Quasi-periodic variations of cometary ion fluxes at large distances from comet Halley

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ABSTRACT. Large variations, with a period of about 4 h, in the energetic ion fluxes have been observed far upstream (between 2 and 10 million kilometers) of comet Halley on both the Vega-1 and Giotto spacecraft. We have fitted the cometocentric distances of the occurrences to a simple model of expanding shells of neutral particles, the production of which is modulated by the spin of the comet nucleus, and have achieved excellent agreement between the two spacecraft. We derive an expansion speed for the neutrals of 6.18 ± 0.14 km s^{-1}. Possible candidates for the neutrals are hydrogen atoms, created by the photo-dissociation of OH with a speed of 8 km s^{-1}, or oxygen atoms, produced from the photo-dissociation of CO_2 with a speed of 6.5 km s^{-1}.

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INTRODUCTION

An unexpected but striking feature of the energetic cometary ion fluxes observed by the TÜNDE-M instrument on board Vega-1 during the inbound leg of its encounter with comet Halley was the large quasi-periodic variation of the flux intensity (Somogyi *et al.*, 1986). At least five enhancements in the fluxes of energetic ions in the hundreds of keV range have been registered, with peak values of about 1 to 2 orders of magnitude larger than the background. Their temporal separation is about 4 h, and they appear from 2-10 $\times 10^6$ km from the nucleus. A somewhat similar but less pronounced periodicity is also present in the energetic ion observations of the EPONA instrument on board Giotto, at distances of 2-7.5 $\times 10^6$ km (McKenna-Lawlor *et al.*, 1986 ; Daly *et al.*, 1986).

An attempt to correlate these enhancements seen by TÜNDE-M with those times when the interplanetary magnetic field was directed towards the cometary bow shock has led to negative results (Kecskeméty *et al.*, 1986, 1988). Thus these particles are not a result of bow shock acceleration.

A tentative explanation of the periodicity was proposed by Kecskeméty *et al.* (1988), based on the assumption of a period spatial structure of neutral particles resulting from the time dependent production of gas on the surface of the rotating nucleus. Considering the 54 h rotation period and the roughly one million kilometer spacing between consecutive peaks, one derives a gas expansion speed of 6 km s^{-1}.

In this paper both Vega-1 and Giotto cometary ion data are studied to investigate whether a single spatial structure could produce the energetic particle profiles seen by both spacecraft.

OBSERVATIONS

The energetic particle telescope TÜNDE-M measured cometary ions in the vicinity of comet Halley arriving from the direction roughly opposite to the comet and perpendicular to the solar direction, in the ecliptic plane. Its geometric factor is 0.25 cm^2 sr. EPONA consists of three particle telescopes with geometric factors of 0.081 cm^2 sr, inclined to the spin axis of Giotto, detecting ions from different directions during one spacecraft rotation. Detailed descriptions of the instruments have been given by Somogyi *et al.* (1986) for TÜNDE-M and by McKenna-Lawlor *et al.* (1987) for EPONA.

The variation of energetic ion fluxes with cometocentric distance as measured by TÜNDE-M along the inbound pass of the Vega-1 trajectory is presented in figure 1. The limits of the energy channel plotted are 64-74 keV for protons, and 126-139 keV for O^+ ions (Kecskeméty *et al.*, 1988). It is evident that the

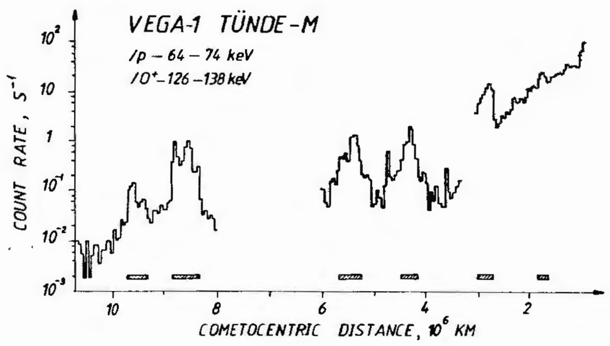

Figure 1
Energetic ion fluxes plotted against cometocentric distance on the inbound pass of the Vega-1 encounter with comet Halley. The energies are given in the upper left corner for protons and for oxygen ions in this channel. The heavy horizontal bars at the bottom indicate the distances of enhanced fluxes used in the least squares analysis.

appearance of quasi-periodic energetic ion flux enhancements begins at 10^7 km from the cometary nucleus.

