NEUTRAL HYDROGEN SHELL STRUCTURE NEAR COMET P/HALLEY DEDUCED FROM VEGA-1 AND GIOTTO ENERGETIC PARTICLE DATA

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Abstract. An existing model based on Vega-1 (Tunde-M) and Giotto (EPONA) energetic particle data, representing neutral gas shells expanding about comet Halley, has been up-dated by incorporating additional information concerning energetic particles recorded by Tunde-M, and neutral gas measurements recorded aboard the Vega-1 and Vega-2 spacecraft, in the original data set. The modified model reproduces reasonably well the positions of the maxima in the intensity profiles of energetic cometary ions observed along the Vega and Giotto trajectories and it is estimated that the velocity of gas in the envisioned neutral shells is ~ 7.3 km/s i.e. close to the velocity (~8 km/s) of the slow hydrogen component of cometary neutrals. Detailed arguments are presented to support the suggestion that, at distances of 2 - 10 x 10^6 km from the comet nucleus, the energetic particles recorded in the quasi-periodic structures identified by the Tunde-M and EPONA instruments were protons.

Introduction

Energetic ion flux measurements, recorded in the energy range from 30 keV to a few hundred keV by the Tunde-M and EPONA experiment aboard Vega-1 and Giotto respectively, during their individual flybys of Halley's Comet (March 1986), reveal the presence of striking quasi-periodic variations in ion flux intensity at cometocentric distances of 2-10 x 10^6 km from the nucleus [Somogyi et al., 1986; McKenna-Lawlor et al., 1989]. The flux variations recorded were characterized by their amplitude (1 to 2 orders of magnitude) and sharpness, see Figure 1. They were separated in time by about 4 hours, and appeared along both the inbound and outbound passes though the comet

A *tentative* explanation of the observations, based on the assumption that the periodic spatial structure of the energetic particle fluxes results from the flight of the spacecraft through a series of expanding neutral gas shells, formed due to injection of neutral gas into the collisional zone from a strong source on the rotating (T ~54 hours) cometary nucleus, has already been considered by Kecskemety et al.[1986], Richter et al.[1989], and McKenna-Lawlor et al.[1989]. According to the model developed by these authors, increased neutral gas densities should be observed with a temporal periodicity of $T_{sc} = L/(V_a \pm V_{sc})$, where $L = V_n T$ is the space between the shells, V_{sc} is the spacecraft velocity relative to the nucleus and V_n is the expansion velocity of the shells. Having applied a least squares fitting procedure to the in situ data recorded at the two spacecraft, the expansion velocity of the neutral gas shells was estimated to be approximately 6.2 km/s.

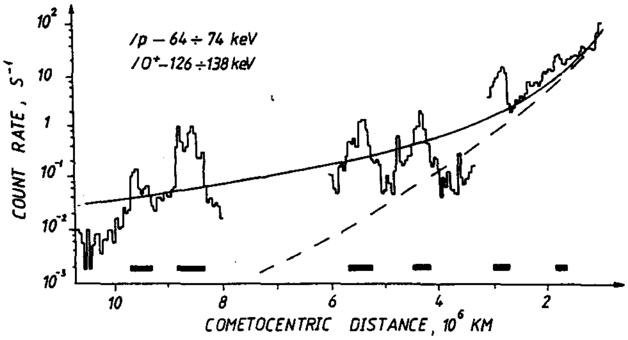

Figure 1. Dependence of energetic ion fluxes on cometocentric distance during the inbound pass of Vega-1 through P/Halley [Kecskemety et al., 1989]. The energy ranges for protons and ions relevant to the channel presented are given above the data. The dashed curve is proportional to the simple Haser dependence of neutral gas number density on cometocentric distance for an ionization time 10^6s and expansion velocity V ~ 1 km/s. The solid curve represents a similar dependence with V_n ~ 1 km/s and V ~ 7.3 km/s for an equal gas production rate. Heavy horizontal bars indicate the locations of those enhanced fluxes used in the least square analysis

In the present paper, additional information concerning energetic ion flux measurements recorded by Tunde-M [Kecskemety et al. 1989] as well as neutral gas density

