]  

(12)

\( \phi(a, b, s) \) is the Kummer’s function, a confluent hypergeometric function. In our case, the indices of the Whittaker function are:

\[ \lambda = -1 \quad \mu = (G + 0.25)^{1/2}. \]  

(13)

Using the Kummer’s function, one can obtain an expression for a normalized ion density, \( f_i(s) \):

\[
f_i(s) = -1 + \frac{2\mu - 1}{2s} + \left[ -\frac{2\mu}{s} \left( s_0 \right)^{2\mu} \beta \phi \left( \frac{3}{2} - \mu, 1 - 2\mu, s \right) \\
+ \frac{3/2 + \mu}{1 + 2\mu} \phi \left( \frac{5}{2} + \mu, 2 + 2\mu, s \right) + \beta \left( \frac{s_0}{s} \right)^{2\mu} \phi \left( \frac{3}{2} - 2\mu, s \right) \right]^{-1},
\]

(14)

where the normalized ion density \( f_i(s) = \alpha \tau n_0(s) \) and where \( s_0 = R_\alpha / V_\tau \):

\[
\beta = \frac{\left[ 1 + (1 - 2\mu)/s_0 \right] \phi \left( \frac{3}{2} + \mu, 1 + 2\mu, s_0 \right) - (3/2 + \mu)/(1 + 2\mu) \phi \left( \frac{3}{2} + \mu, 2 + 2\mu, s_0 \right)}{-\left[ 1 + (1 + 2\mu)/s_0 \right] \phi \left( \frac{3}{2} - \mu, 1 - 2\mu, s_0 \right) + (3/2 - \mu)/(1 - 2\mu) \phi \left( \frac{3}{2} - \mu, 2 - 2\mu, s_0 \right)}.
\]  

(15)
It can be shown that the asymptotic behavior of massless particles: 

\[
\lim_{s \to \infty} f_i(s) = \frac{G}{s^2}. 
\]  

Substituting equation (16) into equation (4), one obtains the asymptotic behavior of the normalized neutral density: 

\[
\lim_{s \to \infty} f_n(s) = \lim_{s \to \infty} [\alpha \tau n_0(s)] = \frac{G^2}{s^4}. 
\]  

For comparison the analogous normalized densities can be obtained from equation (5) neglecting the recombination terms. In this case, the solutions are the well-known old formulae that have been used for several decades: 

\[
f_i^0(s) = \frac{G}{s^2} [1 - e^{-(s-s_0)}], \quad f_n^0(s) = \frac{G}{s^2} e^{-(s-s_0)}. 
\]  

Comparing the asymptotic solutions (16), (17) and (18) we conclude that by neglecting recombination one grossly underestimates the neutral density far from the nucleus. On the other hand, somewhat closer to the nucleus, equation (18) correctly describes the radial dependence of the neutral density, while it overestimates the ion density.

Let us examine expression (9) for active comets in the vicinity of the sun (i.e., for heliocentric distances, \(d\), smaller than 2.5 AU). The recombination rate, \(\alpha\), exhibits a slight electron temperature dependence; however, for these calculations it was taken to be \(10^{-6} \text{ cm}^3 \text{ s}^{-1}\). This value seems to be valid within about a factor of 2 throughout most cometary ionospheres. The uniform gas expansion velocity is of the order of magnitude of \(1 \text{ km s}^{-1}\), while educated guesses for \(\tau\) vary from \(10^4\) to about \(10^6\) s (the latter time corresponds to photoionization alone). Combining these

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**Fig. 1a**

**Fig. 1b**

Fig. 1.—The normalized ion (a) and neutral (b) densities as a function of the dimensionless \(x\) coordinate. The term \(x\) is basically \(\alpha 1/r\); the exact relation can be found in the text. The little kinks in Fig. 1a (labeled by the \(G\) value) are the consequences of the \(f_i(x_0) = 0\) boundary condition.
values with the estimated gas production rates for active comets, one can conclude that for these comets the dimensionless parameter, $G$, is larger than unity.

In Figure 1, we show the normalized densities $f_i$ and $f_n$ plotted against a new, dimensionless parameter,

$$x = G^{1/2}/s,$$

(19)

for $G > 1$ values. Inspection of Figure 1 shows that the $f_i(x)$ and $f_n(x)$ functions exhibit a very interesting scaling behavior; both functions are practically independent of $G$ in this parameter region. The little kinks in Figure 1a are the consequences of the $f_i(x_0) = 0$ boundary condition, $x_0$ being the $x$ value at the nucleus. In Figure 2, we compare the solutions obtained with and without recombination. It can be easily seen, that for this more or less typical $G$ value ($G = 10^3$), recombination brings down the near cometary ion density by about a factor of 30 and strongly increases the neutral density far from the nucleus.

