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MASS SPECTROMETRY OF NEWLY IONIZED COMETARY GAS BY PLASMA INSTRUMENTS ONBOARD THE GIOTTO AND VEGA SPACE PROBES

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One of the basic problems which should be solved during the complex experiments in the Halley comet vicinities on-board the Venera-Halley and Giotto spacecraft in 1986 (Sagdeev et al. 1981, Reinhard, 1981) is the investigation of mass composition of volatile components of cometary coma to identify its parent molecules. For the investigations of coma formation to be more complete and reliable the mass composition measurements should be carried out in the distance range from the comet nucleus r as far as possible.

Outside the contact surface separating the cometary plasma from that plasma, that dynamical properties are determined by the solar wind, that is tosay at distances $r = 10^6 \div 10^7$ km from the comet nucleus, the information on the neutral coma mass composition can be obtained by studying the products of its ionization by the solar wind fluxes and by solar ultraviolet radiation. These ions interact with the magnetic field $\vec{B}$ and with the solar wind plasma, and are picked-up by them. At long distances from the nucleus where the density of newly formed ions is sufficiently small it can be expected that the characteristic time of their inclusion in the solar wind flow due to the collective processes, τ_a, significantly exceeds the period of their cyclotron rotation, $\tau_c = \frac{2\pi Me}{eB}$, where M is the mass, e is the carge of formed ions, c is the light speed.

In this case the direction of arrival of these newly formed ions and their energy will depend on the orientation, of $\vec{B}$ and may change in very wide limits: The arrival direction could be within the space angle 2π and the ion energy can vary from tens electronvolt to hundreds kiloelectronvolt depending on the masses and the arrival direction in the spacecraft coordinate system.

For this investigation a very complex instrument is in principle required, scanning of ion arrival angles, their energies and masses in the wide range of all these parameters and the transmission of a great amount of telemetry information. This problem is foreseen to be solved on-board the Giotto spacecraft with the implanted ion sensor IIS where the analysis of ion masses in various directions is performed by six individual time-of-flight devices within the energy range $\lesssim$70 kev (Johnston et al., 1981). However, the strong restrictions on the transmitted information do not allow the direct method of solving the problem of investigation of newly formed ions to be completely realized. Therefore a priori only six mass groups of ions will be analysed (Johnstone et al. 1981). The Venera-Halley project implies that some information on the energetic part of the distribution function of newly formed ions can be obtained with the TÜNDE-M semiconductor telescope (Somogyi et al. 1983).

In addition to the above-mentioned instruments especially designed to measure newly formed ions in the solar wind, both spacecraft will carry other instruments aboard which are oriented in the direction of the spacecraft velocity vector relative to the comet, v_s. They are studying the cold plasma of the comet ionosphere inside the contact surface. On-board the "Venera-Halley" spacecraft these measurements of cold ionospheric plasma will be carried out by the PLAZMAG-1 instrument (Gringauz et al. 1983), on "Giotto" - with three different and to a great extent dublicating instruments IMS (ion mass spectrometer, Balsiger et al. 1981), NMS (neutral mass-spectrometer in the ion measurement mode, Krankovsky et al. 1981) and PICCA (Positive Ion cluster composition analyser) (Rème et al., 1981).

It can be shown that measurements of these instruments even outside the contact surface (with adequate interpretation) yield in fact complete information on the mass composition of ions formed from ionization of comet coma neutrals and implanted in to the solar wind and hence, on the mass composition of the neutral coma itself. Let us consider a possibility of detecting the solar wind ions formed from the ionization of coma neutrals using the instrument with the narrow acceptance angle $\delta \approx \pm 3 \div 5^{\circ}$ oriented along $\vec{v}_s$ (for example, PLAZMA-1, PICCA, NMS). The estimates by the order of magnitude will be made in the coordinate system (x, y, z) relative to the comet nucleus (*Fig. 1*).

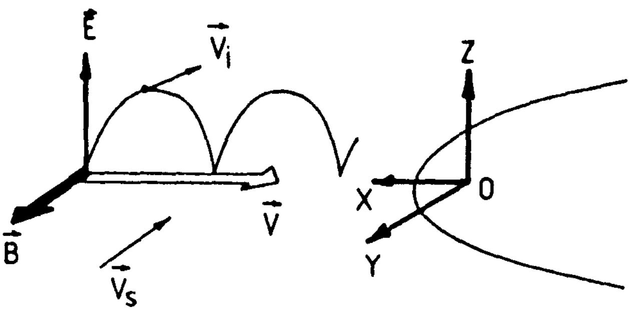

Fig. 1. Mutual orientation of solar wind velocity vectors $\vec{v}$, spacecraft velocities $\vec{v}$, interplanetary magnetic $\vec{B}$ and electric $\vec{E}$ fields, used for estimation. $\vec{v}_i$ is the velocity of an ion formed in the solar wind

We estimate the density n_i^* of only that part of newly formed ions not completing a single cyclotron rotation and thus observable by the narrow angle instrument. These estimates are essential to make any conclusion on the possibility of detection of newly formed ions in the solar wind. The neglection of possible record of such ions during the following cyclotron rotations means that we estimate the lower limit of the instrument sensitivity.