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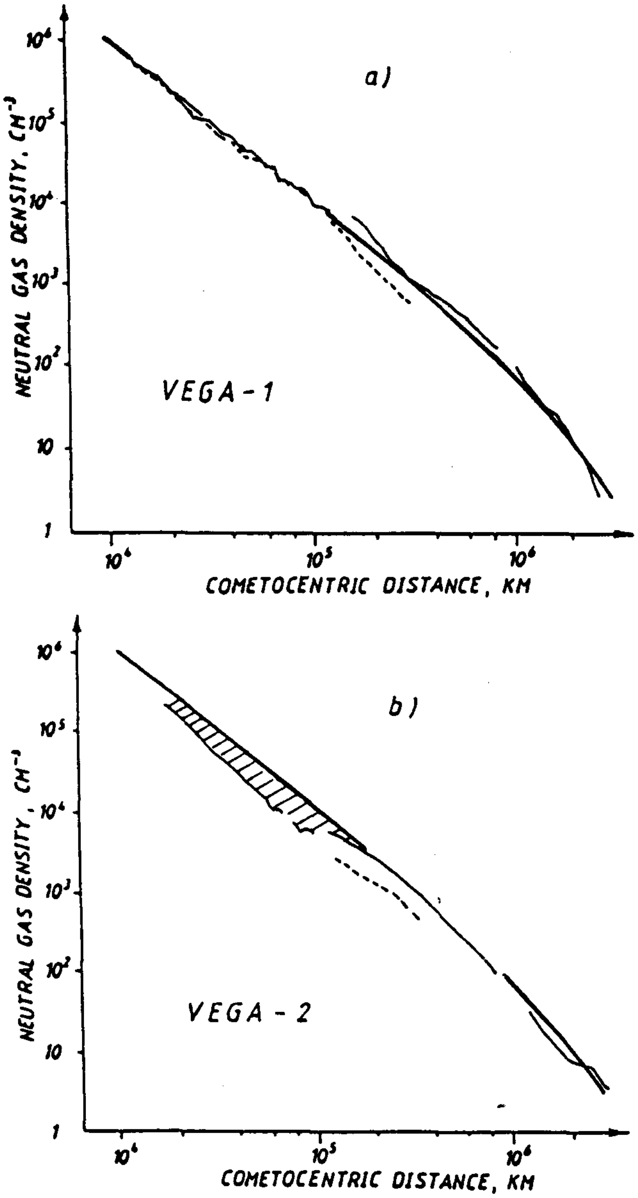

Figure 2. Cometocentric density profiles for neutral particles estimated from the data measured by the RFC instrument (a) onboard Vega-1 (b) onboard Vega-2 during their inbound (broken line) passes through the comet. The thick solid line shows the approximate dependence of $n_n(r) \sim r^2 \exp(-r/\lambda)$ with $\lambda = 2 \times 10^6$ km.

measurements made by the Ram Faraday Cup (RFC) instruments aboard Vega-1 and 2 [Remizov et al. 1986], are incorporated into the previous data set and the expansion velocity of the neutral gas shells recalculated on the basis of this additional information. The possible composition of the quasi-periodic ion fluxes measured at the two spacecraft is then discussed and arguments presented to suggest that the particles recorded were protons.

Data Analysis

The data already considered by Richter et al.[1989], and McKenna-Lawlor et al.[1989] contained (inbound) a data gap at a distance between 6 - 8 x 10^6 km from the nucleus and it was assumed by these authors that this interval contained two unobserved peaks. Recent investigations of the results from Tunde-M reveal, however, that although the instrument operated during this interval in a different mode, and with high background noise, it is nevertheless possible to identify only a single narrow energetic particles peak occurring at ~7.00 UT on March 5th, 1986, approximately in the middle of the previous gap [Kecskemety et al., 1989].

