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Comet P/Halley neutral gas density profile along the Vega-1 trajectory measured by the Neutral Gas Experiment

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Summary. Two complementary gas analyzers comprised the Neutral Gas Experiment (NGE) on the two Vega spacecraft sent to comet Halley. Although no significant mass spectra were obtained, data returned from the Vega-1 experiment have permitted the determination of the total neutral gas density profile along the spacecraft trajectory during the comet encounter. Discounting small fluctuations, the FIS instrument measured a density profile which varied approximately as the inverse radial distance squared. Data from the EIS instrument yielded a series of calibration points; e.g. the neutral density at a radial distance of 10^5 km was about $10^4\,\mathrm{cm}^{-3}$. The combined data provided a calibrated total density profile, and implied a neutral production rate of $1\,10^{30}$ molecules/second (assuming an outflow velocity of $1\,\mathrm{km\,s}^{-1}$) during the hours prior to the spacecraft encounter.

Key words: comets

1. The gas analyzers

Two complementary instruments comprised the Neutral Gas Experiment (NGE) on the Vega spacecraft (Keppler et al., 1986). One unit (FIS) employed a Field Ionization Source which largely preserved the parent molecules in the cometary gas during the ionization process, but had an undesired sensitivity to background gas originating at the spacecraft. The second unit (EIS) used an Electron Impact ionization Source (Curtis and Hsieh, 1986) and an analyzer which discriminated against thermal background gas, but this ion source fragmented the incoming molecules to a greater extent than did FIS.

The FIS ion source produced field ions near the surfaces of 40 needle tips of about 0.1 micron radius, biased at about $+30$ kV. The largely monoenergetic ions with energies near 30 keV were directed through a 0.3 microgram/cm^2 carbon foil, along trajectories nearly perpendicular to the paths of the incoming neutrals. Electrons ejected from the foil by a penetrating ion triggered a two-stage microchannel plate (MCP) detector to produce a start signal. Some nanoseconds later, the ion itself struck a similar detector 7.4 cm downstream from the carbon foil to generate a stop signal. Time of flight (TOF) circuitry converted the start/stop signal pair into a voltage pulse proportional to the square root of the ion mass. FIS produced, over a one second interval, a complete mass spectrum of particles having flight times within the range of 2 to 255 ns. It generated such a spectrum every two seconds.

The EIS employed two cold-cathode electron sources (one of them redundant) to ionize a fraction of the incoming gas. Cometary ions were excluded by repelling electrodes at the gas inlet and outlet. Like the FIS, this instrument was of "flythrough" design, with internal structure which presented a minimum cross section to entering dust particles and neutrals not ionized. The ion source was designed to preserve the initial velocity of the incoming molecules, which was a nearly uniform $79\,\mathrm{km\,s}^{-1}$ for the cometary gas. Ions from this source having $E/e < 30$ eV/e were rejected by the EIS hyperbolic electrostatic analyzer, which dispersed the ions along a 5 cm-long MCP detector. Position sensing was accomplished by measuring the relative amounts of charge collected at the two ends of a resistive anode at the MCP output. EIS was designed to accumulate a spectrum covering the mass interval from 1 to 14 amu over a one-second period, and then switch ranges to accumulate a spectrum covering masses 14 to 28 amu during a later one-second interval.

2. Flight results

Both the FIS and EIS on the Vega-1 spacecraft responded to the passage of comet Halley on March 6, 1986, although neither instrument matched the performance of the lab prototypes. The FIS produced data leading to a total neutral gas density profile near the comet, but gave little mass information because of a combination of instrument problems and excessive counting rates.

