VISCOUS-LIKE INTERACTION OF THE SOLAR WIND WITH THE PLASMA TAIL OF COMET SWIFT–TUTTLE

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ABSTRACT

We compare the results of the numerical simulation of the viscous-like interaction of the solar wind with the plasma tail of a comet, with velocities of H2O+ ions in the tail of comet Swift–Tuttle determined by means of spectroscopic ground-based observations. Our aim is to constrain the value of the basic parameters in the viscous-like interaction model: the effective Reynolds number of the flow and the interspecies coupling timescale. We find that in our simulations the flow rapidly evolves from an arbitrary initial condition to a quasi-steady state for which there is a good agreement between the simulated tailward velocity of H2O+ ions and the kinematics derived from the observations. The fiducial case of our model, characterized by a low effective Reynolds number (Reeff ≈ 20) selected on the basis of a comparison to in situ measurements of the plasma flow at comet Halley, yields an excellent fit to the observed kinematics. Given the agreement between model and observations, with no ad hoc assumptions, we believe that this result suggests that viscous-like momentum transport may play an important role in the interaction of the solar wind and the cometary plasma environment.

Key words: comets: individual (Swift–Tuttle) – plasmas – solar wind

1. INTRODUCTION

The interaction of the solar wind with the plasma environment of a comet has been the subject of numerous studies for the past 50 years. The basic model to describe how this interaction takes place stems from the work of Biermann (1951), Alfvén (1957), Biermann et al. (1967), and Wallis (1973), and primarily involves the effect of mass loading of the solar wind by the picked-up, newly born cometary ions from the expanding neutral envelope of the comet, and the draping of the interplanetary magnetic field into its magnetic tail. Cravens & Gombosi (2004) and Ip (2004) reviewed the current understanding of the interaction of the solar wind with the plasma environment of comets on the basis of these processes.

In addition to these effects, Pérez-de-Tejada et al. (1980) and Pérez-de-Tejada (1989) proposed that, as happens in other ionospheric, unmagnetized obstacles to the solar wind, such as Venus and Mars, several features of the large-scale flow dynamics in the plasma environment of comets can be attributed to the action of viscous-like forces as the solar wind interacts with cometary plasma. As suggested by Reyes-Ruiz et al. (2010, hereafter referred to as RR10), momentum and heat transport coefficients in cometosheath plasmas can be greatly increased with respect to their normal, “molecular” values owing to the turbulent character of the flow (Baker et al. 1986; Scarf et al. 1986; Klímov et al. 1986; Tsurutani & Smith 1986) and/or to the development of plasma instabilities leading to effective wave-particle interactions, as discussed by Shapiro et al. (1995) and Dobe et al. (1999 and references therein) in the ionosheath of Venus. No attempt is made in the present paper to determine the origin of viscous-like forces in these systems. Rather, on the assumption that viscous-like forces are present, we seek to explore their effects and consistency with observations. Nevertheless, a further discussion of this issue is presented below in Section 5.

In situ measurements by the Giotto spacecraft indicate that, as in Venus and Mars, the solar wind flow in the ionosheath of comet Halley exhibits an intermediate transition, also called the “mystery transition,” approximately half-way between the bow shock and the cometopause (Johnstone et al. 1986; Goldstein et al. 1986; Reme 1991). The latter is defined as a transition from a solar wind proton-dominated flow to a plasma population primarily consisting of relatively cold cometary heavy ions for which the density rapidly increases. Below the intermediate transition, as we approach the cometopause, the antisunward velocity of the shocked solar wind decreases in a manner consistent with a viscous boundary layer (Pérez-de-Tejada 1989). Also indicative of the presence of viscous-like dissipation processes, the temperature of the gas increased and the density decreased as the spacecraft moved from the intermediate transition to the cometopause.

