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Alpha particle heating at comet-solar wind interaction regions

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Abstract. The satellite observations at comet Halley have shown strong heating of solar wind alpha particles over an extended region dominated by high-intensity, low-frequency turbulence. These waves are excited by the water group pickup ions and can energize the solar wind plasma by different heating processes. The alpha particle heating by the Landau damping of kinetic Alfven waves and the transit time damping of low-frequency hydromagnetic waves in this region of high plasma beta are studied in this paper. The Alfven wave heating was shown to be the dominant mechanism for the observed proton heating, but it is found to be insufficient to account for the observed alpha particle heating. The transit time damping due to the interaction of the ions with the electric fields associated with the magnetic field compressions of magnetohydrodynamic waves is found to heat the alpha particles preferentially over the protons. Comparison of the calculated heating times for the transit time damping with the observations from comet Halley shows good agreement. These processes contribute to the thermalization of the solar wind by the conversion of its directed energy into the thermal energy in the transition region at comet-solar wind interaction.

Introduction

A dominant feature of the solar wind interaction with comets Giacobini-Zinner and Halley is the presence of high-intensity, low-frequency magnetohydrodynamic (MHD) turbulence over an extended region. At comet Giacobini-Zinner the amplitudes of the MHD fluctuations detected by the magnetometer and plasma instruments aboard the ICE spacecraft were as high as 10^4 nT^2/Hz and extended over a region of size > 10^6 km [*Tsurutani and Smith*, 1986a]. At comet Halley the fluctuations had smaller amplitudes and were detected by the instruments aboard the satellites Giotto [*Glassmeier et al.*, 1987; *Johnstone et al.*, 1987], Sakigake [*Yumoto et al.*, 1986], and VEGA [*Galeev et al.*, 1986]. The high-intensity turbulence in the comet-solar wind interaction region is excited by the cometary ions picked up by the solar wind and is thus an expected feature of the cometary magnetosphere [*Sagdeev et al.*, 1986]. The presence of high-intensity turbulence in the transition region separating the solar wind from the cometary plasma makes the comet-solar wind interaction quite different from the case of planets [*Galeev*, 1987; *Hizanidis et al.*, 1988; *Sharma et al.*, 1988; *Tsurutani*, 1991]. In the familiar terrestrial case the transition from supermagnetosonic to submagnetosonic flow takes place through the formation of a bow shock across which there is a sharp change in the magnetic field and plasma parameters. The transition in the case of comets is more complex, and while the existence of a shock structure is a topic of debate, it is clear that the region is dominated by intense low-frequency fluctuations. Before the spacecraft encounters with comets Giacobini-Zinner and Halley it was recognized that the shock, when it existed, would be weak and also different from the planetary bow shocks [*Wallis*, 1972; *Omidi et al.*, 1986; *Omidi and Winske*, 1987].

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The spacecraft data have shown the complexity of the transition region, but its specific nature is still unclear. At comet Giacobini-Zinner the data from the ICE spacecraft yielded inconclusive results. From the electron data, *Thomsen et al.* [1986] concluded, mainly from the observed anticorrelation between electron density and temperature, that ICE spacecraft did not cross a shock. At comet Halley the observations showed structures that are closer to a shock [*Galeev et al.*, 1986; *Coates et al.*, 1987, 1990]. However, the widespread presence of large-amplitude fluctuations make the transition region quite different from a usual shock, namely, a sharp transition that connects two regions characterized by roughly uniform plasma parameters. This has lead to models of the cometary transition region that are different from the conventional bow shock picture. Considering the predominance of the large-amplitude fluctuations, the transition can be viewed as a multi-step process controlled mainly by the fluctuations, which in turn are excited by pickup cometary ions. The first step of this scenario is the mass loading of the solar wind, which results in the formation of beam and ring distributions of the pickup ions. The free energy of such distributions can drive a wide spectrum of waves unstable, the coupling being the strongest for the low frequency MHD waves [*Brinca*, 1991; *Gary*, 1991]. As the MHD waves are advected downstream into regions of magnetic field gradients and shear, they acquire a parallel electric field because of the finite ion gyroradius effects and become kinetic Alfven waves, which are Landau damped by the solar wind plasma. This creates localized "hot spots" which are distributed over the transition region and where the solar wind plasma is heated locally [*Sharma et al.*, 1988]. Further downstream the Mach number of the flow reduces to less than 2, and the ring distributions become unstable to electrostatic lower hybrid waves. The interaction of these waves with newly born ions leads to quasilinear diffusion and consequently to the observed cometary distributions and the accompanying wave activity [*Hizanidis et al.*, 1988; *Shapiro et al.*, 1993]. In the chain of events described above, the momentum and energy exchange processes are basically nonlocal, distinct from the local nature in a conventional bow shock.

