ANISOTROPY OF THE NEUTRAL GAS DISTRIBUTION OF COMET HALLEY DEDUCED FROM NGE/VEGA 1 MEASUREMENTS

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ABSTRACT

The neutral gas density profile of comet Halley measured by the Neutral Gas Experiment (NGE) on Vega 1 showed an asymmetry between the inbound and the outbound legs during the fly-by on 6 March 1986. The implications of this asymmetry are discussed, and a means to deduce information concerning the neutral gas densities on or near the surface of the nucleus is presented.

Keywords: Neutral Gas Distribution, Halley, Vega 1

INTRODUCTION

The preliminary report of the Neutral Gas Experiment (NGE) on Vega 1, showed an asymmetry in the counting rates between the inbound and the outbound legs during the comet Halley fly-by on 6 March 1986 (Ref. 1). Further analysis of the data confirmed this asymmetry (Ref. 2). The asymmetry and the consequent deviation from the expected R^{-2} dependence with an exponential decay in R, due to radial expansion and ionization of the neutral gas, can be ascribed to an anisotropy of the neutral gas density along the Vega 1 trajectory. Due to the nature of the expanding gas, such an anisotropy in the gas must be caused by variations in the gas production rate in specific regions on or near the surface of the cometary nucleus. To map back to these regions, one needs to take into account the bulk velocity of the gas V, the ionization mean-free-path L, the spacecraft trajectory as a function of time, and the rotation rate Ω of the comet nucleus about a known axis. For the lack of precise information at this time, we make some simplifying assumptions on these parameters. Examples of our results are given for some reasonable values of L and V, and plausible values of Ω about an axis roughly normal to the plane of the Vega 1 trajectory. Comparison of our measurements with ion, dust, and optical observations from Vega 1, UV observations from Suisei, and ground-based observations may be helpful in our attempt to obtain the true values of L, V, and Ω, which would lead to a better understanding of the surface features and gas dynamics of comet Halley.

DATA

Curtis *et al.* (Ref. 2) showed that after subtracting constant background rates from the total counting rates of FIS and EIS, the instruments agreed well in both the inbound and the outbound legs when EIS was not saturated (see Fig. 1). While FIS responded directly to the neutral density, EIS responded to the neutral flux; but since the relative velocity between Vega 1 and comet Halley remained practically constant throughout the fly-by, the EIS counting rate is also directly proportional to the neutral density. The asymmetry in the neutral density was indeed seen by both instruments. We shall concentrate on the data collected at distances $<10^5$ km from the nucleus. For completeness, the 5 EIS data points between 72,095 and 57,030 km on the inbound leg are added to the 79 FIS data points between 55,865 and 72,173 km on the outbound leg to form the database for our investigation. The two FIS data points at about 7×10^4 km on the inbound leg are excluded from the database due to their large deviation from the smooth curve.

The background removed from the FIS data for each leg is ≤ 350 counts/sec, and each data point shown in Fig. 1 is averaged over 10 one-second readouts. Therefore, the structures we see at distances $<10^5$ km from the nucleus are beyond statistical fluctuations.