In a recent study, following Pérez-de-Tejada (1999), RR10 have argued that the super-Alfvénic character of the flow in the cometosheath, downstream from the nucleus and in the tail region, as found from in situ measurements at comet Giacobini–Zinner, suggests that viscous-like effects are, at least, as important as \( J \times B \) forces throughout the region. In situ measurements obtained during the passage of the International Cometary Explorer (ICE) spacecraft through the tail of comet Giacobini–Zinner (Bame et al. 1986; Slavin et al. 1986; Meyer-Vernet 1986; Reme 1991), indicate that along the inbound trajectory (which lies slightly tailward of the comet nucleus) the magnetic field in the so-called transition and sheath regions is approximately 10 nT, the number density is approximately 10 cm\(^{-3}\), and the tailward flow velocity varies from \( \sim 400 \text{ km s}^{-1} \) (near the bow shock) down to 100 km s\(^{-1}\). This implies that \( M_{\text{Al}}^2 \) ranges between 4 and 40 across the cometosheath region tailward of the nucleus. In the vicinity of the plasma tail, the measurements of the ICE spacecraft (Bame et al. 1986; Slavin et al. 1986) indicate that the midplane density, dominated by cometary ions, reaches values of 200 cm\(^{-3}\) at the point where the magnetic field is a maximum 50 nT. With flow speeds of approximately 20 km s\(^{-1}\), the square of the Alfvénic Mach number reaches a minimum value of \( \sim 2 \). The fact that \( M_{\text{Al}}^2 \gg 1 \) in the cometosheath of this comet means that the magnetic energy density is much smaller than the kinetic energy associated with the...
inertia of the plasma. A similar situation is found in the cometotheath of comets Halley and Grigg–Skjellerup, where in situ measurements have been conducted. From the Giotto spacecraft data reported by Reme (1991) and Glassmeier et al. (1986) we can estimate that $M_0^2$ varies from 16, near the bow shock, to approximately 3 in the vicinity of the cometopause of comet Halley. Smaller values of $M_0^2$, approximately 2, are estimated for the cometotheath of comet Grigg–Skjellerup from the data reported by Johnstone et al. (1993) and Neubauer et al. (1993).

This implies that $\mathbf{J} \times \mathbf{B}$ forces are not the dominant dynamical factor responsible for the large-scale properties of the flow in the region. By comparing the magnitude of the terms corresponding to momentum transport due to viscous-like forces and $\mathbf{J} \times \mathbf{B}$ forces in the momentum conservations equation, Pérez-deTejada (1999) argued that downstream from the terminator in the ionosheath of Venus, a scenario analogous to the one considered in this paper, the fact that the flow is super-Alfvenic, as found from the in situ measurements of the Mariner 5 and Venera 10 spacecraft, indicates that viscous-like forces may dominate over $\mathbf{J} \times \mathbf{B}$ forces in the flow dynamics in the boundary layer formed in the interaction of solar wind and ionospheric plasma. If the flow is characterized by a low effective Reynolds number, $Re_{\text{eff}}$, this layer extends over a significant portion of the ionosheath of the solar wind obstacle. RR10 have constrained the value of the effective Reynolds number of the flow, $Re_{\text{eff}}$, by comparing the results of numerical simulations of the interaction between the solar wind and a cometary plasma tail, taking into account the effect of viscous-like forces, with in situ measurements in the ionosheath of comets Halley and Giacobinni–Zinner. Their results indicate that a value of $Re_{\text{eff}} \lesssim 50$ is consistent with the relative location of the cometopause, intermediate transition, and bow shock in these comets.

In this paper, we continue our study of the hypothesis that viscous-like forces are important in the solar-wind–comet plasma interaction, by comparing the flow properties along the plasma tail of a comet, as derived from the results of our numerical simulations, with the kinematics of H$_2$O$^+$ ions determined from spectroscopic, ground-based observations of comet Swift–Tuttle during late 1992 (Spinrad et al. 1994). Since the precise origin of the viscous–like momentum transfer processes invoked in our simulations is not yet clear, our study may contribute to the understanding of this process by placing constraints on the parameters, such as the effective Reynolds number, that control the flow dynamics. This being the first attempt to include viscous-like effects in models of the solarwind–comet interaction, several potentially important factors have been neglected, such as the effects of magnetic fields, possibly important in the midplane of the plasma tail (see above), and ion–neutral collisions, important closer to the comet nucleus. These issues are further discussed in RR10 and shall be considered in future studies.

The paper is organized as follows: in Section 2 we review our numerical simulations of the viscous interaction between the solar wind and the plasma tail of a comet. In Section 3 we present the observations of Spinrad et al. (1994) and the inferred velocity profiles that will be used in the comparison. The results of the comparison between model and observations are presented in Section 4. In Section 5 we discuss several issues related to our results, such as time dependence of the flow on the timescale of the different observations. Finally, a summary of our results and our main conclusions are presented in Section 6.