Neutral gas density measurements made by the RFC instruments aboard Vega-1 and Vega-2 are presented in Figure 2a and 2b respectively, following Remizov et al.[1986]. The smooth heavy line in each figure corresponds to the neutral gas density radial dependence calculated by Haser[1957]. This dependence is close to both the Vega-1 (March 6th) and Vega-2 (March 9th) data for cometocentric distances greater than 1-2 x 10^5 km. Closer to the comet however, the neutral gas densities measured by Vega-2 were lower, by approximately a factor of two, than was expected. The gap between the expected and measured densities is shown by cross-hatching in Figure 2b. If the deficit in neutral gas density recorded onboard Vega-2 is interpreted to result from a variation in the gas production rate at the rotating nucleus, then it appears that Vega-2 approached comet Halley during a period of low gas production and, by comparing Vega-1 and Vega-2 data, we can infer that the gas production rate of P/Halley is variable by a factor of at least 2.

Taking now all the data from Tunde-M and from EPONA, presented in Table 1 of Richter et al.[1989] and applying the same best fit procedure employed by Richter et al.[1989] and McKenna-Lawlor et al.[1989] to the data, with the exception that a single, not a double particle peak is assumed to be present within the data gap on March 5th a new representation of the assumed expanding gas shells, as a function of time, can be generated and represented by diagonal lines, see Figure 3. The inbound and outbound spacecraft trajectories of Vega-1 and Giotto are shown superimposed on this spatial structure, with heavy bars indicating the times and positions of the recorded flux enhancements. The position of the peak at 07.00 UT on March 5th is indicated by a triangle and it is seen to be located at a position predicted by the model to be characterized by a maximum in the particle flux. In general, the modified kinematic model is able to predict reasonably the positions of the measured maxima if the expansion velocity of the neutral gas shells is increased from the value of 6.2 km/s, estimated by previous authors, to 7.3 km/s.

The time and location at which Vega-2 recorded the neutral gas density deficit is marked by an asterisk in Figure 3. It corresponds to a minimum in neutral gas density production according to the present updated model. In the previous model, it would have been situated close to the position of a maximum.

Identity of the Recorded Ions

Tunde-M and EPONA utilize silicon surface barrier detectors which do not have the capability to distinguish mass. Full descriptions of these instruments are contained in Somogyi et al.[1986] and in McKenna-Lawlor et al.[1989]. In order to be detected by such an instrument, a freshly created cometary

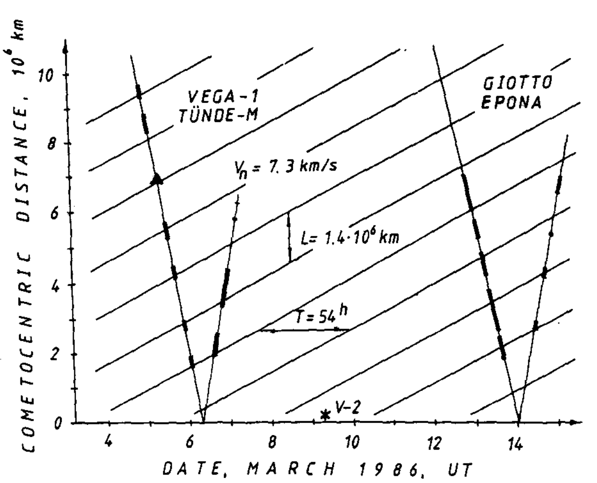

Figure 3. Plot of cometocentric distance vs time. The system of diagonal lines represents the positions of neutral gas shell centres based on a least square solution. The inbound/outbound trajectories of the Vega-1 and Giotto spacecraft appear superimposed on the overall plot. Heavy bars mark the positions of enhanced fluxes of energetic ions recorded by onboard instrumentation.

ion should undergo pitch angle scattering by MHD turbulence and then suitably diffuse in velocity space through the process of second order Fermi acceleration. Figure 4a shows the part of velocity space in the ecliptic plane, solid circle, that can be filled by protons after pitch angle scattering. In order to be registered by Tunde-M, particles should fall within the dashed circle (where the locations, within the observing cone, of the first four channels of the instrument are shown by cross hatching). For successful detection, protons should be accelerated to approximately 25 times their initial energy in the solar wind reference frame (SWRF). Figure 4b shows the corresponding situation for 0^+ ions which, for detection, need only be accelerated by a factor of 4. However, under conditions of strong turbulence, protons can be accelerated approximately 16 times more efficiently than can oxygen ions [Ip and Axford, 1986].