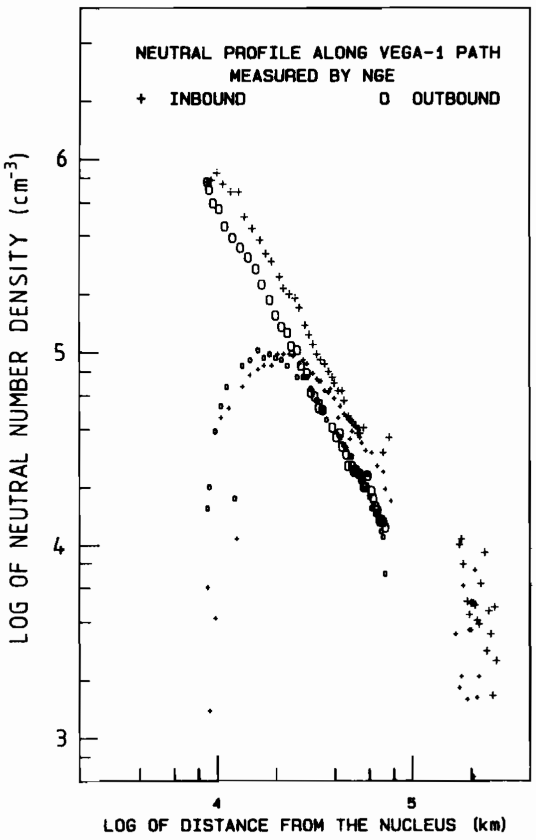

Figure 1. The neutral density as a function of distance from the nucleus converted from FIS (large + and o's) and EIS (small + and o's) total counting rates for the inbound and the outbound legs of the Halley fly-by. At closer distances, the saturation due to large dead time in EIS is apparent. When not saturated, the two counting rates seem to have the same radial dependence in both legs of the trajectory. The scattering in data at ~$2x10^5$ km is due to the fact that the background becomes comparable to the signal; but at <$7x10^4$ km, statistical uncertainty decreases to <10%. At the closest approach, the uncertainties in the FIS counting rates reach ~0.8%. The two FIS data points at ~$7x10^4$ km on the inbound leg are inconsistent with the other data points and therefore are not analyzed. This figure is identical to Fig. 6 of Ref. 2.

ANALYSIS

The asymmetry in the measured neutral density clearly does not allow an expression having R as its only parameter to describe the density distribution along the Vega 1 trajectory. It is necessary to invoke other spatial variables. Fig. 2 shows the two-dimensional geometry of the Halley/Vega 1 system before and after the closest approach on 6 March 1986. Along the Vega 1 path, the angle θ and the distance R are related through

$$\theta = \cos^{-1}(b/R) + \theta_0$$

prior to closest approach, and

$$\theta = \theta_0 - \cos^{-1}(b/R)$$

after closest approach, where b is the impact parameter and θ_0 the corresponding sun-Halley-Vega angle. The respective values are b = 8,890 km and $\theta_0 = 22^o$. As Vega 1 approaches comet Halley, the angle θ decreases and eventually becomes negative after passing the Halley-sun line. From R = 72,095 km on the inbound leg to 72,173 km on the outbound leg, the range of our data set, the angle θ spans from 105^o to -61^o, respectively.

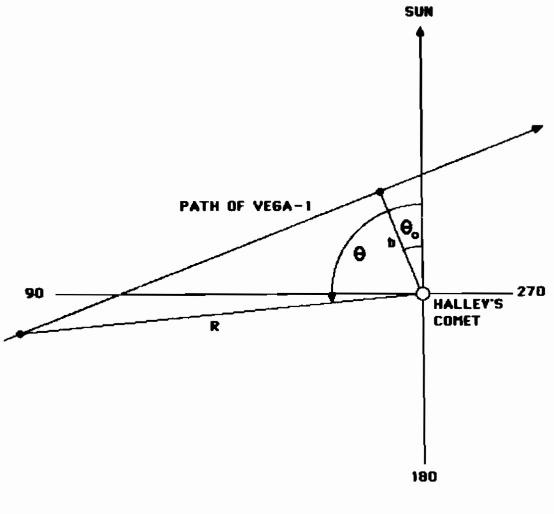

Figure 2. The trajectory of Vega 1 is shown in the Halley-sun frame. This figure shows the relationship between R and θ, the angle from the Halley-sun line. The impact parameter b = 8,890 km, and the angle $\theta_0 = 22^o$.