We have compared our results with the results of numerical models of cometary ionospheres containing many species and many chemical reactions (see review by Mendis and Houpis 1982) and have found reasonably good agreement for the total plasma density. On the basis of Figure 1 one can see that $f_i$ and $f_n$ can be reasonably well approximated by the following expressions:

$$f_i(x) = \begin{cases} 
  x^2 & (x < 1) \\
  x & (x \geq 1) 
\end{cases}$$

(20)

$$f_n(x) = \begin{cases} 
  x^4 & (x < 1) \\
  x^2 & (x \geq 1) 
\end{cases}$$

(21)

This approximation will be used for calculating the charge exchange effects between the solar wind and the cometary atmosphere. An intermediate level of approximation is possible, if the sources and sinks are neglected in the neutral continuity equation (1a) yet kept in the ion continuity equation (1b). Basically, we can use the large $x$ approximation of equation (21) but find an exact solution to the ion continuity equation. For example, for $G = 10^3$ (Fig. 2) this will be a good approximation for $s \leq 10^3$, which for $V = 1$ km s$^{-1}$ and $\tau = 10^6$ s gives $r \leq 10^6$ km. In this case, an analytic

![Diagram](image)

Fig. 2.—Comparison of the normalized particle densities obtained with recombination (solid lines) and neglecting the effect of recombination (dashed lines). The value of the $G$ scaling parameter is 1000.
expression for the normalized ion density $f_i = \alpha \tau n_i$ can be written as a function of $s = r/\sqrt{V_\tau}$ as:

$$f_i(s) = \frac{G}{2s} \left[ 1 + \left( \frac{s_0}{s} \right) \frac{1 - G}{1 + G} \right] \left[ 1 - \left( \frac{s_0}{s} \right) \frac{1 - G}{1 + G} \right] - \frac{1}{G},$$

(22)

where $s_0$ is $s$ at the radius of the nucleus and

$$g = (1 + 4G)^{1/2},$$

and $G$ has its previous meaning. For large $G$ and at all but the smallest $s$, the term of equation (22) in the brackets becomes unity and we reobtain the approximation of equation (20) for large $x$. Equation (22) is valid for all values of $G$ and should be used, rather than equation (21), for small values of $G$ and very small values of $s$. However, for active comets, $G$ is large.

An issue that we have not yet addressed is the degree to which the basic continuity equations (1a) and (1b) are themselves approximations. First, we assume only one neutral component and one ionized component; however, because we are only concerned with the total ionospheric plasma density (or electron density) it does not matter how many neutral or ionized species there are as long as the parameters $V$, $\tau$, and $\alpha$ remain constant. In practice, for the neutrals this means equation (1a) is good except very close to the nucleus (where $V$ is not constant) and very far from the nucleus where $V$ and $\tau$ will change somewhat due to the production of H and OH from $\text{H}_2\text{O}$. And for the ions, this means equation (1b) is good as long as the major ion remains molecular rather than atomic (most likely $\text{H}_2\text{O}^+$) since in this case both $\alpha$ and $\tau$ will remain approximately constant.

III. SOLAR WIND DENSITY

As solar wind particles move along their trajectory, they have a significant probability of participating in a charge transfer interaction with a neutral molecule, which produces a new fast hydrogen atom and a slow heavy ion. Most of the fast neutrals thus produced will leave the vicinity of the comet (the collision frequency of these fast hydrogen atoms with the cometary material is very small) decreasing the momentum of the solar wind. The newly generated heavy ions will be picked up by the solar wind. The effect of this mechanism, and mass loading in general, on the position and strength of the shock wave was studied by Wallis (1971, 1973), Brozzo and Wegmann (1972), and more recently by Schmidt and Wegmann (1980, 1982). These works, however, did not consider the question of what happens in the subsolar region of the cometary atmosphere, where charge exchange has already decreased the solar wind density and the newly formed heavy ions are not accelerated to significant velocities yet.

In this section we calculate the solar wind density or flux along idealized flow lines taking into consideration charge exchange effects. This calculation is similar to some of our earlier work, where we considered solar wind absorption in the ionosheath of Venus (Gombosi et al. 1980, 1981).

Galeev, Cravens, and Gombosi (1982) point out that the mass loading of the solar wind with cometary ions tends to stagnate the solar-wind flow far enough out from the nucleus that charge exchange will not be able to operate to the extent we predict in these calculations. Consequently, the amount of solar wind absorption calculated below is really an upper limit to the actual amount absorbed.