The lower trace in Fig. 1 shows a spectrum produced by the FIS over a 20-second interval nearly one hour before the closest approach ($\sim$275,000 km from the nucleus), which exhibits a peak at channel 40 (mass 28) probably due to molecular nitrogen released from another experiment on the spacecraft. This peak

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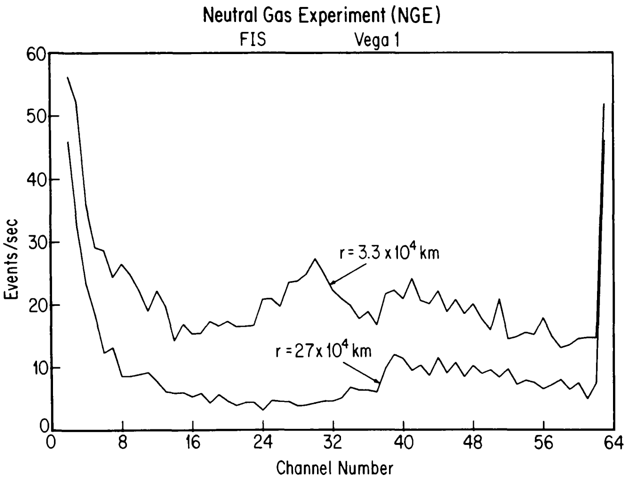

Fig. 1. (Lower trace): FIS spectrum ~275,000 km from the comet nucleus, showing a peak near channel 40 (mass 28) due to N_2 produced at the spacecraft. (Upper trace): FIS spectrum ~33,000 km from the comet nucleus, showing peaks near channel 30 (mass 18) and channel 40 (mass 28) served as a calibration point. Additional peaks at higher mass channels may be largely caused by straggling in the carbon foil. At this distance, spacecraft outgassing masked any gases produced by the comet.

At some intermediate distances, particularly in the outbound leg, a mass peak probably associated with cometary water appears in the spectra. The upper trace in Fig. 1 shows a 20-second spectrum accumulated at a distance of about 33,000 km from the nucleus, with a mass peak occurring at channel 30 (mass 18), in addition to the previously observed signals at channel 40 and above. This peak position shifts between channels 29 and 30, and represents molecules in the mass 16–18 range. The mass resolution is not sufficient for us to clearly identify these events as H_2O rather than O or OH resulting from the photodissociation of water molecules. At closer distances, events at shorter flight times are predominant, and the FIS spectra become relatively featureless. The counting rates were too high for the TOF electronics to resolve particle masses, although the overall rates did not exhibit saturation.

Because of the limited mass resolution of the FIS spectra, only a total neutral density profile was generated by summing the counting rates of channels 8 through 62 (masses 2 to 80 at 30 kV tip bias) as a function of radial distance from the nucleus. (The omitted channels exhibit continuously high counting rates.) The upper traces in Fig. 2 display the radial dependence of the total counting rate for these 55 channels, averaged over 20-second intervals, converted to number densities. The gap near 10^5 km results from a data loss. The density profiles in both legs display an r^{-2} dependency, with a small exponential correction, but the inbound density reaches a maximum about one minute before the closest approach. From its calculated sensitivity, the uncorrected FIS counting rate was several times higher than expected for the number densities deduced from the EIS data. Uncertainties in the ionization or detection efficiencies, or other instrument effects, could account for this discrepancy.

The EIS data complement the FIS data by providing closer estimates of the cometary neutral gas density at distances between 40,000 and 150,000 km from the comet nucleus. Although the EIS counting rate in all channels was inflated by secondary ions produced by electrons leaking from the ion source into the analyzer region, the EIS should not have been strongly sensitive to thermalized gas in the vicinity of the spacecraft. As happened with the FIS instrument, mass resolution was severely compromised by electronics problems. The EIS density profile for neutrals in the mass range from about 6 to 18 is given by the lower traces in Fig. 2. For the inbound leg, power law behavior of the counting rate was observed in the distance range between 40,000 and 150,000 km. An apparent saturation of the instrument caused a deviation from a constant slope of about −2 at distances less than 40,000 km, and a turnover in the total counting rate at a distance of about 18,000 km from the nucleus. As the spacecraft reached the closest approach point, the EIS counting rate dropped precipitously. While it recovered somewhat during the outbound leg, the counting rate remained below the inbound rate at comparable distances, in agreement with the FIS results. Note that at radial distance greater than ~40,000 km, there is general agreement between FIS and EIS on both inbound and outbound legs. At closer distances, the EIS saturation results in an incorrect profile from that instrument.