The most pronounced peaks in the EPONA fluxes are found in the data of telescope 3, sector 2, which points in a direction 55° from the Sun-spacecraft line. For comparison with the TÜNDE-M data, the energy channel 2 of EPONA is selected (44-78 keV for protons, 97-144 keV for H_2O^+). The ion fluxes measured in this channel are plotted for cometocentric distances less than 8×10^6 km in figure 2. As in the case of the TÜNDE-M data (fig. 1), the EPONA energetic particle fluxes exhibit a periodicity of a few hours.

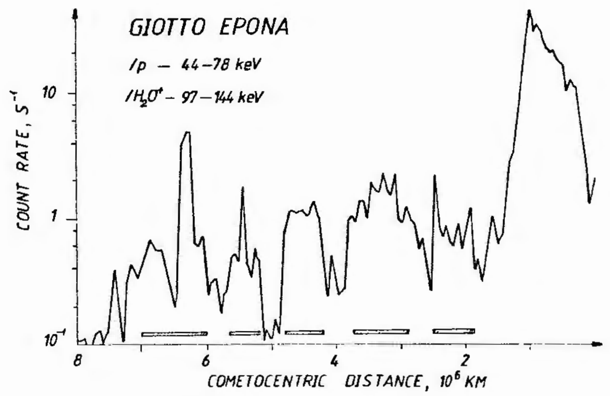

Figure 2
Energetic ion fluxes plotted against cometocentric distance on the inbound pass of the Giotto encounter with comet Halley. The energies are given in the upper left corner for protons and for water ions in this channel. The heavy horizontal bars at the bottom indicate the distances of enhanced fluxes used in the least squares analysis.

MODEL CALCULATIONS

The camera observations from Vega-1 and 2, and from Giotto reveal a highly varying dust production over the surface of the nucleus (Sagdeev *et al.*, 1986 ; Keller *et al.*, 1986). It is therefore reasonable to assume that the neutral gas production possesses similar variations. Thus our model presupposes the existence of a relatively small active region that produces a substantial increase in the amount of neutral gas when facing the Sun. The inflow of neutral gas into the collisional zone (a few thousand kilometers from the nucleus) will therefore be modulated by the rotation period of the nucleus. Outside this zone, the neutrals expand radially in all directions with a speed of V_n, forming shells of spherical symmetry, if Kepler forces and solar radiation pressure are neglected (fig. 3). The spatial distance separating adjacent shells is

$$L = V_n \cdot T$$

where $T = 54$ h, the spin period of the cometary nucleus. When a spacecraft passes through this spatial structure inbound, it will observe increased neutral gas fluxes with a temporal periodicity of

$$T_{sc} = \frac{L}{V_n + V_{sc}}$$

where V_{sc} is the speed of the spacecraft relative to the nucleus. For Vega-1 and Giotto, $V_{sc} = 79.2$ and 68.4 km s^{-1}, respectively. Ions created from neutrals near the spacecraft will clearly have this same periodicity. Furthermore, numerical calculations carried out by one of us (P.W.D.) show that the pick-up ions resulting from such a shell-like neutral gas distribution will exhibit oscillations with the same period T_{sc} as the neutrals, although with an amplitude variation of about a factor of two.