The spacecraft data of the magnetic field fluctuations and particle distributions from the Giotto spacecraft encounter with comet Halley [*Neugebauer et al.*, 1987] show good agreement with the scenario of the transition region given above. The solar wind protons are heated at a number of isolated heating events over a wide region, and many of these events correlate with high shear in the magnetic field. However, the alpha particle heating observed in the same encounter has different features from the proton heating, and its correlation with magnetic shear is not evident. Compared to the protons the alpha particles have been observed to be heated faster and over shorter heating scalelengths, and they also reach higher thermal velocities at the heating events. Also the initial thermal speeds of the alpha particles are lower than those of the protons, as is expected for the low-speed solar wind [*Neugebauer*, 1981] at the Giotto encounter. In this paper we examine the heating of alpha particles by the low frequency MHD waves. The scalelengths associated with the heating of the alpha particles by Alfven waves are found to be long compared to the observations and thus cannot account for the observed heating. The interaction of the alpha particles with the parallel magnetic field gradients associated with the compressive (magnetosonic) components of the MHD fluctuations can lead to the transit time damping [*Dawson and Uman*, 1965; *Fisk*, 1976]. In the next section the nature of the low-frequency MHD waves at the comet Halley interaction region, the excitation mechanisms and observations are summarized. In section 3 the alpha particle heating by low frequency waves through the Landau damping of kinetic Alfven waves is examined. A comparison of the heating times shows that the alpha particle heating by this mechanism is not strong enough to account for the observations. The heating times and scalelengths of transit time damping at the comet Halley transition region are computed in section 4 and show good agreement with observations. In the final section the role of this and other heating mechanisms in the comet-solar wind transition regions is discussed.