2. DESCRIPTION OF OUR NUMERICAL SIMULATIONS

Profiles for the tailward velocity of the H$_2$O$^+$ cometary plasma along the tail are obtained from the set of numerical simulations described in detail in RR10. Briefly, we use a two-dimensional, hydrodynamic, two species, numerical code including the effects of viscous-like forces resulting from turbulence and/or wave-particle interactions in the flow. The code solves the continuity, momentum, and energy equations in Cartesian coordinates and in conservative form, which for species $a$ can be written as

$$\frac{\partial\vec{U}^a}{\partial t} + \frac{\partial\vec{E}^a}{\partial x} + \frac{\partial\vec{F}^a}{\partial y} = \vec{S}^{ab}, \quad (1)$$

where

$$\vec{U}^a = \begin{pmatrix} \rho^a \\ \rho^a V^a_x \\ \rho^a V^a_y \\ E^a \\ \end{pmatrix}, \quad (2)$$

$$\vec{E}^a = \begin{pmatrix} \rho^a V^a_x V^a_x + \frac{k^a T^a}{\gamma^a} - k^a T^a_x \\ \rho^a V^a_x V^a_y - k^a T^a_y - k^a T^a_x \\ \frac{2}{3} k^a p^a V^a_y + \frac{k^a}{2} T^a - k^a T^a_y \\ \frac{2}{3} k^a p^a V^a_y + \frac{k^a}{2} T^a - k^a T^a_y \\ \end{pmatrix}, \quad (3)$$

and the inter-species coupling term, taken from the work of Szego et al. (2000), is

$$\vec{S}^{ab} = \begin{pmatrix} 0 \\ \rho^a_{\text{vab}} (V^a_x - V^b_x) \\ \rho^a_{\text{vab}} (V^a_y - V^b_y) \\ \frac{1}{2} k^a_{\text{ij}} \rho^a_{\text{vab}} (T^a - T^b) + \frac{k^a}{2} \rho^a_{\text{vab}} (V^b - V^a)^2 \\ \end{pmatrix}, \quad (4)$$

In the preceding equations $\rho^a$ is the mass density of gas $a$, $V^a_x$, and $V^a_y$ are its velocity components, $T^a$ is its temperature, and $E^a_{\text{tot}}$ is the total energy density of species $a$ defined by

$$E^a_{\text{tot}} = \rho^a e^a + \frac{1}{2} \rho^a (V^a)^2 \quad (6)$$

with $e^a$ being the internal energy per unit mass. In Equations (3) and (4), the coefficients $k^a_{\text{ij}}$ ($i = 1, 5$) are the following combinations of dimensionless numbers and the adiabatic index for the gas, $\gamma^a$:

$$k^a_1 = \frac{1}{\gamma^a M_0^2}, \quad (7)$$

$$k^a_2 = \frac{1}{Re_{\text{eff}}^a}, \quad (8)$$

$$k^a_3 = (\gamma^a - 1), \quad (9)$$

$$k^a_5 = \frac{\gamma^a (\gamma^a - 1) M_0^2}{Re_{\text{eff}}^a}, \quad (10)$$
Present code, \( \nu_o \) No. 1, 2010 VISCOUS-LIKE SOLAR-WIND–COMET TAIL INTERACTION 483

to actually and the flow parameters, the spatial coordinates. For simplicity we have assumed that speed is defined as proportion of the flow variables and parameters, the reference sound

\[
M_o = \frac{V_o}{C_{so}},
\]

(12)

\[
R_{\text{eff}}^a = \frac{\rho_0 V_o a L}{\sigma_o^a},
\]

(13)

\[
Pr^a = \frac{\mu_o a^2}{k_o^a}.
\]

(14)

Quantities with subindex \( o \) are those used for the normalization of the flow variables and parameters, the reference sound speed is defined as \( C_{so} = \sqrt{\gamma_o^a P_o/\rho_o} \), \( \gamma_o^a \) is the specific heat at constant pressure for gas \( a \) and \( L \) is the normalization for the spatial coordinates. For simplicity we have assumed that the flow parameters, \( \mu \) and \( \kappa \), are uniform and that \( \mu^a = \mu_o^a \), \( k^a = k_o^a \), \( \mu_b = \mu_o^b \), and \( k^b = k_o^b \).