A formula for the cometocentric distances of the shells can be found as follows : let T_0 be some time when the nucleus emits enhanced numbers of neutral particles, and let us designate the corresponding shell as number zero. Then the n-th shell is created at time $T_0 + nT$, that is, n rotations later. The center of the n-th shell reaches a radial distance of R at a time

$$t = \frac{R}{V_n} + T_0 + nT . \qquad (1)$$

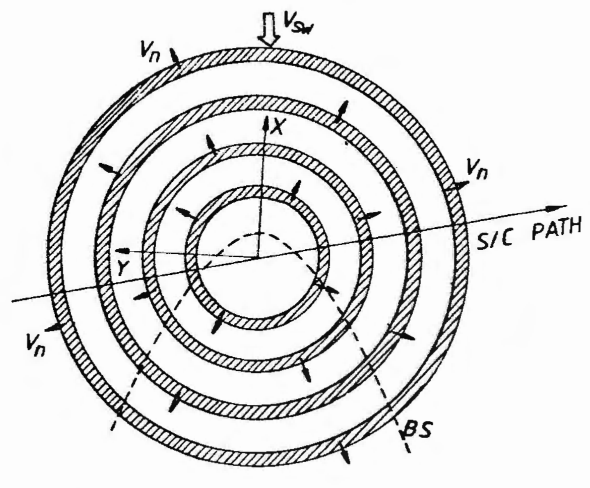

Figure 3
The shell structure of neutral particles surrounding the comet nucleus, created by a rotating modulated gas production rate. The solid line represents the path of a spacecraft, and the dashed line shows the bow shock. The shells are expanding with speed, V_n. The solar wind speed, V_{sw}, is also indicated.

For the spacecraft, the relationship between inbound cometocentric distance and time is

$$R = (T_{enc} - t) \cdot V_{sc} \quad (2)$$

where T_{enc} is the time of encounter. (Eq. (2) neglects the closest approach separation, which is legitimate at these distances.) The encounter times for Vega-1 and Giotto are days 6.3056 and 14.0021 of March 1986. Solving for t in (2) and equating it to the right-hand side of (1), we obtain

$$\begin{aligned} T_{enc} - \frac{R}{V_{sc}} &= \frac{R}{V_n} + T_0 + nT \\ RV_{sc} &= (T_{enc} - T_0 - nT)\, V_{sc}\, V_n - RV_n \\ &= \{(T_{enc} - nT) \cdot V_{sc} - R\}\, V_n \\ &\quad - \{V_{sc}\}\, V_n T_0 \,. \end{aligned} \quad (3)$$

The right-hand side of (3) is linear in the two unknowns, V_n and $V_n T_0$.

To estimate these unknowns by the least squares fit method, we must first find a set of R values for given shell numbers n. Let us suppose that the spacecraft is within the n-th shell when the energetic ion flux is above 20 % of the maximum value of that peak. These intervals are marked by thick horizontal bars in figures 1 and 2, providing the distances of the leading (R_L) and trailing (R_T) edges of each shell. Two more enhancements are also included that do not fulfil the criterion, namely that observed closest to the bow shock by TÜNDE-M (because of high background from the bow shock, as mentioned later in the Discussion) and the first peak seen by EPONA, which is possibly due to variations in the ion acceleration process. The ion flux enhancement observed closest to the comet by Giotto is not included in the set of data, as it is influenced by the cometary bow shock. The least squares fit is carried out by taking for R in eq. (3), the center distance $(R_L + R_T)/2$, with a standard deviation equal to half the shell width, $(R_L - R_T)/2$.

Table 1 lists the distances of the leading and trailing edges of the shells with their assigned shell numbers. These assignments assume that there are two unobserved peaks in the data gap of figure 1 near 7×10^6 km, and that the first Giotto shell is identical to the second last Vega-1 shell. Relaxing this second condition (i.e., assuming a different correspondence between the two sets of shells) leads to significantly worse results, as indicated by the goodness-of-fit parameter, χ^2. Similarly, assuming only one peak in the data gap roughly doubles the value of χ^2.