For a radially expanding neutral gas that also undergoes partial ionization, the density at any point along the trajectory can be written in the form

$$n(R,\theta,t) = n_0 f(a,\Sigma,t_0;R,\theta,t) R^{-2} \exp(-R/L) \ , \quad (1)$$

where L is the scale height determined by the effective loss mechanisms, n_0 a normalization constant, and f the measure of anisotropy along the spacecraft trajectory at (R,θ,t), and represents the relative gas density at some source point on or near the nucleus (a,Σ,t_0). At time t_0, the angle Σ, measured from the Halley-sun line, is given by

$$\Sigma = \theta - 2\Omega R/V + \Omega(t - t_0) \quad , \qquad (2)$$

where V is the bulk velocity of the expanding gas, assumed to be in the radial direction. This expression is valid, since R >> a, where a is of the order of the size of the nucleus. Any time can be chosen as t_0, if the orientation of the nucleus with respect to the sun at that time is known. Here, we have assumed that the nucleus' axis of rotation is perpendicular to the plane of Vega 1's trajectory.

From the above considerations, one can deduce from the measured density $n(R,\theta,t)$, an anisotropy amplitude f, for a given L. This amplitude can then be mapped to a source region (a,Σ,t_0) on or near the surface of the nucleus to represent the relative gas production rate from that region at time $t_e (= t - R\Omega/V)$. In so doing, it is necessary to know the correct values for L, Ω, and V, which, unfortunately, are not certain at this writing. To obtain a qualitative picture of (1) the observed anisotropy along the Vega 1 path during the fly-by, and (2) the possible locations of the sources of the measured anisotropy, we choose $L = 2 \times 10^6$ km (Ref. 3) and 3×10^5 km, which fits our outbound profile best; $\Omega = 1.9 \times 10^{-3}$ °/sec for a period of 2.2 days (Ref. 4), and 5.6×10^{-4} °/sec for a period of 7.4 days; and a typical bulk velocity of V = 1 km/sec.

RESULTS AND DISCUSSION

Using Eq. (1) and the values of L given in the previous section, two samples of amplitude f are shown as functions of θ in Figs. 3 and 4. Both figures show a minimum at the sub-solar point (θ = 0°) and higher fluxes near the dawn terminator with a swelling in the morning sector. The difference between the two figures lies only in the magnitudes of f at θ's corresponding to large R's. This is expected; for a small L (Fig. 4), a larger f is required to compensate the more rapid exponential decay at large distances.

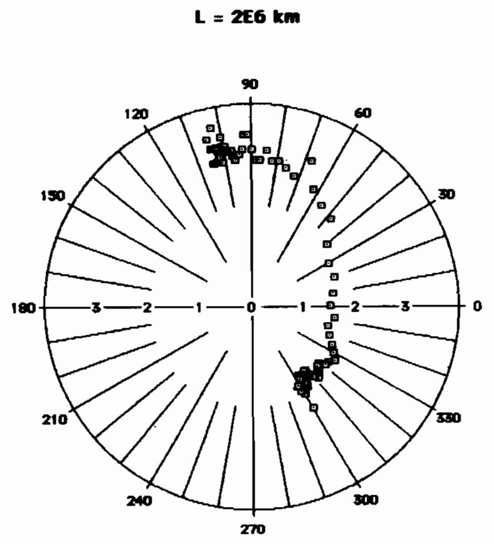

Figure 3. The function $f(a,\Sigma,t_0;R,\theta,t)$ in Eq. (1) plotted against the angle θ, as defined in Fig. 2. The angle 0° is the sunward direction. The normalization factor n_0 is set at 3.6×10^{13} cm^{-3} km^2, and L = 2×10^6 km. It appears that there is more gas in the morning sector.