Note that in the adimensional form of the equations \( v_{ab} \) can be viewed as the ratio of the flow crossing time, \( t_r = L/V_o \) to the inter-species coupling timescale, \( 1/v_{ab} \). In order to preserve the symmetry between the coupling terms for both species, guaranteed by the identity \( \rho^a v_{ab} = \rho^b v_{ba} \), we scale \( v_{ab} \) as \( \rho^b \) and \( v_{ba} \) as \( \rho^a \) with a single proportionality constant, \( v_o \), which we take as uniform and constant. In our present code, \( v_o \) enters as a parameter that can be varied to compare the importance of inter-species coupling to viscous-like forces.

The terms \( T_{xx}^a, T_{xy}^a, \) and \( T_{yy}^a \) in Equations (3) and (4) represent the components of the viscous-like stress tensor given by

\[
T_{xx}^a = \frac{4}{3} \frac{\partial V_x^a}{\partial x} - \frac{2}{3} \frac{\partial V_y^a}{\partial y},
\]

(15)

\[
T_{xy}^a = \frac{\partial V_x^a}{\partial x} + \frac{\partial V_y^a}{\partial y},
\]

(16)

and

\[
T_{yy}^a = - \frac{2}{3} \frac{\partial V_x^a}{\partial x} + \frac{4}{3} \frac{\partial V_y^a}{\partial y}.
\]

(17)

As is done in multiple fluid dynamics applications (Lesieur 1990), we use the Boussinesq hypothesis in writing the Reynolds stress tensor, i.e., we adopt a “standard” form for the relation between the viscous-like stress tensor and the large-scale flow velocity, using an effective viscosity coefficient that encapsulates turbulent viscosity as well as the possible effect of wave-particle interactions or any other plasma instabilities leading to an increased coupling between ions in these collisionless plasmas.

Also, in Equations (3) and (4), \( \dot{q_x}^a \) and \( \dot{q_y}^a \) are the components of the effective heat flux vector for species \( a \) (under the Boussinesq hypothesis):

\[
\dot{q}_x^a = - \frac{\partial T^a}{\partial x},
\]

(18)

and

\[
\dot{q}_y^a = - \frac{\partial T^a}{\partial y}.
\]

(19)

Furthermore, we have assumed throughout this work that both gases are ideal so that

\[
\varepsilon^a = \frac{1}{\gamma_o^a - 1} \frac{p^a}{\rho_o^a},
\]

(20)

with the equation of state \( p^a = \rho^a RT^a \). We have assumed that both the solar wind plasma and the cometary plasma, in the tail region, are characterized by an adiabatic index, \( \gamma^a = \gamma^b = 5/3 \).

An analogous set of equations and definitions are written for species \( b \) by interchanging the superscripts \( a \) and \( b \) in Equations (1)–(20), with \( v_{ab} = v_{ba} \). All equations are coupled by the source term \( \dot{S}_{ab} \) in Equation (1) and are solved simultaneously. The adimensional numbers \( M_o, Re^a_{\text{eff}}, Re^b_{\text{eff}}, \) and \( v_o \) are the basic parameters of our model.

The code uses an explicit MacCormack scheme which is second-order accurate in space and time. In the current implementation of the code we use a non-uniform, Cartesian computational grid. The \( x_i \) points are geometrically distributed from \( x_{\min} \) to \( x_{\max} \) with \( nx \) elements. The \( y_j \) points are equispaced at the initial location of the tail (from \( y = 0 \) to \( y = 1 \) having 50 grid points) and geometrically distributed from \( y = 1 \) to \( y = y_{\max} \). In both series the common ratio is 1.02. We do not include the effect of magnetic fields (see the introduction) or a source of newborn ions in our simulations other than the assumed inflow in our boundary condition (see below).

The simulations are designed to study the dynamics of solar wind and cometary plasma in and around the plasma tail of a comet. In our simulation domain the \( x \)-coordinate is measured along the axis of the plasma tail, increasing in the antisunward direction. The \( y \)-coordinate is measured perpendicular to the plasma tail of the comet starting from the Sun–comet line. The origin of our simulation box is located sufficiently tailward of the cometary nucleus to justify our assumption that the flow entering through the left-hand boundary \( (x = 0) \) is mostly in the \( x \)-direction.