Table 1
Cometocentric positions of shells

Vega-1			Giotto		
Shell n	Distance 10^6 km R_L	R_T	Shell n	Distance 10^6 km R_L	R_T
1	9.7	9.3	7	7.0	6.0
2	8.85	8.3	8	5.7	5.2
5	5.7	5.25	9	4.85	4.2
6	4.5	4.15	10	3.8	2.65
7	3.0	2.7	11	2.5	1.85
8	1.9	1.6			

The results of the optimum fitting procedures for Vega-1 and Giotto, together and individually, are given in table 2. The errors quoted for V_n are the standard deviations derived from the statistical analysis. The actual width of the neutral gas velocity distribution must be much smaller, since the existence of a shell structure out to distances of 10^7 km presupposes a well-defined expansion velocity. If the neutral speed distribution were to have a width of as much as 0.6 km s^{-1}, then at 8×10^6 km the shell structure would be completely smeared out. The values of T_0 in table 2 are not those of the zeroth shell, but for convenience have been increased by multiples of T to make them just less than the Vega-1 encounter time.

Table 2
Results of least squares fitting

Run	$\chi^2/(N-2)$	V_n km s^{-1}	T_o, days in March 1986
Vega-1	1.497	6.19 ± 0.21	4.83
Giotto	0.093	6.09 ± 0.20	4.92
Both	0.755	6.18 ± 0.14	4.86

Within the error bars, the values of V_n for Vega-1 and Giotto separately and combined are in excellent agreement. This supports the idea that the quasi-periodic flux enhancements in the energetic ion fluxes observed independently by Vega-1 and Giotto are produced by a single shell structure. The result using both Vega-1 and Giotto data is that $V_n = 6.18 \pm 0.14$ km s^{-1}. Figure 4 shows the shell structure based on this solution: the diagonal lines are the positions of a given shell as a function of time.

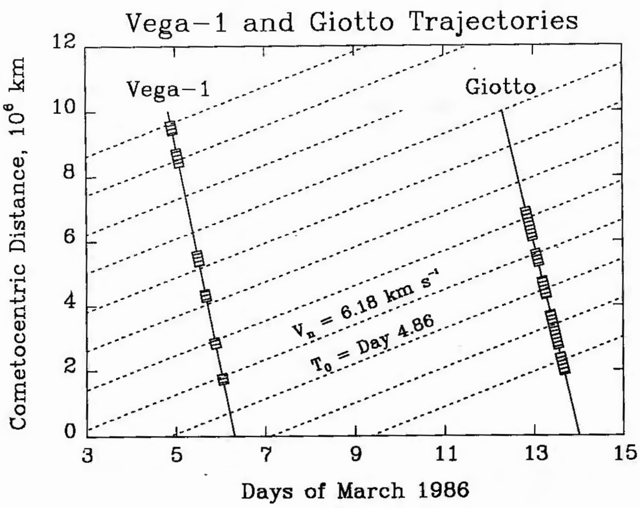

Figure 4
The inbound trajectories of Vega-1 and Giotto are shown as a plot of cometocentric distance against time. The enhanced ion fluxes are indicated along the trajectories with shaded boxes. The diagonal lines are the positions of the centers of the neutral shells based on the least squares solution of this work.

The two spacecraft trajectories are also drawn in, with shaded boxes for the times and positions of the observed enhanced ion fluxes. With minor exceptions, the observed position of the enhancements are in agreement with the predictions of the simple shell model, depending only on the two parameters V_n and T_0.

DISCUSSION

The relatively simple kinematic model described above is able to reproduce the position of the maxima of the intensity profiles of energetic cometary ions as observed along the inbound passes of the Vega-1 and Giotto trajectories. However, we are far from being convinced that the hypothesis of a connection between the quasi-periodicity of ion fluxes and the rotation of the cometary nucleus has been proved. Not only are other explanations possible, but this model meets several difficulties, which are discussed below.

First of all, we have assumed for simplicity that there is only one region of active neutral gas production, whereas the camera observations indicate several active regions emitting excess amounts of dust. To interpret dust flux measurements on board Giotto, Massonne and Grün (1986) used a model of one large and three small active regions on the surface of the nucleus. Although we do not know how the neutral species from which the observed ions originate are linked to the dust jets, there probably exist more than one gas jet. This can be responsible for the complicated internal structure of several ion flux peaks (figs. 1 and 2). It should also be noted that, because of dissociation and sublimation time delays, it is not possible to associate the phase T_0 with a particular dust jet.