Low Frequency Turbulence at Comet-Solar Wind Interaction

The fluctuations at the comet-solar wind interaction regions have been observed over a wide range of frequencies, from the low-frequency MHD waves (10^{-2} Hz) to the high-frequency plasma waves (10^5 Hz). The excitation mechanisms of these waves and related issues such as instabilities and nonlinear effects have been reviewed by *Tsurutani* [1991]. Here we summarize the main features for the low- frequency waves which are crucial for this study and which also contain most of the wave energy. At the comet Giacobini-Zinner encounter the ICE spacecraft measured intensities as large as 10^4 nT^2/Hz with a bandwidth of $\approx 3 \times 10^{-2}$ Hz [*Tsurutani and Smith*, 1986a,b]. Taking the typical value of the power spectral density to be 10^2 nT^2/Hz, the energy density of these waves is $\approx 10^{-11}$ ergs/cm^3, which corresponds to $\Delta B/B \approx 0.4$, although values of $\Delta B/B \approx 0.7 - 0.8$ are also observed both upstream and downstream. Since the fluctuations are present over a region of size $\approx 10^6$ km, the total energy content is $\approx 5 \times 10^{22}$ ergs. In the case of comet Halley [*Glassmeier et al.*, 1987] the magnetic field fluctuations have lower power spectral densities, with $\Delta B/B \approx 0.3$, but are spread over a larger volume, with a typical size $\approx 1.5 \times 10^6$ km, resulting in total energy $\approx 2 \times 10^{24}$ ergs. The weaker wave intensity at comet Halley compared to comet Giacobini-Zinner may be explained in terms of the different gas production rates, $Q \approx 10^{30}$ mol/s and 5×10^{28} mol/s, respectively [*Galeev et al.*, 1991]. At a distance r from the cometary nucleus the instability source is proportional to Q/r^2, while the position of the strong coupling region or bow shock is proportional to Q. Consequently, the instabilities in this region are driven by a source that is proportional to Q^{-1}. Further, the shorter interaction region at comet Giacobini-Zinner leads to a weaker thermalization of the resonant cometary ions and yields larger amplitudes with more coherence, as was shown by spacecraft data [*Tsurutani and Smith*, 1986b; *Tsurutani et al.*, 1987]. Also at comet Halley the shear and compressional components of the low-frequency fluctuations are almost equal, the shear component being slightly stronger [*Glassmeier et al.*, 1987]. The power spectral index of the low-frequency MHD fluctuations at comet Giacobini-Zinner has a value $\approx 5/3$, corresponding to the Kolmogorov spectrum of fully developed isotropic hydrodynamic turbulence [*Tsurutani and Smith*, 1986a]. At comet Halley, in the upstream region as well as the cometosheath, this index has a higher value, ≈ 2 [*Glassmeier et al.*, 1987, 1989]. This leads to a puzzling issue in the following sense. At comet Giacobini-Zinner the fluctuations were observed to be coherent with clear monochromatic wave packet structure [*Tsurutani and Smith*, 1986a], although with larger $\Delta B/B$ values. At comet Halley, no coherent structures were observed and a wide range of modes were present, leading to a more turbulent case, albeit lower values of $\Delta B/B$. Thus the fluctuations at comet Halley are expected to be closer to the case of fully developed turbulence characterized by the Kolmogorov spectrum, while they are observed to be just the opposite. This is due to the dominance of the fluctuation spectral density arising from the wave-particle interactions $\left(|B_k|^2 \sim k^{-2}\right)$ over that from the quasi-linear wave-wave interactions [*Galeev et al.*, 1987]. This indicates the importance of the kinetic processes at the comet-solar wind interaction. Also, it may be noted that in both the comets the power spectral densities of the fluctuations are about two orders of magnitude higher than that of the average solar wind [*Tsurutani and Smith*, 1986a; *Glassmeier et al.*, 1987].

The turbulence in the transition region is driven by the kinetic energy of solar wind. In the solar wind frame this may be viewed as the excitation of plasma modes by the cometary ions picked up upstream by the inductive electric field due to the flow. A pickup ion will have a beam velocity $V_\parallel = V_{SW} \cos\phi$ along the ambient magnetic field and a gyration (ring) velocity $V_\perp = V_{SW} \sin\phi$, V_{SW} being the solar wind flow speed and ϕ being the angle of the flow with respect to the magnetic field. The free energy associated with the beam and ring distributions of the pickup ions can excite instabilities over a wide spectrum of waves. Considering only the low-frequency MHD waves, the shear (Alfven) mode that propagates along the magnetic field can be destabilized by the beam as well as the ring components of the cometary ion distribution. A firehose type nonresonant instability is excited when the beam speed exceeds a threshold value and the concentration of the ion beams is high [*Sagdeev et al.*, 1986; *Goldstein and Wong*, 1987]. On the other hand, a resonant instability is excited when the beam speed exceeds the wave speed and has high growth rates even for low concentrations of the pickup ions [*Gary and Winske*, 1986; *Thorne and Tsurutani*, 1987]. The nonresonant instability is usually the weaker of the two, and its growth rate becomes comparable to that of the resonant mode when the ratio of the cometary beam to the solar wind ions becomes greater than 0.02 [*Gary and Winske*, 1986]. This ratio is ≈ 0.03 at comet Halley [*Coates et al.*, 1990] and ≈ 0.002 at comet Giacobini-Zinner [*Gloeckler et al.*, 1986] near the bow wave region, and hence the nonresonant mode would be important in the case of comet Halley. Both the resonant and nonresonant instabilities excite waves propagating sunward. The ring distribution of the cometary ions can destabilize the parallel propagating shear Alfven modes [*Goldstein and Wong*, 1987; *Lakhina*, 1987] and the fast MHD (magnetosonic) mode, which has a frequency close to the cyclotron frequency of the pickup water group ions [*Thorne and Tsurutani*, 1987]. Simulations [*Gary et al.*, 1988] of the magnetic fluctuations excited by injected proton and oxygen ions show the excitation of ion-ion right-hand modes with amplitudes whose scaling with injected energies agrees with the observations. These waves propagate sunward like the beam-excited waves. In summary, whether the excitation is by the beam or ring distribution or a combination of both, the modes have frequencies corresponding to the cyclotron frequency of the singly ionized water group ions and propagate as MHD waves in the solar wind. Further, the high spectral power density of these waves, observed to be about two orders of magnitude above the average solar wind value, indicates the key role they play in the transition region.