The initial condition for our simulations consists of a dense, slow-moving layer of cold plasma representing the tail extending over the whole \( x \) range of the simulation box and contained between \( y = 0 \) and \( y = 1 \). Both gas species, protons and \( H_2O^+ \) ions, are present in the tail with a uniform initial density, although the density of \( H_2O^+ \) ions is much greater than that of protons. From \( y = 1.5 \) to \( y = y_{\max} \) the flow has the properties of the shocked solar wind with Mach number \( M_{so} = 2 \) in all cases considered for our model. Such value for \( M_o \) is taken from the simulations of Spreiter & Stahara (1980) who computed the flow in the ionosheath of Venus as the solar wind flows past the planet’s terminator toward the tail. No significant differences in our results are found using a value of \( M_o \) between 1.5 and 3. A value of the Mach number outside this range is not expected. For \( y > 1.5 \), fast-moving hot protons are the dominant species with a density 400 times lower than the density of \( H_2O^+ \) ions in the tail. Between \( y = 1 \) and \( y = 1.5 \) there is a transition region from the cometary tail flow (below \( y = 1 \)) to the solar wind flow (above \( y = 1.5 \)).

The boundary conditions for our simulations are the following. At the left-hand boundary we assume a steady inflow preserving the properties of the initial condition described above. At the top boundary \( (y = y_{\max}) \) we assume the flow has the properties of the solar wind flow as in the initial condition. At the bottom boundary \( (y = 0, \) the tail midplane) we assume that the flow is symmetric, so that the \( y \) derivatives of all quantities are taken as zero. At the right-hand boundary we use a zero derivative outflow boundary condition.
The basic properties of the flow resulting from our simulations are shown in Figure 1. Density contours and velocity vectors for both solar wind protons and cometary H$_2$O$^+$ ions, once the flow settles to a quiescent evolution, are shown. A brief description of the main results of RR10 is as follows. In the context of our hydrodynamical, viscous interaction model, two processes dominate the dynamics of the flow, first, viscous-like stresses transfer momentum from the solar wind to the cometary plasma in the tail giving rise to a boundary layer above the cometopause and accelerating cometary material tailward. Second, cometary plasma diffuses into the solar wind owing to the relatively weak interspecies coupling. The action of these processes results in the development of a distinct transition in the flow, which can be identified as the height of the viscous boundary layer formed over the obstacle, intermediate between the shock front and the cometopause. The precise location of these transitions depends on the model parameters and we have found that a model characterized by $Re_{a,b}^eff = 30$ and $v_o = 0.1$ after 1500 simulation time units. The top panel shows the configuration for the proton plasma (species $a$) and the right side panel shows the “equilibrium” configuration for cometary H$_2$O$^+$ ions. Density and velocity are in normalized units.

As we have stated, the main aim of this paper is to constrain the value of the Reynolds numbers and the interspecies coupling timescale in our models by comparing the results of simulations using different values of these parameters with the kinematics determined from the observations.

3. OBSERVATIONAL DATA

On six nights between 1992 November 23 and December 24, Spinrad et al. (1994) carried out long-slit spectroscopic observations of comet Swift–Tuttle using the Lick Observatory 0.6 m Coudé Auxiliary Telescope with an echelle spectrograph in long-slit mode and a narrowband filter centered at $\lambda$6199 Å. Several rotational transition lines of the H$_2$O$^+$ ion are located in the wavelength range of the filter. From these observations they derived the flow velocity of the H$_2$O$^+$ ions along the center of the tail.

Plasma velocities are derived from the Doppler shift of H$_2$O$^+$ emission as one moves along the slit. The slit is aligned along the Sun–comet vector and greater shifts are observed as distance from the cometary nucleus increases. The slit covers a distance, at the comet, up to $4 \times 10^5$ km tailward from the nucleus, depending on the comet–Earth distance.

Spinrad et al. (1994) found that, in general, velocity increases in a more or less linear manner as one moves away from the nucleus along the Sun–comet vector in the antisunward direction. Typically the velocity increases from zero (or almost) at the cometary nucleus to 20–30 km s$^{-1}$ at $3 \times 10^5$ km from the nucleus as illustrated in Figure 2.

4. RESULTS

We have carried out a series of numerical simulations with different values for the basic parameters of the problem; $Re_{a,b}^eff$ and $v_o$, and in this section we compare the resulting profiles of tailward velocity, $V_x$, corresponding to a time $t = 1500 t_{cross}$ in our simulations, and measured at the first active row of the simulation grid, i.e., at the tail midplane with the tail kinematics as observed by Spinrad et al. (1994).