The slow component of hydrogen atoms, coming from radical photodissociation of OH (which itself originates from the photodissociation of cometary water molecules), has a velocity of approximately 8 km/s [e.g. Mendis et al., 1985]. There is no intensive source of fast heavy atoms near P/Halley. As a result of CO/CO_2 photodissociation, a minor fraction of C, O fragments can attain velocities of 6 - 10 km/s. However, the production rate of such atoms is some three orders of magnitude less than the production rate of the slow component of hydrogen atoms [Ip and Axford, 1987]. Also, the electron dissociative recombination of CO^+, and CO_2^+ ions can provide a flux of heavy suprathermal atoms but their production rate is even less than that for the C, O fragments [McKenna-Lawlor et al., 1988].

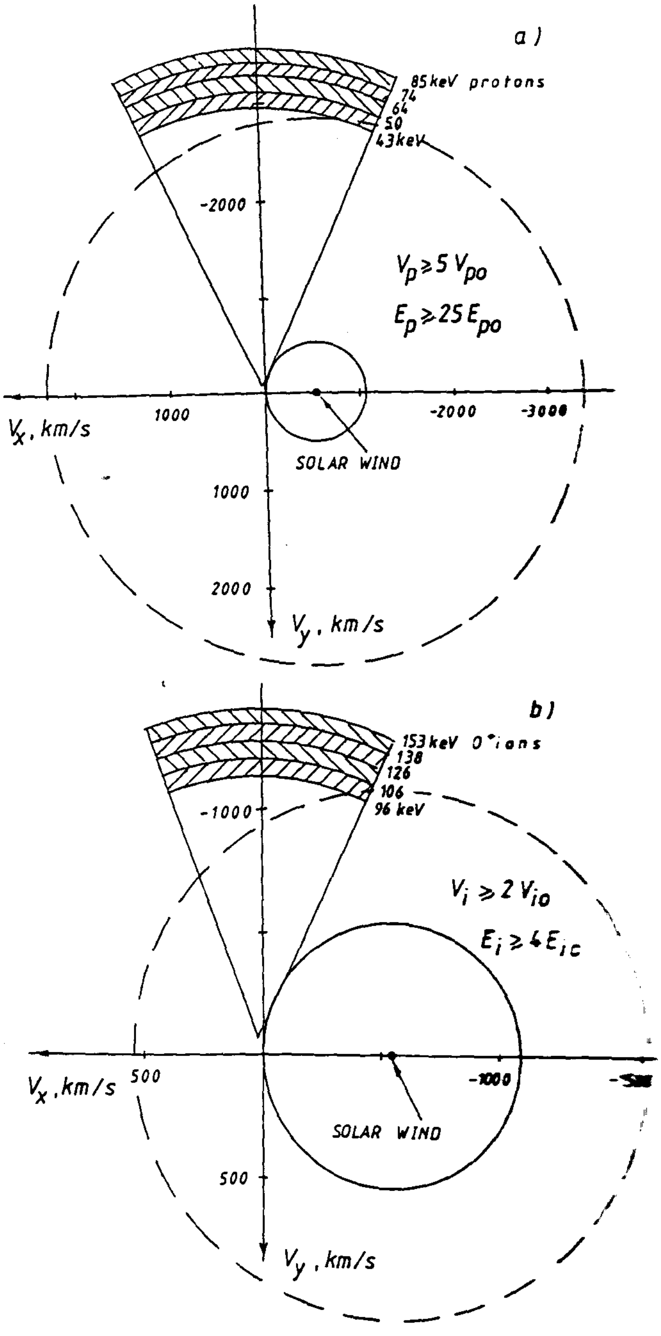

Figure 4. Diagram of TUNDE-M observing geometry in velocity space (ecliptic plane) when ions registered are (a) protons and (b) O^+ ions.The locations of the first four instrument channels on the observing cone are indicated by cross hatching.