Kinetic Alfven Wave Heating

The transition region is characterized by highly turbulent fluctuations and relatively hot plasma, with the ratio of the bulk plasma to magnetic energy densities, $\beta \sim 0.5$. Also, the ions have large gyroradi; for instance, for the plasma and field values at the comet Halley encounter at ~ 1923 spacecraft event time (SCET) ($\sim 1.1 \times 10^6$ km from the cometary nucleus) the proton gyroradius $\rho_p \sim 70$ km, and for typical waves at the water group ion gyrofrequency and wavelength given by the condition $\omega = kv_A$, $k\rho_p \sim 0.2$. The advection of low-frequency MHD waves into the density and magnetic field gradients in the transition region leads to mode conversion into kinetic Alfven waves at resonance layers or high-shear regions [*Hasegawa and Chen*, 1976]. These kinetic Alfven waves have parallel electric fields due to the finite ion gyroradius and can heat the plasma by Landau damping. The heating of the solar wind protons observed at comet Halley [*Neugebauer et al.*, 1987] can be accounted for by this process [*Sharma et al.*, 1988]. The heating rate of alpha particles by the same process is obtained as follows.

In the presence of a wave with electric field $E_\parallel$ parallel to the ambient magnetic field, a parallel current $j_\parallel$ leads to plasma heating with a rate given by

$$\frac{d}{dt}(nT) = \frac{1}{2}Re(j_\parallel E_\parallel^*), \qquad (1)$$

where n and T are the plasma density and temperature, respectively, and $E_\parallel^*$ is the complex conjugate of $E_\parallel$. From (1) it is evident that for a given $E_\parallel$ the heating rate is proportional to the parallel current $j_\parallel$, and for different ion species the heating rates may be compared from the respective parallel currents. In a collisionless plasma the kinetic nature of the Alfven waves arises from the finite gyroradius effects, and the parallel current $j_\parallel$ can be calculated using the drift kinetic equations for the electrons and ions [*Hasegawa and Chen*, 1976]. The parallel current of an ion species j (= α, p) is given by

$$j_{\parallel j} = -i\omega_{pj}^2 I_o(\lambda_j)\exp(-\lambda_j)[1+\xi_j Z(\xi_j)]\frac{\omega\, E_\parallel}{k_\parallel^2 v_{Tj}^2}, \qquad (2)$$