Secondly, there is the question of the identification of the dominant neutral species in the shells, and how they acquire a velocity as high as 6 km s^{-1}. Hydrodynamical models (e.g. Mendis *et al.*, 1985) and *in situ* measurements (Krankowsky *et al.*, 1986) indicate that parent neutrals leave the nucleus with speeds of only 1 km s^{-1}. The most abundant parent neutral is H_2O, which photo-dissociates into H and OH, after which the OH molecule further dissociates into O and H. The first process gives the H atom an additional velocity of 19 km s^{-1}, the second 8 km s^{-1}. (The velocities of OH and O are only slightly different from that of the H_2O molecule.) Both slow and high speed H atoms are actually observed in the Lyman-α isophotes of comet Bennett (Keller and Thomas, 1975). Since the value of 8 km s^{-1} is close to our measured value of 6.18 km s^{-1}, one possibility is that the expanding shells consist mainly of this component of H atoms. However, Daly and Jockers (1988) show that the effect of radiation pressure on these atoms makes it impossible to them to get beyond 8×10^6 km from the nucleus along the Giotto inbound trajectory. For Vega-1, the result would not be much different.

Alternatively, the shells could contain predominantly O atoms produced either from dissociative recombination of CO^+ or CO_2^+ ions, or by photo-dissociation of CO or CO_2 molecules (Ip and Axford, 1987). The former processes yield velocities for the O atoms of about 4 km s^{-1} (Feldman, 1978) while the latter give values of about 4 and 6.5 km s^{-1} respectively. Plasma wave observation by Sakigate at 7-9 $\times 10^6$ km from comet Halley indicate the presence of O^+ ions at such distances (Yumoto *et al.*, 1986). By calculating neutral particle trajectories using Kepler orbits, Erdös and Kecskeméty (1987) and Daly (1987) have found that neutrals can achieve such large cometocentric distances only when they have a high initial speed relative to the nucleus (more than 5 km s^{-1}).

Both species suffer from the problem that the pick-up ions that are formed from them have, under normal solar wind conditions, energies lying below the thresholds of the TÜNDE-M and EPONA experiments. Further acceleration is therefore necessary to explain the observations. Taking into account the threshold differences for the two species, the required acceleration must be 10 times greater for H^+ than for O^+. If second order Fermi acceleration is responsible for the additional energy, then it is 16 times more effective for H^+ than for O^+ (Ip and Axford, 1986), making both species equally likely candidates.

The fast component of H atoms will create neutral shells that are intersected by the spacecraft with a period of about 12 h. However, the density of this component will be lower than that of the slow component because of the difference in speeds. Thus this 12 h structure will not show up against the more pronounced 4 h profile.

Thirdly, the model cannot explain the sharpness of the structure seen by TÜNDE-M. Even if the active region that ejects neutrals switches on and off precisely when subjected to direct sunlight, the variation of the production rate for the daughter atoms is smoothed out by the long time scales for dissociation (10^5-10^6 s). One can try to attribute this sharpness to non-linear dependence of the acceleration of pick-up ions on the neutral gas density.

So far we have dealt with ions observed far upstream of the bow shock, which seem to be most probably ionized and accelerated from fast neutral species. Closer to the nucleus (within 3×10^6 km) another population appears, the flux of which increases gradually towards the nucleus (fig. 1). This population is generated by the ionization and acceleration of the cometary neutrals with speeds of 1 km s^{-1}, forming a high background to the shell structure. For this reason, it is impossible to employ the 20 % criterion for the innermost ion peak in the TÜNDE-M data.

It should be pointed out that the neutral gas detectors on board Vega-1 (Remizov *et al.*, 1986) or Giotto (Krankowsky *et al.*, 1986) were not sensitive enough to detect neutral particles beyond distances of about one million kilometers. Therefore it is not possible to verify our shell model on the basis of *in situ* neutral gas measurements.

