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COMET HALLEY NEUTRAL GAS DENSITY PROFILE ALONG THE VEGA 1 TRAJECTORY MEASURED BY NGE

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ABSTRACT

Two complementary gas analyzers comprised the Neutral Gas Experiment (NGE) on the two Vega spacecraft. Data returned from the Vega 1 experiment have permitted the determination of the total neutral gas density profile along the spacecraft trajectory. 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 10^5 km is about 10^4 cm^{-3}. The combined data provide a calibrated total density profile, and imply a neutral production rate of 1×10^{30} molecules per second.

Keywords: Cometary Atmosphere, Neutral Gas Analyzer, Comet Halley

THE GAS ANALYZERS

Two separate instruments comprised the Neutral Gas Experiment (NGE) on the Vega spacecraft (Ref. 1). These independent gas detection systems were mounted on a platform which could be rotated to point the gas inlets in the direction of the comet-spacecraft relative velocity vector. The systems were based on complementary operating principles. 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 (Ref. 2) with an analyzer which discriminated against thermal background gas, but the ion source fragmented the incoming molecules to a greater extent than did FIS. The complementary data sets from these instruments were intended to provide a realistic picture of the cometary atmosphere.

The FIS 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 accumulated, over a one second interval, a complete mass spectrum of particles having flight times within the range of 2 to 255 ns. It generated spectra at a rate of one 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 "fly-through" 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 78 km/sec for the cometary gas. Ions from this source having $E/q < 30$ 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 14 to 28 amu during a later one second interval.

The NGE electronics interleaved the FIS and EIS spectra so that a FIS spectrum was transmitted after each of the two types of EIS spectra. Thus, a FIS spectrum was transmitted every two seconds, and the EIS low mass range and high mass range spectra were each transmitted at four second intervals.

Time and budgetary constraints prevented the construction of the neutral particle accelerator necessary to measure the FIS and EIS sensitivities to a 78 km/sec neutral beam prior to launch. We have calculated the FIS sensitivity based on simple theory and results obtained from a prototype operated in a high vacuum environment in the

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laboratory. Because the EIS required a directed beam to measure its sensitivity, we have calculated its response on the basis of its geometry, the measured electron current produced by the ion source, and the electron-impact ionization cross section of the detected species.

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 operated at full design capability. The FIS produced data leading to a total neutral gas density profile near the comet. In most mass channels, the FIS total counting rate (after background correction) varied approximately as the inverse square of the spacecraft-comet distance, but showed a maximum about 1,200 km (or 1 minute) before the closest approach point. The EIS instrument exhibited the same behaviour over a portion of its mass range (~6-18 amu) at distances between 40,000 and 150,000 km, which permitted estimates of the total neutral density within those distance and mass ranges. During the close approach phase, the EIS showed evidence of saturation, producing much lowered counting rates in the mass range mentioned.

The FIS and EIS density profiles exhibit two common features in those regions where the EIS instrument was not saturated: (1) both instruments indicate that the neutral density at any given radial distance was higher on the inbound leg than on the outbound leg and, (2) both instruments show similar density vs. distance profiles on a given leg. Since the instruments are of different design and have different sensitivities to noise sources, it seems unlikely that instrumental effects are responsible for the observed differences in the inbound and outbound density profiles.

The FIS spectra were similar to those generated by the lab prototype, but with two substantial differences. First, the spectra showed much less mass resolution than had been achieved earlier. Second, a preponderance of events occurred at TOF intervals which did not correspond to expected mass peaks, the latter being generally visible only at distances greater than 20,000 km from the nucleus. The positions of the major identifiable mass peaks, water and nitrogen (the latter produced at the spacecraft), show that the needle tip bias supply operated at a level of ~30 kV instead of the intended 50 kV. Housekeeping data indicate short term fluctuations of several kilovolts in the tip bias, which had the effect of broadening all the mass peaks. Figure 1 shows a spectrum produced by the FIS over a 20 second interval nearly one hour before the closest approach (~275,000 km from the nucleus), which exhibits a peak near channel 40 (mass 28) probably due to molecular nitrogen released at the spacecraft. Additional peaks at higher mass channels may be largely artifacts 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 appeared in the spectra. Figure 2 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 water molecules rather than oxygen atoms resulting from the photodissociation of water molecules.