Since the flow variables in our simulations are in dimensionless form, in order to compare the velocity with the observations we must adopt a definite value for the normalization lengthscale and velocity. This in turn sets the value for the normalization timescale. The normalization speed is set to $V_o = 300$ km s$^{-1}$, the speed of the shocked solar as it flows past the terminator and into the tail in the models of Spreiter & Stahara (1980). To set the normalization lengthscale consider that in our simulations $L$ is approximately the half-thickness of the plasma tail. According to the emission intensity measured by Spinrad et al. (1994) across the tail of comet Swift–Tuttle, most of the emission detected, presumably tracing the gas density, is concentrated in a region approximately $5 \times 10^4$ km wide. Hence, we set $L = 2.5 \times 10^4$ km in our simulations. As argued before, the origin of our simulation box is set far behind the cometary nucleus to justify assuming that the flow entering through the left-hand boundary of our box ($x = 0$) is mostly in the $x$-direction. In all cases shown here the origin is located a distance of 1.5$L$ behind the nucleus. This choice is also dictated by the location behind the tail where the observed velocity reaches the assumed inflow velocity into our simulation box.

4.1. Effect of Viscosity

In Figure 3, we first compare the observations of Spinrad et al. (1994) with the results of three different cases having different value of the parameter measuring the relative importance of viscous forces, the Reynolds number, $Re_{a,b}^eff$. As discussed in RR10 there are no significant differences in the dynamics of the H$_2$O$^+$ ions in cases having different values for the Reynolds number for each species as long as the Reynolds number for H$_2$O$^+$ ions, $Re_{a,b}^eff$, remains the same. Hence, in Figure 3 we compare the observed kinematics to the results obtained when
Rea,b discrepancy with the observations, cases with the observed plasma velocities and in fact, given their strong

Figure 3. Comparison of the tailward velocity of H$_2$O$^+$ ions in our numerical simulations (lines) and from the spectroscopic observations (symbols) of Spinrad et al. (1994) for models with different Reynolds number. The vertical dotted line indicates the position of the nucleus in the observations.

$Re_{\text{eff}}^{a,b} = 10$, $Re_{\text{eff}}^{a,b} = 30$, and $Re_{\text{eff}}^{a,b} = 100$. All cases are characterized by an interspecies coupling parameter $v_o = 0.1$.

As discussed in RR10 the effect of decreasing the Reynolds number is to increase the efficiency of momentum transport from the solar wind to the cometary material. In doing so, the erosion of the cometary plasma tail by the solar wind is more effective, and the plasma in the tail is accelerated to greater velocities as we move along the tail. This can be seen from comparing the resulting tailward velocity of our simulations in Figure 3 for the cases with $Re_{\text{eff}}^{a,b} = 10$ (dash-dotted line), $Re_{\text{eff}}^{a,b} = 30$ (solid line), and $Re_{\text{eff}}^{a,b} = 100$ (dashed line). The case with the lowest Reynolds number leads to a much greater acceleration of cometary material while the low viscosity case, high Reynolds number, yields almost no acceleration of material at the midplane of the tail.

It is evident in Figure 3 that the case with $Re_{\text{eff}}^{a,b} = 30$ and $v_o = 0.1$ (our fiducial case in RR10) gives the best fit to the observed plasma velocities and in fact, given their strong discrepancy with the observations, cases with $Re_{\text{eff}}^{a,b} = 10$ and $Re_{\text{eff}}^{a,b} = 100$ can be confidently ruled out.

4.2. Effect of Interspecies Coupling

A comparison of the results of our simulations with the kinematics determined from the observations of Spinrad et al. (1994) for cases having a different interspecies coupling timescale is presented in Figure 4. The Reynolds number, $Re_{\text{eff}}$, is the same in all cases. The effect of decreasing the interspecies coupling is to increase the ease with which both species “penetrate” each other.

There are no significant differences in the H$_2$O$^+$ velocity profiles along the tail for models with weak ($v_o = 0.01$), medium ($v_o = 0.1$), or strong ($v_o = 1$) interspecies coupling. All three cases agree equally well with the observed kinematics at comet Swift–Tuttle.