CONCLUSIONS

In this work we have demonstrated that the periodic energetic ion flux enhancements observed on Vega-1 and Giotto while approaching comet Halley can be fitted to a single simple model of periodic neutral gas production from a rotating cometary nucleus. Nevertheless, the explanation of periodic ion flux enhancements presented in this paper meets a number of difficulties, some of which have been discussed here. More sophisticated models including the shape and cometocentric dependence of the enhancements, upstream acceleration processes, as well as Kepler and radiation pressure effects, are necessary for the final verdict on this hypothesis.

REFERENCES

Daly, P. W., Can neutral particles from comet Halley have reached the ICE spacecraft ?, *Geophys. Res. Lett.*, **14**, 648-651, 1987.

Daly, P. W., and K. Jockers, The effect of Kepler orbits on the distribution of neutrals and ions around comet Halley, *Adv. Space Sci.*, in press, 1988.

Daly, P. W., E. Kirsch, S. McKenna-Lawlor, D. O'Sullivan, A. Thompson, T. R. Sanderson, and K.-P. Wenzel, Comparison of energetic ion measurements at comets Giacobini-Zinner and Halley, in *Proc. of the 20th ESLAB Symposium on the Exploration of Halley's Comet,* eds. B. Battrick, E. J. Rolfe, and R. Reinhard, *ESA SP-250,* **3,** 179-183, 1986.

Erdős, G., and K. Kecskeméty, Distribution of neutral gas molecules at large distance from Halley's comet, in *Proc. of the Symposium on the Diversity and Similarity of Comets,* eds. E. J. Rolfe and B. Battrick, *ESA SP-278,* 223-227, 1987.

Feldman, P. D., A model of carbon production in a cometary coma, *Astron. Astrophys.*, **70,** 547-553, 1978.

Ip, W.-H., and W. I. Axford, The acceleration of particles in the vicinity of comets, *Planet. Space Sci.*, **34,** 1061-1065, 1986.

Ip, W.-H., and W. I. Axford, Stochastic acceleration of cometary ions : the effect of neutral composition and source strength distributions, in *Proc. of the Symposium on the Diversity and Similarity of Comets,* eds. E. J. Rolfe and B. Battrick, *ESA SP-278,* 139-144, 1987.

Kecskeméty, K., T. E. Cravens, V. V. Afonin, G. Erdős, E. G. Eroshenko, L. Gan, T. I. Gambosi, K. I. Gringauz, E. Keppler, I. N. Klimenko, R. G. Marsden, A. F. Nagy, A. P. Remizov, A. K. Richter, W. Riedler, K. Schwingenschuh, A. J. Somogyi, K. Szegö, M. Tátrallyay, V. Varga, M. I. Verigin, and K.-P. Wenzel, Energetic pick-up ions outside the comet Halley bow shock, in *Proc. of the 20th ESLAB Symposium on the Exploration of Halley's Comet,* eds. B. Battrick, E. J. Rolfe, and R. Reinhard, *ESA SP-250,* **1,** 109-114, 1986.

Kecskeméty, K., T. E. Cravens, V. V. Afonin, G. Erdős, E. G. Eroshenko, L. Gan, T. I. Gambosi, K. I. Gringauz, E. Keppler, I. N. Klimenko, R. G. Marsden, A. F. Nagy, A. P. Remizov, A. K. Richter, W. Riedler, K. Schwingenschuh, A. J. Somogyi, K. Szegö, M. Tátrallyay, V. Varga, M. I. Verigin, and K.-P. Wenzel, Pick-up ions in the unshocked solar wind at comet Halley, *J. Geophys. Res.*, in press, 1988.

Keller, H. U., and G. E. Thomas, A cometary hydrogen model : comparison with OGO-5 measurements of comet Bennett (1970II), *Astron. Astrophys.*, **39,** 7-19, 1975.

Keller, H. U., C. Arpigny, C. Barbieri, R. M. Bonnet, S. Cazes, M. Coradini, C. B. Cosmovici, W. A. Delamere, W. F. Huebner, D. W. Hughes, C. Jamar, D. Malaise, H. J. Reitsema, H. U. Schmidt, W. K. H. Schmidt, P. Seige, F. L. Whipple, and K. Wilhelm, First Halley multicolour camera imaging results from Giotto, *Nature,* **321,** 320-326, 1986.