where ω_{pj} is the plasma frequency, $v_{Tj} = (T_j/m_j)^{1/2}$ is the thermal speed, I_o is the modified Bessel function of order zero, $\lambda_j = (k_\perp v_{Tj}/\Omega_j)^2$, $\xi_j = (\omega - \vec{k}\cdot\vec{v}_{oj})/\sqrt{2}\, k_\parallel v_{Tj}$, Ω_j is the cyclotron frequency, $Z(\xi_j)$ is the plasma dispersion function and $\vec{v}_{oj}$ is the average flow velocity. We shall consider the flows with respect to the solar wind protons and define ν_o as the drift velocity of the alpha particles with respect to the protons. Then $\xi_p = \omega\sqrt{2}\, k_\parallel v_{Tp}$, and $\xi_\alpha = \left(\omega - \vec{k}\cdot\vec{v}_o\right)/\sqrt{2}\, k_\parallel v_{T\alpha}$. A heating timescale τ can be defined by equating the right hand side of (1) to nT/τ. Then the ratio of the proton heating time τ_p to that of the alpha particles τ_α, is given by

$$\frac{\tau_p}{\tau_\alpha} = \frac{n_p T_p}{n_\alpha T_\alpha}\, \frac{\mathrm{Re}\left(j_\parallel^{(\alpha)} E_\parallel^*\right)}{\mathrm{Re}\left(j_\parallel^{(p)} E_\parallel^*\right)}.$$

This equation combined with the expression for $j_\parallel$ given by (2) yields

$$\frac{\tau_p}{\tau_\alpha} = y\frac{T_p}{T_\alpha}\,\frac{I_o(\lambda_\alpha)exp(-\lambda_\alpha)}{I_o(\lambda_p)exp(-\lambda_p)}\,\frac{\omega - \vec{k}\cdot\vec{v}_o}{\omega}\,\frac{v_{Tp}^3 exp(-\xi_\alpha^2)}{v_{T\alpha}^3 exp(-\xi_p^2)}, \qquad (3)$$

where $y = Z_\alpha^2 m_p/m_\alpha$, Z_α being the charge number of alpha particles. The difference in the heating rates as given by this expression arises from three factors of different physical origins. The first is the difference in the response to an electric field, as given by $y = Z_\alpha^2 m_p/m_\alpha$. The second effect arises from the perpendicular dynamics of the ions, which yields an effective electric field averaged over the gyro-orbits and results in the ratio of terms that depend on λ_α and λ_p. Finally the Landau damping rate, which depends on the ratio of the wave phase velocity to the particle thermal speed, is represented by the ratio of exponential terms arising from the Maxwellian distributions. In the solar wind plasma the factor $\left(\omega - \vec{k}\cdot\vec{v}_o\right)/\omega$ can be taken to be of the order of unity. Further, the thermal speeds of the alpha particles are close to those of the protons, and the last factor is close to unity. With $v_{T\alpha} \approx v_{Tp}$, $\lambda_\alpha \approx 4\lambda_p$ and $I_o(\lambda_\alpha)exp(-\lambda_\alpha)/I_o(\lambda_p)exp(-\lambda_p) \approx 0.5 - 1.0$ for λ_p in the range 0 – 0.5. It may be noted that there is no measured value of λ_p, and so it is essential to consider a range of values. Consequently, with $Z_\alpha = 2$ and $m_\alpha = 4m_p$ the ratio in (3) is $\approx 1/5 - 1/10$. Thus the Alfven wave heating, which can account for the proton heating, is considerably weaker for alpha particles and cannot account for the observed alpha particle heating.

Alpha Particle Heating by Transit Time Damping

The compressive (magnetosonic) component of the turbulent MHD waves produces large parallel gradients in the ambient magnetic field, and their interactions with the magnetic moments of the ions lead to a form of wave-particle interaction, analogous to that of charged particles with electric fields. During this interaction the magnetic moment of the particle is assumed to be an adiabatic invariant, and so this process is relevant for the particles whose gyroperiods are short compared to the wave period. This condition is valid for alpha particles in the vicinity of comets, as the MHD waves have frequencies close to the gyrofrequencies of the water group ions. Further, since the magnetic moment $\mu = mv_\perp^2/2B$ is a constant, the heating leads to an increase of the parallel temperature. The wave damping arising from this interaction is the transit time damping, and the heating rate may be obtained as before from the parallel current of the particular species and the parallel electric field, in this case associated with the parallel magnetic field gradients. The heating rate due to transit time damping has been calculated considering fluid electrons and ions described by the drift kinetic equation [*Dawson and Uman*, 1965; *Ott et al.*, 1978]. The electrons thermalize along the magnetic field, so that the force due to the pressure gradient is balanced by that due to the parallel electric field $E_\parallel$. For a Maxwellian ion distribution at equilibrium the heating rate is given by