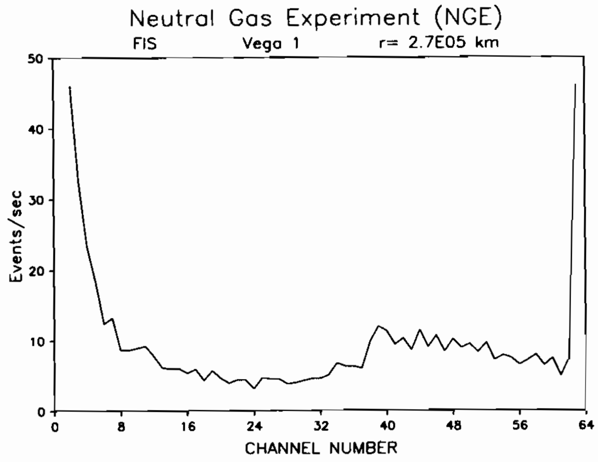

Figure 1. FIS spectrum ~275,000 km from the comet nucleus, showing a peak near channel 40 (mass 28) due to N_2 produced at the spacecraft.

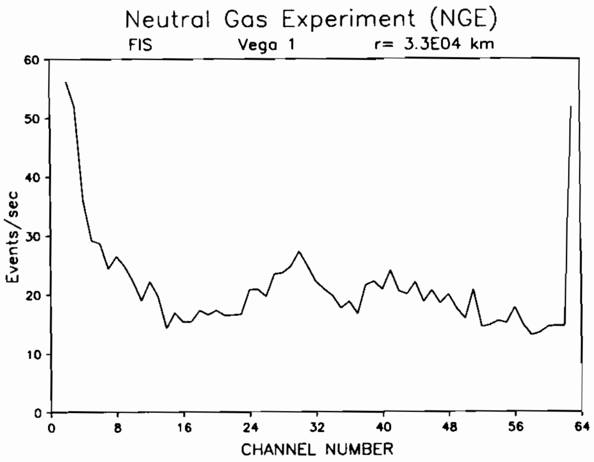

Figure 2. FIS spectrum ~33,000 km from the nucleus, showing peaks near channel 30 (mass 18) and channel 40 (mass 28).

At closer distances, events at shorter flight times were predominant, and the FIS spectra became relatively featureless. The counting rates were too high for the TOF electronics to resolve particle masses, although the overall rates did not exhibit saturation. Figure 3 shows such a spectrum, accumulated for 20 seconds at a distance of about 9,000 km from the nucleus.

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

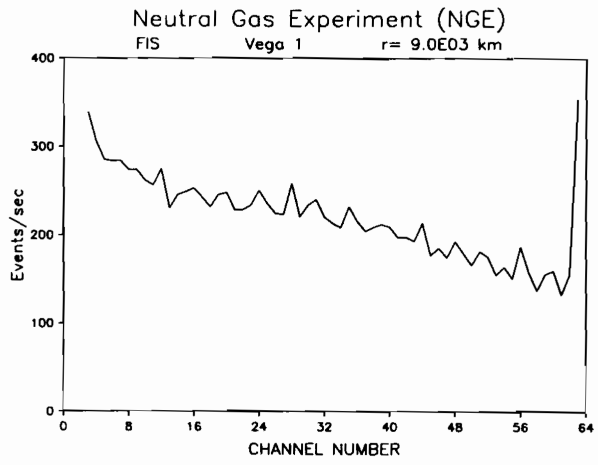

Figure 3. FIS spectrum ~9,000 km from the nucleus, showing the loss of mass resolution at high counting rates.