The characteristic ionization time of both the slow hydrogen and oxygen component of cometary neutrals is of the order of 10^6 s. Both components originate from the OH radical within cometocentric distances of $r \sim 2 \times 10^5$ km. Therefore, for the range covered by the data of Tunde-M and EPONA, Haser's [1957] point source consideration is a reasonable assumption and the neutral gas number density can be approximated by the expression,

$$n_n(r) \sim (\exp(-r/v_0\tau_r)/v_0 + \exp(-r/v_H\tau_r)/v_H)/r^2$$

This summed functional dependence with $v_0 = 1$ km/s and $v_H = 7.3$ km/s, is represented by the solid curve in Figure 1. The dashed curve shows the corresponding dependence of the oxygen component alone. Both terms become equal at $r \sim 2 \times 10^6$ km, suggesting that, outside this limit, accelerated protons should mainly be detected while, inside this limit accelerated heavy ions may be observed by energetic particle instruments. This expectation is supported by McKenna-Lawlor et al., [1989] who demonstrated, though comparing data from the Implanted Ion Spectrometer on Giotto and EPONA data recorded at a location close to the inbound bow shock, that the fluxes recorded by EPONA were due to ions of the water group.

Flux variations

The sharp quasi-periodic flux variations of energetic particle fluxes recorded by Tunde-M and EPONA are difficult to explain in terms of expected variations in neutral gas density. The amplitude of different components of the neutral gas variation can be estimated by solving the following system of equations,

$$\frac{dN_{H_2O}}{dt} \approx Q_{H_2O}(t) - \frac{N_{H_2O}}{\tau_{H_2O}}$$

$$\frac{dN_{OH}}{dt} \approx \frac{N_{H_2O}}{\tau_{H_2O}} - \frac{N_{OH}}{\tau_{OH}} ,$$

where N_{H_2O} and N_{OH} respectively represent the total number of H_2O and OH molecules in cometary space; τ_{H_2O} and τ_{OH} are the photodissociation scale times for these molecules and Q_{H_2O} is the water molecule production rate. Assuming that Q_{H_2O} is subject to temporal variations by a factor of 2 (see Figure 3 and its discussion) and that the nucleus is deemed to be active during a time t (see Figure 5a), then the equations can be easily solved to yield the temporal variation of OH, as well as that of slow hydrogen production rates ($Q_{OH} \sim N_{H_2O}/\tau_{H_2O}$, $Q_H \sim N_{OH}/\tau_{OH}$). The solution concerned is shown in Figure 5b,c (for simplicity, it is taken to be $\tau \sim \tau_{OH} \sim T/2$; $\tau_{H_2O} \sim T/2$; $\tau_{OH} \sim T$). The variation in the density of slow hydrogen is thus expected to be of the order of a few percent ($\delta n/n \sim 4\%$). Similar estimates apply to oxygen atoms which also originate from OH photodissociation.

On the basis of the above, large variations are not expected in the source term S(v,x) of the following equation, which describes the diffusion in velocity space of pick-up ions [see e.g. Gribov et al., 1987; Isenberg, 1987],

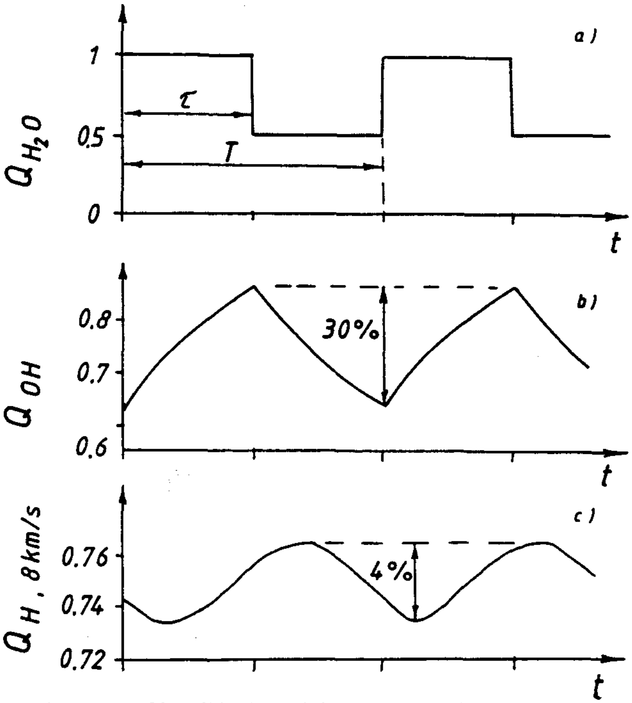

Figure 5. Simplified models of temporal variations in the water production rate based on (a) Vega-1,2 RFC data (a) and (b) estimated temporal variations in OH and (c) slow hydrogen component production rates.