$$\frac{d}{dt}(nT_i) = \sqrt{\pi} nT_i \omega \xi_i e^{-\xi_i^2} f(T_e, T_i) \left(\frac{\Delta B}{B}\right)^2, \quad (4)$$

where

$$f(T_e, T_i) = 1 + \frac{T_e}{T_i} + \frac{1}{2}\frac{T_e^2}{T_i^2}. \quad (5)$$

This heating arises from the interaction of the ions with the parallel electric field set up by the electron pressure gradient and with the parallel gradient of the magnetic field via their magnetic moments. The first is given by the terms proportional to the elecron temperature T_e in the expression for $f(T_e, T_i)$ in (5), which is valid for $T_e < T_i$. The effects of the interaction with the magnetic field are given by the other factors in (4).

The data from comet Halley obtained by the Giotto spacecraft, whose path traversed the bow wave region, show strong heating of the alpha particles [*Neugebauer et al.*, 1987]. Over the whole region of the Giotto measurements where the magnetic field showed strong fluctuations, the thermal velocities of the alpha particles increased to nearly double their initial values. The data from the Suisei satellite [*Takahashi et al.*, 1987] taken farther downstream around the cometopause (1.5-5 x 10^5 km), show weak fluctuations in the magnetic field, and the temperature of the alpha particles was observed to be nearly constant. This correlation between the heating of alpha particles and the level of magnetic turbulence indicates the important role of heating mechanisms associated with magnetic field fluctuations, such as the transit time damping.

The MHD waves observed at comet Halley show almost equal equipartition of the fluctuation energy among the transverse and compressional modes [*Glassmeier et al.*, 1987]. At comet Giacobini-Zinner the transverse waves were observed to be mainly parallel propagating Alfven waves at larger distances. However, closer to the shock, a strong correlation between density and magnetic field fluctuations was observed [*Tsurutani et al.*, 1987], showing the presence of magnetosonic waves. The mechanisms for the generation of the comperssional MHD waves has been investigated for the planetary bow shock [*Kennel*, 1986] and for the cometary case [*Kotelnikov et al.*, 1991]. The essential idea is wave refraction in the foreshock region arising from the transverse inhomogeneities. In the comet-solar wind interaction region the plasma β is close to unity, and the phase velocity of these waves is comparable to the solar wind proton thermal velocity, leading to Landau damping. However the quasilinear velocity diffusion leads to a plateau in the proton velocity distribution, and this overcomes the damping, yielding a spectrum of compressional waves [*Kotelnikov et al.*, 1991].

The heating of alpha particles over the entire transition region is large; for example, the thermal velocity increases from 50 km/s to 100 km/s on average [*Neugebauer et al.*, 1987, Figure 4]. However this increase takes place through a number of small increases at localized spots, and the increases in the temperature at the separate heating events are small. Also, the changes in the density at most of these events are small compared to the changes in the thermal speeds and thus may be neglected. From (4) the local increase in temperature ΔT_α over a time Δt may then be expressed approximately as

$$\frac{\Delta T_\alpha}{T_\alpha} = \frac{\Delta t}{\tau_{H\alpha}}, \quad (6)$$

where the transit time heating timescale $\tau_{H\alpha}$ is defined by equating the right-hand side of (4) to $n_\alpha T_\alpha / \tau_{H\alpha}$. This yields

$$\tau_{H\alpha}^{-1} = \sqrt{\pi}\omega\xi_\alpha exp(-\xi_\alpha^2) f(T_e, T_\alpha)(\Delta B/B)^2. \quad (7)$$