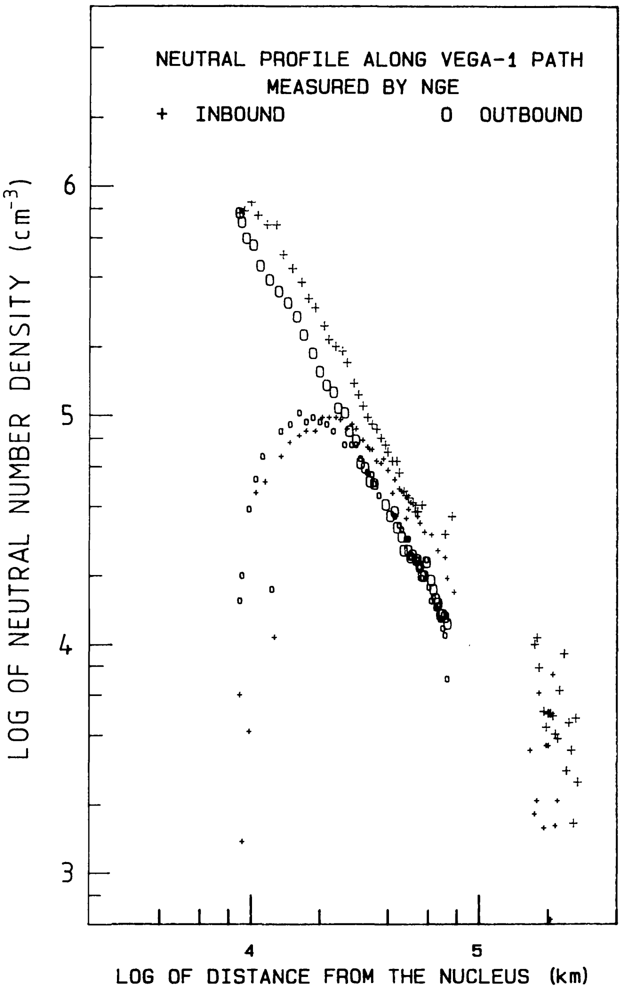

Fig. 2. Total neutral density profiles deduced from the FIS (large + and 0 symbols) and EIS (small symbols) counting rates. The EIS profiles show instrument saturation at distances less than ~40,000 km, and are inaccurate within that distance range

3. The neutral density

From the calculated EIS sensitivity, we estimate the total neutral density at a distance of 10^5 km on the inbound leg to have been about $10^4\,cm^{-3}$, to within a factor of 4, allowing for uncertainties in the emission current of the electron source and the overall efficiency of the detection system. This figure is in basic agreement with that of Gringauz et al. (1986) on Vega 1, but is more than an order of magnitude higher than the density for water obtained by Krankowsky et al. (1986) on the Giotto spacecraft. There are two factors which may account for this. First, it appears that comet P/Halley was considerably more active (was producing more gas) just prior to the Vega 1 encounter on March 6 than it was for the later Giotto encounter. Gringauz et al. inferred a total gas production rate of about $1.3\,10^{30}\,s^{-1}$, while Krankowsky et al. calculated a total production rate only half as great during their later encounter. Second, the water density profile data of Krankowsky et al. show a substantial deviation from a simple power law dependence, owing to a large photodestruction effect. Our analysis of our data shows only a small exponential correction to a simple r^{-2} dependency over the distance range shown. While water was presumably the major constituent of gas released at the nucleus, it was probably only a minor neutral species at 10^5 km.

It is also possible that a higher rate of dust production during the Vega 1 encounter resulted in larger amounts of water being transported as subliming ice to distances beyond 10^4 km, providing fresh sources of neutral gas molecules at distances between 10^4 and 10^5 km. Further, when rotation of the comet nucleus is taken into account, azimuthal variations in gas production at the nucleus have a substantial effect on the observed radial dependence of the neutral gas density (Hsieh et al., 1987).

From our estimate of the neutral gas density at 10^5 km, we infer a total neutral gas production rate of about $1\,10^{30}\,s^{-1}$ at the comet surface about one day prior to the encounter, assuming a uniform flux with a $1\,km\,s^{-1}$ constant velocity. (This production rate is insensitive to the inclusion of a photoionization length of about $2\,10^6$ km in the calculation.) The number is in basic agreement with the projections of both Gringauz et al. and Krankowsky et al., since their measurements of the neutral density at distances of 10^4 km and less (where we have no good measurement) differ by only a factor of 2.

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