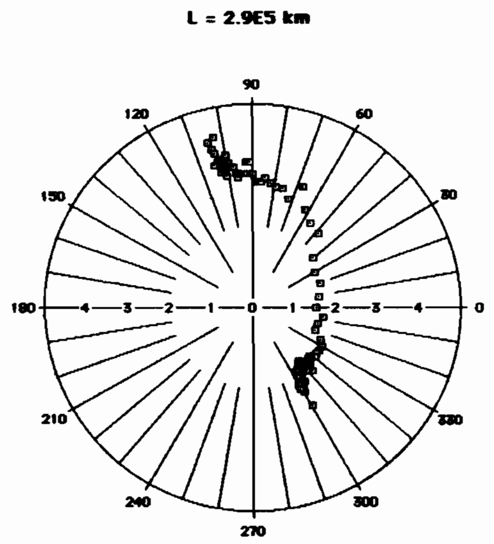

Figure 4. Same as Fig. 3, except L = 2.9×10^5 km, the value least-square fitted to the outbound data between 9,548 and 72,173 km. The anisotropy in this case is greater than that in Fig. 3, due to a small L.

These figures describe only the deviations from the $R^{-2}\exp(-R/L)$ at given time and location along the Vega 1 path, i.e., $f(a,\Sigma,t_0;R,\theta,t)$ *vs.* θ. How one compares these results directly with those from other observations is not immediately obvious. However, the results of directly tracing these anisotropies back to locations on or near the surface of the nucleus may be more readily interpreted and, thus, more useful in correlative studies. Employing Eq. (2) and the selected values of L, V, Ω, and t_0, one can produce the results of mapping-back, as shown in Figs. 5 and 6, where we choose L = 2.9×10^5 km, V = 1 km/sec, $\Omega = 1.9\times10^{-3}$ °/sec (rotation period of 2.2 days for Fig. 5), $\Omega = 5.4\times10^{-4}$ °/sec (rotation period of 7.4 days for Fig. 6), and $t_0 = 07^h20^m06$ UT, the time of closest approach.

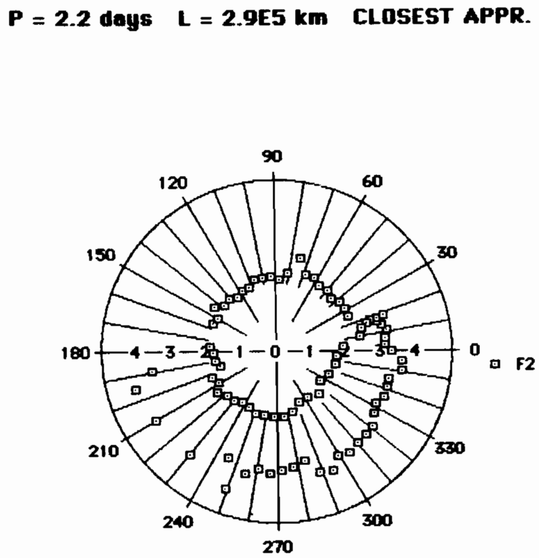

Figure 5. The amplitude f for the case L = 2.9×10^5 km mapped back to the surface of the nucleus. Each angular position (Σ) corresponds to a location on or near the surface for a particular orientation of the nucleus. Here we chose the orientation at the time of closest approach, when the nucleus is lengthwise along the Halley-sun line (180°-0° line) with its larger end facing the sun (0°). Due to the 2.2-day rotation period of the nucleus, gas coming from the 3rd and 4th quadrants could reach Vega 1 twice, while gas from the 1st and 2nd quadrants only once. The sequence of the points follow an S-shape pattern starting at $\Sigma = 190°$ and ending at $\Sigma = 25°$. The polar plot does not convey the time-dependence of the data points (see text).

The effect of the different rotation rates is striking. If the nucleus had rotated one revolution every 2.2 days (Fig. 5), then Vega 1 would have sampled neutral gas emitted from the entire belt girding the nucleus in the plane of Vega 1's path, and a good portion of the belt twice. However, if the rotation rate is much slower, e.g., 7.4 days (Fig. 6), then only a small portion of the belt is sampled twice and about half of the belt is not sampled at all.