The MHD fluctuations have a typical frequency $\approx 6 \times 10^{-2}$ s^{-1} [*Glassmeier et al.*, 1987] and amplitudes in the range $\Delta B/B \approx 0.1 - 0.5$ at comet Halley, and we shall take a typical value of $\Delta B/B \approx 0.3$. In the rest frame of the solar wind protons, which constitute the bulk component, the phase speeds of the waves are close to the Alfven speed v_A, and the typical plasma parameters at comet Halley are $n \approx 6$ cm^{-3}, $B \approx 6$ nT, and $v_A \approx 55$ km. The factor $\xi\, exp(-\xi)^2$ in (7) for the alpha particles and the protons has the ratio,

$$I_R = x \cdot \frac{v_{Tp}}{v_{T\alpha}} \cdot exp\left[-\frac{v_A^2}{2v_{T_p}^2}\{x^2\frac{v_{Tp}^2}{v_{T\alpha}^2} - 1\}\right]. \quad (8)$$

where $x = \left(\omega - \vec{k}\cdot\vec{v}_o\right)/\omega_e$. Defining $y = v_{Tp}/v_{T\alpha}$ and $v_A^2/2v_{Tp}^2 = B^2/8\pi nT_p = 1/\beta$, equation (8) can be rewritten as

$$I_R(x,y) = xy\ \exp\left[-\frac{1}{\beta}(x^2y^2 - 1)\right] \equiv \sqrt{\beta} e^{\frac{1}{\beta}}\ ze^{-z^2}, \quad (9)$$

where $z = xy/\sqrt{\beta}$. The values of I_R can now be estimated using values of x and y from the observations. Let us first consider x=1, i.e., the relative drift between the protons and alpha particles is negligible. The values of y during 1922–1956 SCET at comet Halley encounter [*Neugebauer et al.*, 1987] are roughly between 1 and $1/\sqrt{2}$. With $\beta = 0.5$, this yields I_R values in the range 1.0 - 1.9, the maximum value of I_R for this value of β being 2.2. Since the flow velocity of the protons is larger than that of the alpha particles and for the compressional waves propagating sunward, $x < 1$. In this case, I_R has slightly higher values, and we take a typical value of ≈ 2.0. The temperatures in the transition region are $T_e \simeq 15\ eV$ [*Reme*, 1987], $T_p \simeq 25\ eV$, and $T_\alpha = 100$ eV, giving $f(T_e,T_p)/f(T_e,T_\alpha) \approx 1.5$, and (7) then yields $\tau_p/\tau_\alpha \approx 1.3$. Thus the transit time heating is more efficient for alpha particles, in agreement with the observations which show the alpha particle thermal speeds to be larger than that of the protons on the average. A comparison of the observed and computed heating times in a set of heating events [*Neugebauer et al.*, 1987, Figure 4] during which the alpha particle heating is significant are given in Table 1. The different events are characterized by the initial and final values of the spacecraft event times and the thermal speed $v_{T\alpha}$ of *Neugebauer et al.* [1987], which is $\sqrt{2}v_{T\alpha}$. The heating time given by (7), however, does not depend on the choice of the thermal speed variable. The observed heating times Δt_{obs} and the value Δt_{com} computed from (6) are seen to compare quite well. In five out of eight heating events in Table 1, the computed heating time Δt_{com} is smaller than the observed time Δt_{obs}. The events at 1922–1924, 1930–1932, and 1950–1951 SCET were accompanied by compressions in the alpha particle density, but there is no discernible trend of its effect on the heating. The heating events in Table 1 are in the downstream region except for the first two. At comet Giacobini-Zinner the large-amplitude waves were found to propagate antisunward in the downstream region [*Tan et al.*, 1933]. However, at comet Halley there is no observation of large-amplitude, low-frequency waves propagating away from the Sun, and the theories predict sunward propagating modes, as discussed in section 2. If we consider antisunward propagating waves at comet Halley, $x > 1$ and I_R will be reduced to smaller values.