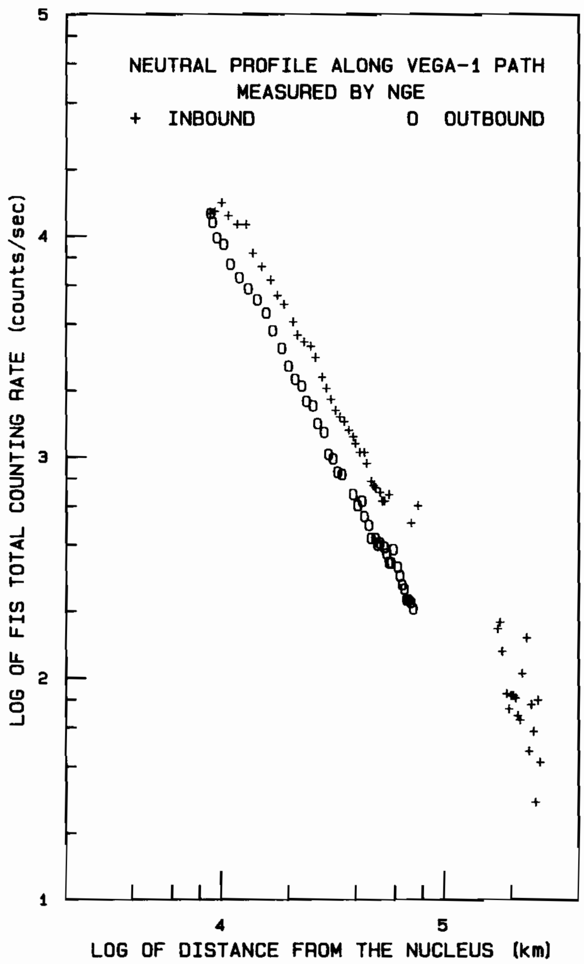

Figure 4. The rates for the sum of FIS channels 8-62, after background subtraction, shown as a function of distance from the nucleus.

nucleus. (The omitted channels exhibit excessive noise). Figure 4 displays the radial dependence of the total counting rate for these 55 channels, averaged over 20 second intervals. The gap near 10^5 km results from a data loss. A background correction has been applied by substracting from each rate a constant whose value was determined by measuring the rates far (~5×10^5 km) from the comet. For the outbound leg, a slightly smaller constant was used than for the inbound leg, to reflect the lower background measured long after the encounter. Note that the resulting event rate plot displays an approximate inverse r^2 dependence for both the inbound and outbound legs. As mentioned previously, the maximum counting rate occurred just prior to the closest approach point, and the outbound counting rate was slightly lower than the inbound rate at comparable distances, which is indicative of a large scale asymmetry in the cometary neutral gas density profile.

From its calculated sensitivity, the FIS counting rate was several times higher than exptected for the number densities deduced from the EIS data. Uncertainties in the ionization or detection efficiencies may account for this discrepancy. However, it must also be pointed out that the FIS was strongly sensitive to spacecraft outgassing, since unfortunately it had to be mounted on a solar panel where its view direction was inclined upward at an angle of 7 degrees, directly over the top of the spacecraft. It appears that the FIS responded to spacecraft interactions with cometary gas and dust during the approach, which enhanced the density of thermalized gas near the spacecraft in direct proportion to the cometary gas/dust density. Thus, the FIS sensitivity to secondary molecules produced by impacting cometary matter may account for a major portion of the observed surplus in the counting rate.

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 enhanced by secondary ions produced by electrons leaking from the ion source into the analyzer region, the EIS was not strongly sensitive to thermalized gas in the vicinity of the spacecraft. As happened with the FIS instrument, mass resolution was compromised, in this case by fluctuations in the bias voltage applied to the analyzer section. As a further result of the fluctuations, masses 1 to 18 appeared in the EIS low mass range interval, rather than the intended masses 1 to 14. A corrected counting rate profile (incorporating a background subtraction technique similar to that of FIS) for neutrals in the mass range from about 6 to 18 is shown in Fig. 5. Mass 6 to 18 was the entire range of one section of the EIS position-sensing circuitry, covering channels 41 to 61 in the low mass range. For the inbound leg, power law behavior of the counting rate was observed in the distance range between 40,000 and 150,000 km. The apparent saturation referred to earlier 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 during the outbound leg, the counting rate remained below the inbound rate at comparable distances, in agreement with the FIS results. Figure 6 shows the