At t_0, the time of closest approach, the comet nucleus was apparently oriented lengthwise along the Halley-sun line with its bigger end pointing to the sun (Refs. 5 and 6). The angles shown in Figs. 5 and 6 refer then to locations on or near the comet at this particular orientation. The amplitudes plotted are the relative densities coming from these locations at the corresponding times of emission. For example, in Fig. 5, the density measured at R = 72,095 km, t = 07^h05^m03 UT on 6 March comes from a region near the smaller end of the nucleus ($\Sigma = 189°$) some $\Omega R/V$ (= 20.0 h) earlier, i.e., 11^h03^m28 UT on 5 March. Gas comng from the same region emitted at a later time, 22^h38^m14 UT on 5 March, was detected again by Vega 1 at t = 07^h26^m30 on 6 March when R = 31,696 km. Between 11^h03^m28 UT on 5 March,

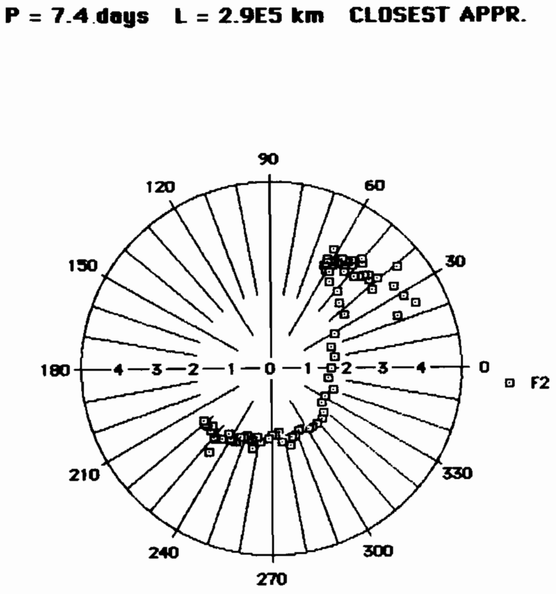

Figure 6. Same as Fig. 5, except the period of nucleus rotation is 7.4 days. The slower rotation rate would prevent Vega 1 from sampling gas coming from a large portion of the nucleus, but gas coming from regions between $\Sigma = 20°$ and $65°$ could reach Vega 1 twice. The series of points starts at $\Sigma = 22°$ and ends at $\Sigma = 218°$.

when the sampled region was behind the dawn terminator (0 = 105°), and $22^{h}38^{m}14$ UT on the same day, when the same region was on the afternoon side (0 = 308°), the gas production at this region had reduced by half. We notice that, for the entire portion of the belt that had been sampled twice by Vega 1, the gas production was reduced significantly in time. We also note again that the production of gas, as detected, seems higher in the early morning sector than in the sub-solar region. This must be checked with complementary observations.

Obviously, the polar plots in Figs. 5 and 6 can only show the fixed locations on the nucleus and their relative gas production rates, but cannot convey the specific times of emission. A detailed tabulation would be required for each figure in order to convey the complete picture. Due to space limitations, such tabulations will not be presented here, but can be made available to interested investigators.

In the above discussion, we note that the dependence of the results on L, V, and Ω can be identified separately. The amplitude f, which gives the relative production rate at a given site at a given time, depends solely on L; while the time of emission depends only on V; and the location of emission Σ depends on both V and Ω. These parameters can also be inferred separately by other means, such as photometric and spectroscopic measurements from spacecraft and ground-based observations. Correlated with these observations, we may converge on these important parameters, which would help to construct a self-consistent story of gas emission from the nucleus, and to confirm the correct rotation rate of the nucleus.

CONCLUSIONS

By taking into account the geometry of the Halley/Vega 1 system during the fly-by on 6 March 1986, and assuming the bulk velocity and the mean-free-path of the expanding neutral gas from the nucleus and the rotation of the nucleus, we have shown how the asymmetry detected by NGE on Vega 1 can be traced back to regions on or near the nucleus to obtain their relative gas production activities at specific times of emission. By correlating with other observations, we hope to verify the features of the neutral gas distribution, to arrive at reasonable values of the three assumed quantities, and thus help to construct a more complete and self-consistent model of gas emission from comet Halley.

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