Discussion and Conclusions

The spacecraft data from the encounters with comets Halley and Giacobini-Zinner have provided data on the basis

Table 1. Comparison of the Calculated and Observed Heating Times for the Observed Heating Events [*Neugebauer et al.*, 1987]

Period, SCET	$v_{T\alpha}$, km/s	Δt_{obs}, s	Δt_{coms}, s
1922-1924	45 - 70	120	100
1926-1927	65 - 80	60	110
1930-1932	60 - 90	120	85
1936-1937	60 - 80	60	115
1940-1942	90 - 105	120	66
1948-1949	75 - 85	60	55
1950-1951	70 - 85	60	80
1953-1956	70 - 100	180	155

The period identifies the events in terms of the spacecraft event times (SCET). The initial and final values of the alpha particle velocity $w_{T\alpha}$ are used to compute the heating time Δt_{com} from equations (6) and (7). The thermal velocity $w_{T\alpha}$ is related to the thermal velocity $v_{T\alpha}$ used here as $w_{T\alpha} = \sqrt{2}v_{T\alpha}$. The observed heating time Δt_{obs} are seen to compare well with the computed values

of which the various physical processes occurring in the solar wind-comet interaction can be identified and studied in detail. An important issue arising from these observations is whether this interaction leads, as in the terrestrial and planetary cases, to a bow shock that mediates the supermagnetosonic to submagnetosonic transition of the solar wind flow. The plasma and field data indicate that the transition region is different from a bow shock in the traditional sense, namely, a discontinuity connecting two roughly uniform regions characterized by different plasma parameters [*Papadopoulos*, 1985]. The transition region at comet Halley is widely interpreted as a shock [*Galeev et al.*, 1986; *Coates et al.*, 1990], whereas its nature at comet Giacobini-Zinner is less clear [*Thomsen et al.*, 1986; *Smith et al.*, 1986]. This scenario has been extended to the Giotto encounter with comet Gregg-Skjellerup, where a bow shock at $\sim 1 \times 10^4$ km from the comet nucleus was predicted [*Huddleston et al.*, 1992]. The transition of the solar wind flow from supermagnetosonic to submagnetosonic is viewed, in this paper, without a bow shock because of the mass loading by the cometary ions and the associated intense turbulence [*Hizanidis et al.*, 1988; *Sharma et al.*, 1988]. The thermalization of alpha particles by transit time damping strengthens this picture of the transition region.

The MHD turbulence at the cometary bow shocks has been found to be effective for the acceleration of the heavy cometary ions [*Isenberg*, 1987; *Gombosi et al.*, 1989]. However, for protons and alpha particles the cyclotron-resonant waves have short wavelengths, where the spectral energy is small. For these ions the transit time damping in the compressional components of the MHD turbulence is a source of the observed heating. This process is effective for ions whose magnetic moment is an adiabatic invariant during the magnetic field variations. Since the dominant fluctuations are near the cyclotron frequency of the heavy cometary (water group) ions, this mechanism should in principle work for protons as well as alpha particles. However, the proton heating by transit time damping is found to be weaker due to the difference in the flow speeds in the solar wind, in agreement with the observations [*Neugebauer et al.*, 1987]. Other heating processes such as ion-ion hybrid resonance heating [*Sharma and Papadopoulos*, 1990] have also been found to contribute to the alpha particle heating.

Computer simulations [*Omidi and Winske*, 1987, 1991] of the comet-solar wind interaction using a hybrid simulation code (massless fluid electrons and kinetic ions) have shown the dominant effects of the solar wind mass loading and the generation of large-amplitude waves. These simulations largely show the formation of more coherent but high-amplitude waves and thus compare well with the observations at comet Giacobini-Zinner [*Omidi and Winske*, 1991]. The processes discussed here would, on the other hand, be more relevant to the highly turbulent case of comet Halley. Thus depending on the nature of the comet, for instance, the mass outflow rate, its interaction with solar wind could be dominated by different processes.

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