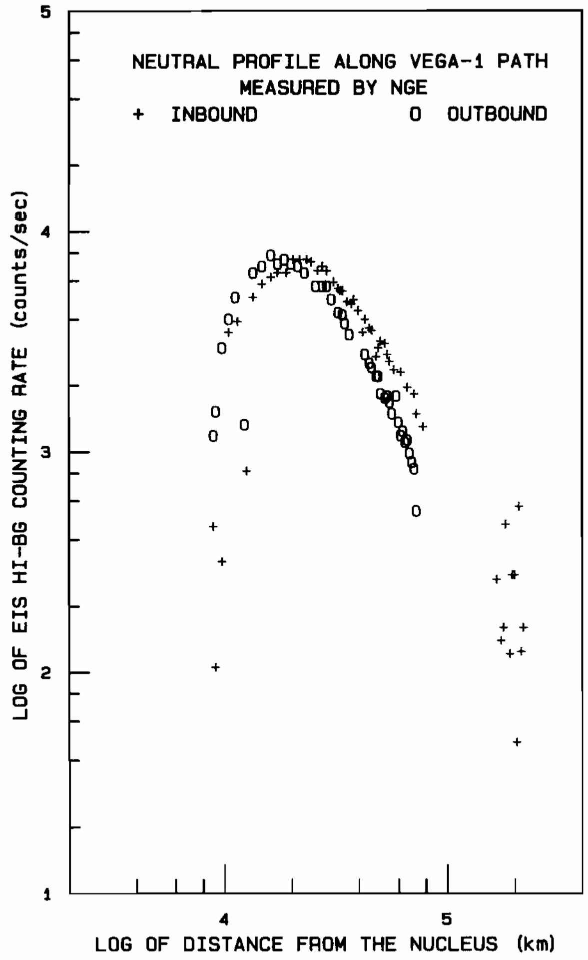

Figure 5. The rates for the sum of EIS channels 41-61, after background subtraction, shown as a function of distance from the nucleus.

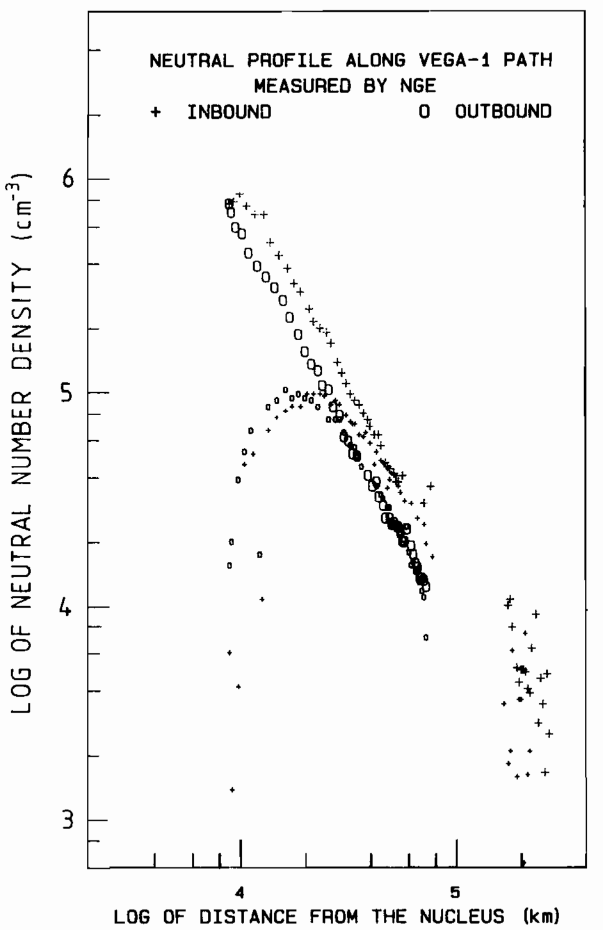

Figure 6. Neutral density profiles from the FIS and EIS counting rates. The EIS profile is considered inaccurate where it is inconsistent with the FIS profile.

neutral density profiles inferred from the FIS and EIS counting rates. The EIS profile is considered accurate only where it agrees with the FIS profile. The implications of the lower neutral density in the outbound leg for the overall comet neutral gas structure are discussed in a separate paper (Ref. 5).

From the calculated EIS sensitivity, we estimate the neutral density at a distance of 10^5 km on the inbound leg to be about 10^4 cm^{-3}, to within a factor of 4, allowing for uncertainties in the total 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. (Ref. 3) on Vega 1, but is more than an order of magnitude higher than that obtained by Krankowsky et al. (Ref. 4) on the Giotto spacecraft. There are two reasons for this. First, it seems clear that Comet Halley was considerably more active (was producing more gas) on March 6, during the Vega 1 encounter, than it was during the later Giotto encounter. Gringauz et al. inferred a total gas production rate of about 1.3×10^{30} sec^{-1}, while Krankowsky et al. calculated a total production rate only half as great during their later encounter. Second, the neutral density profile data of Krankowsky et al. show a much larger deviation from a simple power law dependence, owing to a larger photodestruction effect. The analysis of our data does not show a significant exponential correction to a simple inverse r^2 dependency over the distance range shown.

There are several factors which could account for this. It is 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. The dust also partially blocks sunlight, reducing photoionization. Further, since the Vega 1 spacecraft had a large tangential velocity component with respect to the comet nucleus during the period of our measurements, any azimuthal variation in gas production at the comet nucleus could have a substantial effect on the observed radial dependence of the neutral gas density.

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} sec^{-1} at the comet surface, assuming a uniform flux with a 1 km/sec constant velocity. (This number is insensitive to the inclusion of a photoionization length of about 2 x 10^6 km in the calculation.) Interestingly, this figure 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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