$$\frac{1}{v^2}\frac{\partial}{\partial v}\left[v^2 D(v)\frac{\partial f}{\partial v}\right] + v_{sw}\frac{\partial f}{\partial x} - \frac{1}{3}\frac{\partial v_{sw}}{\partial x} v \frac{\partial f}{\partial v} + S(v,x) = 0$$

where f(v,x) is the distribution function; v is the velocity and D(v) the velocity diffusion coefficient of pick-up ions and v_{sw} is the solar wind velocity. The analytical solution of this equation presented by Isenberg[1987] shows that the value of f(v), at the local pick-up energy in the SWRF, is proportional to the source term. Thus the amplitude variations of f(v) at the local pickup energy are proportional to the amplitude variations of S: $\delta f/f \sim \delta S/S \sim \delta n/n \sim 4\%$.

The same does not apply to variations of accelerated ions since, in this case, f(v) decreases very rapidly as v increases and the slope of f(v) is a function of the diffusion coefficient D. In consequence, small changes in D and thus in the f(v) slope, could lead to a large change in f(v) itself. In the case where the magnetic field power spectrum density can be approximated by a power law dependence on the wave number $|B_k|^2 \sim A(x)/k^2$, the diffusion coefficient is inversely proportional to the ion velocity $D(x) \sim A(x)/v$ and the asymptotic solution of the diffusion equation reduces to $f(v) \sim \exp(-v/v_0)$ [Isenberg, 1987], where $v_0 \sim A(x)$ is that parameter characterizing the slope of f(v) and so,

$$\frac{\delta f}{f} \sim \frac{v}{v_0}\frac{\delta v}{v_0} \sim \frac{v}{v_0}\frac{\delta A}{A} \sim \frac{v}{v_0}\frac{\delta n}{n}$$

A value for the v_0 parameter can be estimated from experimental spectra. For example from the spectra measured by Tunde-M published in Figure 6 of Kecskemety et al.[1989], we can estimate that $v_0 = 30$ km/s for $v \sim 1100$km/s if the registered ions are assumed to be oxygen. If the ions are assumed to be protons then $v_0 = 130$ km/s. For protons having an energy that is ≥ 25 times the initial pickup energy the asymptotic solution is reasonable and we can estimate that $\delta f/f \sim 25\ \delta n/n \sim 1$. For heavy ions, the asymptotic solution is not applicable as their energy is quite close to the initial pick-up energy (only ≥ 4 times more) and in this case, variations in their flux are mainly determined by source term variations.

Conclusion

The model of expanding shells of neutral gas about the comet Halley nucleus presented by Richter et al.[1989] and McKenna-Lawlor et al.[1989] has been modified to incorporate additional data from Tunde-M. The model reproduces, reasonably well, the positions of the quasi-periodic maxima in the particle records and shows a minimum in neutral gas density at a location where the neutral gas density measurements from Vega-1 and 2 recorded a deficit. The estimated velocity of gas in these shells is ~ 7.3 km/s, which is very close to that of the slow hydrogen component of cometary neutrals (~ 8 km/s).

Arguments in favour of the interpretation that the energetic particles registered in the quasi periodic flux enhancements at cometocentric distances of $2 - 10 \times 10^6$ km were protons include (a) at $\geq 2 \times 10^6$ km from the nucleus, hydrogen is the main component of cometary neutral gas while there is no significant production of fast component heavy neutrals at the comet (b) small variations in the slope of spectra of 25 times accelerated hydrogen ions can lead to large variations in the ion fluxes observed in the 100 keV range. It is, on the other hand difficult to produce large variations in fluxes of moderately-accelerated heavy ions.

Although the quasi-periodic structures revealed by the energetic particle records may represent intensity variations marking the flight of the spacecraft through expanding shells of neutral hydrogen atoms, more sophisticated quantitative models should be developed to fully elucidate the nature of the phenomena observed.

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