Since at the initial moment the velocity of newly formed ions is approximately equal to the speed of cometary neutrals, $v_n \approx 1$ km see (except fast hydrogen atoms), and small compared to $v_s = 70 \div 80$ km/sec (Sagdeev et al., 1981, Reinhard, 1981), such ions can be considered as being at rest.

Furthermore these ions will be accelerated by the induced electric field $\vec{E} = -1/c[\vec{v},\vec{B}]$, where $\vec{v}$ is the solar wind velocity. In the time τ_o ($\ll \tau_c$) they have the velocity $v_i \approx \frac{eE}{M} \cdot \tau_o$. The mutual orientations of $\vec{v}_s$ and $\vec{E}$ is not known. However, one can expect that these vectors will be significantly nonparallel. So, in making estimates by the order of magnitude we take that the angle between these vectors (and between $\vec{v}$ and $\vec{B}$) is about 90^o. *Fig. 1* shows a possible mutual orientation of all above mentioned vectors. In such a case the newly formed ions disapper from the instrument's sight of view when the ratio of their velocity to that of the spacecraft is $v_i/v_s \gtrsim \delta$ (see *Fig. 2*), i.e. in the

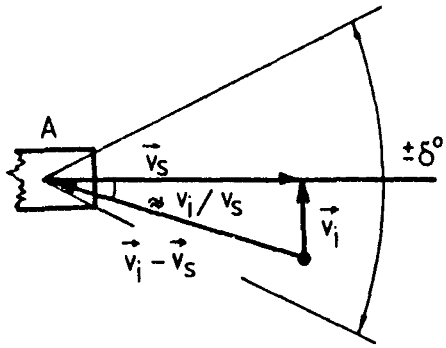

Fig. 2. Ion velocity relative to A aperture of the instrument with narrow acceptance angle oriented along the spacecraft velocity vector $\vec{v}_s$ is equal to $\vec{v}_i - \vec{v}_s$. In the case $v_i/v_s \gtrsim \delta$ ions are out of the sight of view of the instrument.

time $\tau_o \cdot \approx \tau_c \cdot \frac{\delta}{2\pi} \cdot \frac{v_s}{v}$ after their formation. This enables us to estimate the rate of disappearance of newly formed ions from the instrument's sight of view as $4 \approx n_i^*/\tau_o$. On the other hand, the rate of formation of new ions $Q \approx n_n/\tau_i$ where n_n is the density of the appropriate neutral molecules, τ_i is the ionization time scale by the solar ultraviolet radiation and by the solar wind. The equality of the rates of formation of new ions and their disappearance from the sight of view of the instrument with the narrow acceptance angle yields the following estimate for n_i^*:

$$n_i^* \approx n_n \cdot \frac{\tau_o}{\tau_i} \approx n_n \cdot \frac{\delta}{2\pi} \cdot \frac{\tau_c}{\tau_i} \cdot \frac{v_s}{v} \qquad (1)$$

Let us numerically estimate the obtained expression for ions with M = 20 amu. The cyclotron period of these ions in a magnetic field of B = 8 γ is $\tau_c \approx 160$ sec. Taking $\tau_i \approx 10^6$ sec (see for example Brandt and Mendis, 1979), v = 400 km/sec, v_s = 80 km/sec and $\delta \approx 5^o$, we obtain from (1) $n_i^* = 4.5 \cdot 10^{-7}\ n_n$.

From this estimate it follows that, as the spacecraft approaches the Halley Comet the measurements of newly formed heavy ions in the solar wind can be started already from a distance where the density of appropriate neutral molecules reaches the value $n_n \approx 20\ cm^{-3}$. The instruments PLASMAG-1 and NNS operate at large distances from the comet nucleus already in the specific mode which allows for enhancing their sensitivity to $n_i^* \approx 10^{-5}\ cm^{-3}$ due to the increasing time of particle accumulation (Gringauz et al., 1982, Krankowsky et al., 1981). According to the recent semi-empirical photometric model of Newburn (1981) the gas production rate by the Halley comet nucleus at a heliocentric distance of 0.9 a.u. is $Q \approx 4.10^{29}$ sec^{-1}, after it has passed through perihelion in 1910. Using the known equation for the radial distribution of the density of neutral particles:

$$n_n = \frac{Q}{4\pi r^2 v_n} \cdot e^{-\frac{r}{v_n \tau_i}}$$

it can be estimated that $n_n \approx 20\ cm^{-3}$ is achieved at $r = 8.10^5$ km.