Krankowsky, D., P. Lämmerzahl, I. Herrwerth, J. Woweries, P. Eberhardt, U. Dolder, U. Herrmann, W. Schulte, J. J. Berthelier, J. M. Illiano, R. R. Hodges, and J. H. Hoffmann, *In situ* gas and ion measurements at comet Halley, *Nature,* **321,** 326-329, 1986.

Massonne, L., and E. Grün, Structures in Halley's comet dust coma, in *Proc. of the 20th ESLAB Symposium on the Exploration of Halley's Comet,* eds. B. Battrick, E. J. Rolfe, and R. Reinhard, *ESA SP-250,* **3,** 319-322, 1986.

McKenna-Lawlor, S., E. Kirsch, D. O'Sullivan, A. Thompson, and K.-P. Wenzel, Energetic ions in the environment of comet Halley, *Nature,* **321,** 347-349, 1986.

McKenna-Lawlor, S., E. Kirsch, A. Thompson, D. O'Sullivan, and K.-P. Wenzel, The lightweight energetic particle detector EPONA and its performance on Giotto, *J. Phys. E : Sci. Instrum.*, **20,** 732-740, 1987.

Mendis, D. A., H. L. Houpis, and M. L. Marconi, The physics of comets, *Fund. Cosmic Phys.,* **10,** 1, 1985.

Remizov, A. P., M. I. Verigin, K. I. Gringauz, I. Apáthy, I. Szemerey, T. I. Gombosi, and A. K. Richter, Measurements of neutral particle density in the vicinity of comet Halley by PLASMAG-1 on board Vega-1 and Vega-2, in *Proc. of the 20th ESLAB Symposium on the Exploration of Halley's Comet,* eds. B. Battrick, E. J. Rolfe, and R. Reinhard, *ESA SP-250,* **1,** 387-390, 1986.

Sagdeev, R. Z., F. Szabó, G. A. Avanesov, P. Cruvellier, L. Szabó, K. Szegö, A. Abergel, A. Balazs, I. V. Barinov, J. L. Bertaux, J. Blamont, M. Detaille, E. Demarelis, G. N. Dul'nev, G. Endröczy, M. Gardos, M. Kanyo, V. I. Kostenko, V. A. Krasikov, T. Nguyen-Trong, Z. Nyitrai, I. Reny, P. Rusznyak, V. A. Shamis, B. Smith, K. G. Sukhanov, F. Szabó, S. Szalai, V. I. Tarnopolsky, I. Toth, G. Tsukanova, B. I. Valníček, L. Varhalmi, Yu. K. Zaiko, S. I. Zatsepin, Ya. L. Ziman, M. Zsenei, and B. S. Zhukov, Television observations of comet Halley from Vega spacecraft, *Nature,* **321,** 262-266, 1986.

Somogyi, A. J., K. I. Gringauz, K. Szegö, L. Szabó, Gy. Kozma, A. P. Remizov, J. Erö Jr., I. N. Klimenko, I. T. Szücs, M. I. Verigin, J. Windberg, T. E. Cravens, A. Dyachkov, G. Erdős, M. Faragó, T. I. Gombosi, K. Kecskeméty, E. Keppler, T. Kovács Jr., A. Kondor, Y. I. Logachev, L. Lohonyai, R. Marsden, R. Redl, A. K. Richter, V. G. Stolpovskii, J. Szabó, I. Szentpétery, A. Szepesváry, M. Tátrallyay, A. Varga, G. A. Vladimirova, K.-P. Wenzel, and A. Zarándy, First observations of energetic particles near comet Halley, *Nature,* **321,** 285-289, 1986.

Yumoto, K., T. Saito, and T. Nakagawa, Long-period HM waves associated with cometary O^+ (or H_2O^+) ions : Sakigake observations, in *Proc. of the 20th ESLAB Symposium of the Exploration of Halley's Comet,* eds. B. Battrick, E. J. Rolfe, and R. Reinhard, *ESA SP-250,* **1,** 249-253, 1986.