5. DISCUSSION

In this section, we seek to discuss the issue of time dependence in our solutions and in the observed velocity profiles. The results of our numerical simulations are evolving constantly, albeit the rate at which the flow properties change slows down considerably after the initial transition from our arbitrary initial condition. There also appears to be an evolutionary trend in the kinematics of the flow according to the observations of Spinrad et al. (1994). For example, if we compare the observations of the nights of November 23 and 26, there is a slight increase in the slope of the velocity versus distance relation as can be seen from comparing the sequence of squares (November 23) and the sequence of diamonds (November 26) in Figure 3. Compared to the velocity corresponding to the night of November 30 (triangles in Figure 3) there is no appreciable difference to the flow measured on November 26. A similar tendency is observed by comparing the velocity profiles for the nights of December 23 and 24 in the observations of Spinrad et al. (1994), albeit these have a shallower slope.

The results of our simulations are reminiscent of this behavior. Considering the values of $L$ and $V_o$ adopted, the timescale for the solar wind to cross a distance $L$ is $t_{\text{cross}} \approx 80$ s. Hence, a timescale of 1200 $t_{\text{cross}}$ in our simulations corresponds approximately to 1 day in the observations of comet Swift–Tuttle. So, for example, the system takes about 1 day to go from the full, unperturbed tail scenario of the initial condition, to the eroded tail condition illustrated in Figure 1. As we have argued, following this rapid evolution process, the flow continues to evolve in a quiescent, much slower manner. In Figure 5 we compare two tailward velocity profiles from our numerical simulations taken with a time difference of 3 days (solid and dashed lines), with the velocity profiles derived from the observations of Spinrad et al. (1994) corresponding to the nights of November 23 (squares) and November 26 (diamonds). If we extend our simulations for another 3 days, no significant changes result in the velocity profiles as the simulations have already reached a quasistationary state. We believe that the difference in flow properties observed between the observations of late November and those conducted one month later reflect a difference in conditions of the solar wind (and initial mass function, IMF) incident on the comet, an effect known to give rise to drastic changes in the properties of the plasma tail such as the thickness of the tail as it emerges from the nucleus.

Rather than showing profiles giving an exact fit of our results to the observations (making the appropriate ad hoc modifications), our aim has been to illustrate the fact that the evolutionary trend in our model is qualitatively consistent with the observations.
6. ON THE ORIGIN OF VISCOUS-LIKE FORCES

It is worth emphasizing that in the model we have presented we assume that plasma turbulence and/or wave-particle interactions lead to momentum transport and heat dissipation that can be modeled as a viscous process. This assumption is one of the most important issues to be resolved in connection to the viscous interaction model. It is the focus of our current research efforts but to date the precise origin of the viscous-like momentum transfer processes invoked in the viscous flow interpretation of the intermediate transition, in the ionosheath of comet Halley and in other ionospheric obstacles to the solar wind, is not yet clear.

From the estimation of the viscosity coefficient in a magnetized plasma (e.g., Spitzer 1962), we can readily verify that if viscous-like processes like the ones invoked in this study are to play a role in the dynamics of the flow, they must arise from non-collisional processes. Using, for example, properties of the shocked solar wind in the vicinity of the plasma tail measured at comet Giacobini–Zinner, as described in Section 1, we can calculate the “classical” of “normal” viscosity coefficient resulting from particle interactions according to Spitzer (1962, Equations (5)–(55)) to be $\mu \sim 10^{-11} \text{g cm}^{-1} \text{s}^{-1}$, reflecting the inefficiency of momentum transport across field lines, via collisions, in a tenuous plasma threaded by a strong, uniform magnetic field. Using the flow properties quoted above for comet Giacobini–Zinner (Section 1), this viscosity coefficient corresponds to a Reynolds number ($\rho o V oL o / \mu$), which measures the relative importance of viscous forces in the flow dynamics, that is $Re > 10^{10}$, indicating that viscous processes resulting from particle collisions are negligible in these environments.