Let us approximate the solar wind flow lines (both in the undisturbed and shocked regions) by straight lines as shown in Figure 3. This approximation is a reasonable one, either in the subsolar region which is our basic concern, or upstream some distance from the contact discontinuity. The solar wind density at $r$ is (for details, see Gombosi et al. 1980):

$$n_{sw}(r, \phi) = n_{sw}^0 \exp \left[ - \int_{r \cos \phi}^{\infty} dz \sigma n_n(r) \right],$$

(23)

where $n_{sw}^0$ is the undisturbed solar wind density, $\sigma$ is the charge transfer cross section, and $n_n$ is the neutral cometary density. The solar wind density can be expressed using the results of the previous section for $n_n$:

$$n_{sw}(x, \phi) = n_{sw}^0 \exp \left[ - \frac{\sigma^2Q}{4\pi\alpha\tau V} x^2 \right] x \int_0^x \frac{dx_1 f_n(x_1)}{x_1 (x^2 - x_1^2 \sin^2 \phi)^{1/2}},$$

(24)

where $x$ is defined by equation (19). Substituting equation (21) into equation (24), one obtains the following solar wind
density function:

\[
n_{sw}(x, \phi) = \begin{cases} 
    n_{sw}^0 \exp \left( -\frac{x^3}{2} K \frac{\phi - \sin \phi \cos \phi}{\sin^2 \phi} \right) 
    & x < 1 \\
    n_{sw}^0 \exp \left( -\frac{1}{2} K \frac{\phi - \sin \phi \cos \phi}{\sin^2 \phi} \right) + K \left[ -\frac{x \phi}{\sin \phi} - \frac{x}{\sin \phi} \arcsin \left( \frac{\sin \phi}{x} \right) \right] 
    & x \geq 1, 
\end{cases}
\]

where

\[
K = \sigma \left( \frac{Q}{4 \pi \alpha \tau V} \right)^{1/2} = \frac{\sigma V}{\alpha} G^{1/2}.
\]  

Near the Sun-comet line \(\phi \to 0\), and the solar wind density becomes:

\[
n_{sw}(X, 0) = \begin{cases} 
    n_{sw}^0 \exp \left( -\frac{1}{2} Kx^3 \right) 
    & x < 1 \\
    n_{sw}^0 \exp \left[ -K \left( x - \frac{1}{3} \right) \right] 
    & x \geq 1. 
\end{cases}
\]

In our calculations we used a charge exchange cross section of \(1.9 \times 10^{-15}\) cm\(^2\), which was obtained on the basis of laboratory studies of collisions of energetic protons with many types of constituents (Tawara 1978). Again, using the \(V = 1\) km s\(^{-1}\) and \(\alpha = 10^{-6}\) cm\(^3\) s\(^{-1}\) values, we obtain a relation between \(K\) and \(G\):

\[
K = 1.9 \times 10^{-4} G^{1/2}.
\]

In Figure 4, we plot the solar wind density along the Sun-comet axis as a function of \(s\) for various \(G\) values. Inspection of Figure 4 shows that the solar wind is actually absorbed by the charge exchange process in a relatively small region; the radial distance of this region from the nucleus, however, depends on the value of \(G\), which depends, among other things, on the gas production rate of the comet.

IV. THE STANDOFF DISTANCE OF THE CONTACT DISCONTINUITY

Magnetohydrodynamical calculations of the solar wind--cometary interaction have become rather sophisticated during the last decade (for an excellent review, we again refer to Mendis and Houpis 1982). These calculations, however, had significant difficulties maintaining a reasonable standoff distance. For some active comets the observations seem to indicate a tangential discontinuity at a distance of about \(10^6\) km from the nucleus, whereas calculations usually predict a considerably smaller value (cf. Mendis and Houpis 1982).
fig. 4.—Solar wind particle density along the Sun-comet line as a function of the \( s = r/V_r \) variable. The curves are labeled with the \( G \) scaling parameter value.

In this section, we point out that charge exchange imposes an upper limit for the standoff distance of the contact discontinuity. As the charge transfer process replaces fast solar wind ions by slow heavy ions, it actually decreases the momentum of the solar wind. The new ions will be accelerated by the \( V_{sw} \times B \) Lorentz force, and at the same time both \( V_{sw} \) and \( B \) will decrease. In the relatively small region where the bulk of solar wind ions participate in charge exchange processes, the solar wind is gradually replaced by a new plasma population containing heavy cometary ions. A pressure balance surface between the weakened solar wind and the cometary ionosphere will develop somewhere in this region. This surface, however, might not necessarily be a classical contact surface, as some of the new ions might penetrate it, possibly carrying the remnants of the interplanetary magnetic field into the ionosphere.

The "ionopause" will develop approximately where the solar wind pressure is balanced by the pressure of the outflowing cometary ions. As we expect, this surface is at larger distances than the calculations of Houpias and Mendis (1981) indicated; consequently the pressure of cometary neutrals plays a relatively minor role in maintaining the pressure balance, because the surface lies outside the ion-neutral collision region.