Beginning from these distances from the nucleus the newly formed heavy cometary ions obviously can be detected by the "Venera-Halley" and Giotto instruments when $\tau_c \cdot \frac{\delta}{2\pi} \cdot \frac{v_s}{v} \lesssim \tau_a \lesssim \tau_c$. If the characteristic time of newly formed ion included in the solar wind flow $\tau_a \gg \tau_c$ and the variation of the magnetic field value (and adiabatic acceleration of heavy ions) at a distance of $v\tau_c$ can be neglected, then the estimate of the visible part of newly formed ions should be increased by $2 \cdot \frac{\min(r,\ v_n \tau_i)}{v\tau_c}$, due to registration of heavy ions formed upstream the spacecraft. In such a case the presence of heavy comatary ions in the solar wind may be obviously detected from $r = 2.10^6$ km.

Let us now estimate from which distances from the comet nucleus the newly formed light hydrogen ions can be detected in the solar wind. In this case, taking into account upstream formed H^+ ions for distances $r \gtrsim v_H \tau_i$ from the nucleus, we obtain with the evident changes of notation:

$$n^*_{H^+} \approx n_H \cdot \frac{\delta}{2\pi} \cdot \frac{2v_H v_s}{v^2} \qquad (2)$$

instead of expression (1).

From (2) with $v_H = 10$ km/sec and earlier values of the other parameters we get $n^*_{H^+} = 1.4.10^{-4}\ n_H$. So the newly formed H^+ ions in the solar wind obviously can be detected by the PLASMAG-1 and NMS instruments at these distances from the nucleus, where the density of hydrogen neutral molecules is $n_H \approx 0.07\ cm^{-3}$. For the Halley Comet (after perihelium at 0.9 a.u. and $Q_H \approx 6.6.10^{29}\ sec^{-1}$ (Newburn, 1981) such values of n_H can be realized at $r \approx 8.10^6$ km.

As has been shown, the sensitivity of the instruments designed to measure cold ionospheric plasma on board the Venera-Halley and Giotto spacecraft is quite adequate for detecting in the solar wind newly formed ions of the main components of the comet coma practically from the beginning of their appearance. As the spacecraft approaches the nucleus a possibility of measuring the secondary components of coma ionization products is expected. In this case the spectrum of newly formed ions recorded by the electrostatic analyser along the spacecraft velocity vector relative to the comet will consist of some maxima with the energies approximately equal to $Mv_s^2/2$. So, when measuring the newly formed ions in the solar wind (similar to the measurements of ionospheric plasma inside the contact surface) the mentioned instruments will function as a mass-spectrometer. Here, similar to the ionospheric measurements the mass resolution $\Delta M/M$ will be determined by (and approximately equal to) the electrostatic analyser energy resolution $\Delta E/E \approx 4\%$ (Gringauz et al. 1983). Since the energy spread of the ions with the same mass recorded by such an instrument is estimated as $\Delta E/E \approx \delta^2 \approx 0.7\%$, it can be neglected. The mass resolution $\Delta M/M \approx 4\%$ provides the identification of all ions with mass numbers $\lesssim 25$, which obviously predominate outside the contact surface. Within the limits of sensitivity of the instruments with narrow acceptance angle the complete identification of ion-masses in the solar wind is provided by the energy spectrum measurements in the closely fitting energy ranges.

In addition to fairly comprehensive qualitative information on mass numbers of newly formed ions in the solar wind, and hence on coma mass composition, the above discussed measurements can assure quantitative data on the near cometary space properties. To make the interpretation of the measured spectra more comprehensive, it is essential to use the information on the vector values $\vec{v}$ and $\vec{B}$ obtained with the other instruments. In this case the determination of partical concentration of the coma molecules and the products of their ionization seems possible. The information on the coma relative composition, however, could be obviously obtained with n_i^* relations in the energy spectrum maxima formed by ions with various mass numbers, not using the experimental results of other instruments.

The simple estimations made in this paper were aimed to show that the sensitivity of the instruments for studying the cometary ionosphere is sufficient to measure the coma ionization products formed in the solar wind, and hence, that such measurements are possible. It is obvious that the problem should be thoroughly analysed taking into account the mutual orientation of $\vec{v}$, $\vec{B}$, v_s the expansion velocity of the coma neutral hydrogen part, the formed ion and solar plasma interaction and so on. Note also that in the case when $\vec{v}_s$ is in the plane of cyclotron rotation of newly formed ions, the measured energy spectra of ions with similar mass numbers can form two maxima wich differ in energy by $\sim (v/v_s)^2$. If $\vec{v}_s$ is oriented towards $\pm (\vec{v}\times\vec{B})$ the ion resolution by mass numbers might be essentially worse etc. We believe however, that the possibility of measurements of ions formed in the solar wind with the instruments already installed on board the spacecraft and with the control of unfavorable conditions, it will justify the efforts which should be made for not quite trivial analysis of experimental results and the acquired data significantly enrich our knowledge about the coma characteristics of Halley Comet at fairly large distances from its nucleus.

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