An additional feature possibly leading to increased transport processes in these plasmas is the existence of strong fluctuations in the magnetic field in the cometary plasma, as marked by increases in particles Halley and Giacobini–Zinner (Baker et al. 1986; Scarf et al. 1986; Klimov et al. 1986; Tsurutani & Smith 1986). Similar conditions have also been observed in the ionosheaths of Venus and Mars, for which Cravens et al. (1980) have derived an expression for the effective heat conductivity in a plasma threaded by a fluctuating magnetic field on the basis of a quasi-linear theory of particle transport. Assuming that the Prandtl number of the flow is near unity, Pérez-de-Tejada (1995) has calculated an effective viscosity coefficient for the ionosheath of Venus derived on these results. If we use the same procedure to calculate the effective viscosity coefficient for the solar wind around the tail of a comet (with the conditions measured at comet Giacobini–Zinner, Bame et al. 1986; Slavin et al. 1986) we find $\mu \sim 10^{-11} \text{g cm}^{-1} \text{s}^{-1}$. The effective Reynolds number based on this effective viscosity coefficient and the flow properties described above is $Re > 10^{5}$, indicating that “viscosity” resulting from magnetic field fluctuations is negligible, at least as estimated by Cravens et al. (1980). Assuming that the Prandtl number is not very different from unity, as argued by Pérez-de-Tejada (1995), we can also neglect heat conduction resulting from such processes.

It is also possible that, as in many fluid dynamics applications, turbulence, such as that detected in comet Giacobini–Zinner (e.g., Tsurutani & Smith 1986), is characterized (sometimes even defined) by a dramatic increase in the efficiency of transport processes in the flow. In the case of momentum transport this leads to the concept of turbulent or eddy viscosity (Lesieur 1990). Notwithstanding the significant uncertainties in the precise formulation of turbulent “viscous” stresses in terms of the large-scale flow properties, particularly in MHD turbulence, the likely importance of eddy viscosity in the flow in the cometary plasma is expected in view of the large value of the Reynolds number as estimated above.

Finally, as discussed by Shapiro et al. (1995), and Dobe et al. (1999, and references therein), conditions in the ionosheath of Venus and Mars favor the development of plasma instabilities leading to effective wave-particle interactions. If this mechanism also operates in cometary plasmas, it may lead, as in these planets, to increased coupling between the solar wind and cometary plasma in a viscous-like manner, as suggested by Pérez-de-Tejada (1989).

Considering all this, it is fair to say that until a precise mechanism leading to momentum transport as we have assumed is clearly identified, the viscous-like model for the solar wind–comet plasma interaction must be considered a phenomenological model. Our aim in this paper has been to constrain the parameters of such a model by comparing its predictions with ground-based observations of ion dynamics in the tail of a particular comet.

7. CONCLUSIONS

In RR10 we have presented the first numerical simulations of the interaction of the solar wind with the plasma tail of a comet including the effects of viscous-like forces as originally proposed by Pérez-de-Tejada et al. (1980). In this paper, we have carried out a comparison of the tailward velocity profiles of the cometary ions derived in our numerical simulations with the kinematics of H2O+ ions determined from spectroscopic, ground-based observations along the tail of comet Swift–Tuttle (Spinrad et al. 1994).

Our main result is that the case we have chosen as fiducial in a previous study, on the basis of a comparison of our phenomenological model with in situ measurements at comets Halley and Giacobini–Zinner (RR10), characterized by a low Reynolds number ($Re^{e,b} = 30$) and moderate interspecies coupling parameter ($v_{c} = 0.1$) gives one of the best fits to the flow kinematics observed by Spinrad et al. (1994). Cases with a much larger Reynolds number (smaller viscosity) are ruled out by the observations. Hence, on the basis of these results and in the framework of the viscous interaction model, we conclude that an efficient viscous-like momentum transfer between the solar wind and cometary material in the plasma tail is necessary to explain the observed kinematics in comet Swift–Tuttle. The fact that a similar conclusion is reached from the analysis at comets Halley and Giacobini–Zinner (RR10) suggests that viscous-like momentum transfer may be a dynamically important process in the interaction of the solar wind and the plasma environment of comets in general.

We conclude by pointing out several issues yet to be addressed that may have important consequences on the results of our simulations and on the conclusions of this study. Our simplified treatment does not consider the ongoing creation of H2O+ ions in the tail region due to the ionization of cometary neutrals. At this stage in our ongoing modeling effort, we have also neglected the effect of the draped IMF on the flow dynamics (although as discussed in Section 1 we do not expect these to be dominant in the cometary environment), three-dimensional effects, and time dependence of the incoming flow. Finally, perhaps the most important issue yet to be addressed is the effect of the precise form of the viscous-like transport and effective inter-species coupling terms in the equations of motion. We believe that further assessment of the relevance of these factors is beyond the
scope of the present study. They are the subject of work currently in progress and will be reported in future contributions.

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