At the ionopause the pressure balance equation is (see, for instance, Shelby 1969):

\[
n_{sw} m_p (V_{sw} \cdot \mathbf{n})^2 = n_c m (V \cdot \mathbf{n})^2,
\]

where \( m_p \) is the molecular weight of the solar wind ions, \( V_{sw} \) is the solar wind bulk velocity vector, \( \mathbf{n} \) is the normal vector of the contact surface, and the right-hand side contains the previously discussed cometary parameters. Equation (29) represents the balance between the dynamic pressure of the altered solar wind and the dynamic pressure of the expanding cometary ionosphere. This equation is not exact in that on the solar wind side of the discontinuity, the solar wind is actually shocked solar wind and on the comet side, the ionospheric flow has gone through an inner shock and has thermalized. However, equation (29) still provides a good representation of the actual pressure balance.

Assuming that the contact surface is axisymmetric with respect to the Sun-comet axis, equation (29) yields:

\[
R \cos \phi + \sin \phi \frac{dR}{d\phi} = R \frac{V}{V_{sw}} \left[ \frac{n_c (R) m}{n_{sw} (R, \phi) m_p} \right]^{1/2},
\]

where \( R(\phi) \) is the equation of the contact surface. At the subsolar point \( (\phi = 0) \), equation (30) yields an implicit equation for the standoff distance, \( R_s \) :

\[
n_c (R_s) = \frac{V_{sw}^2 m_p}{V^2 m}.
\]

Substituting equations (20) and (27) into equation (31), one obtains an equation for the standoff \( X \) value:

\[
g(x_s) = \gamma,
\]
where

\[ g(x) = \begin{cases} x^2 \exp \left( \frac{1}{2} K x^3 \right) & (x < 1) \\ xe^{K(x-2)^3} & (x \geq 1) \end{cases} \tag{33} \]

and

\[ \gamma = \alpha \tau_n \frac{V_w m}{V^2 m}. \tag{34} \]

We are now in a position to use our results to estimate comet Halley parameters. The numerical values we used were taken from Newburn (1981) and from Newburn and Reinhard (1981). The average solar wind parameters were taken to be \( V_w = 350 \text{ km s}^{-1} \), \( m_p = 1 \), and \( n_w = 5 \text{ cm}^{-3} \), where \( d \) is the heliocentric distance in AU. The remaining parameters are \( \alpha = 10^{-6} \text{ cm}^2 \text{ s}^{-1} \) (ions of type \( \text{H}_2\text{O}^+ \)), \( V = 1 \text{ km s}^{-1} \), \( \tau = \tau_0 d^2 \) (where \( \tau_0 \) was taken to be \( 10^4 \text{ s}, 10^5 \text{ s}, \) and \( 10^6 \text{ s} \)), \( m = 18 \), \( Q = 2.9 \times 10^{29} d^{-2.5} \text{ s}^{-1} \). The case \( \tau_0 = 10^6 \) corresponds to a case of only photoionization.

In Figure 5 we show the estimated standoff distances as a function of the heliocentric distance. Solid lines represent the maximum standoff distance that can be obtained by taking into account solar wind absorption for various ionization lifetimes, while dashed lines were obtained by neglecting the effect of charge exchange on the standoff distance. The results show that charge exchange can increase the standoff distance considerably, indicating that a relatively simple model can reasonably well delineate some of the basic characteristics of the solar wind–cometary interaction.

V. DISCUSSION

In this paper, we have considered a simple model of a cometary spherically symmetrical atmosphere and ionosphere. In § II, we found an analytic solution of the governing equations, thus describing the radial distribution of the neutral and ion densities. This new solution was compared to the well-known solution of the equations containing only ionization terms. By neglecting recombination one significantly overestimates the ion density in the vicinity of the comet. For instance, using comet Halley parameters estimated by Newburn and Reinhard (1981), for 0.9 AU heliocentric distance the difference amounts to a factor of 50. At large distances from the nucleus, where ions became

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the major constituent if there were no solar wind interactions, the recombination results in a $r^{-4}$ decay of the neutral density and not the exponential decrease predicted by the model neglecting recombination.

In the second part of this paper we considered an axisymmetrical model of the solar wind-cometary interaction taking into consideration the loss of solar wind ions due to charge exchange. The calculations predict that for active comets, solar wind absorption due to charge exchange becomes important at a few thousand kilometers from the nucleus, and a surface separating the shocked solar wind from the cometary ionosphere develops in this region. These calculations are in a reasonable agreement with the few observations available for the ionopause location at comets (cf. Mendis and Houfis 1982, and Combi and Delsemme 1980).

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