P/HALLEY, THE MODEL COMET, IN VIEW OF THE IMAGING EXPERIMENT ABOARD THE VEGA SPACECRAFT

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ABSTRACT. In this paper, those results of the VEGA imaging experiments are summarized that probably have general validity for any comet. Shape, size, surface structure, jet activity, and rotation pattern are considered in this respect. It is pointed out that imaging data provide indispensable information for an understanding of cometary activity.

1. Introduction

More than three years have passed since the flyby missions to Comet Halley. Contrary to early expectations, the data evaluations are not yet finished, and many interesting results are just now being published. The imaging experiment of the VEGA mission is no exception. On the other hand, it is easier to put the results into broader context and sort out what is specific to this particular comet and what has a more general bearing. This paper is intended to summarize those results of the VEGA imaging experiment that, in our opinion, are valid for any comet.

The results presented here are based on 63 near-nuclear images exposed during the VEGA-1 flyby on 6 March 1986 and 11 images taken during the VEGA-2 flyby on 9 March 1986. The details of the encounters are best summarized by Sagdeev and Szegő (1987).

Flyby imaging experiments offer exceptionally good opportunities to examine cometary nuclei visually. Though this seems to be a trivial statement, it is not so. The focal length of the VEGA telescope was 1200 mm, and the observational range was between 50,000 and 9,000 km, providing scales between 0.7 and 0.1 km per pixel for the near-nuclear images, giving a resolution soon achievable with future ground-based or Earth-orbiting telescopes. If cometary activity were isotropic around the nucleus, most of the emitted material would remain between the object and the probe's telescope, which is always the case for ground observation. Improved visibility was partly due to anisotropic activity, allowing us to image the nucleus from directions not screened by emitted dust. We will come back to this matter later.

2. Shape and Size of the Nucleus

Before the flyby missions, the conventional wisdom was that cometary nuclei are small (with typical radii of about 5 km), relatively bright (0.1 was assumed to be the standard albedo), and more or less spherical (Divine et al., 1986). The size and albedo determination were interdependent, as size was derived from the observed brightness. The spherical shape was only a matter of convenience, since cometary breakups have argued against it, and oblate shapes were also considered in the literature. So the observational evidence from the flyby missions that the nucleus of P/Halley was much larger and darker came as a surprise to most people. Furthermore, IRAS results soon proved

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that low albedo is not an exception but a rule, and the very irregular shape of comet nuclei is also seems to be typical.

A three-dimensional shape of P/Halley has been reconstructed using 63 near-nuclear images taken by the VEGA-1 probe, providing almost 160° of coverage, nearly symmetrical to the long axis of the nucleus; 3 near-nuclear images taken by the VEGA-2 probe, providing almost 70° of coverage slightly asymmetric to a line perpendicular to the long axis; and the single view provided by the Halley Multicolor Camera (HMC) experiment from the Giotto probe. To combine the images ex-

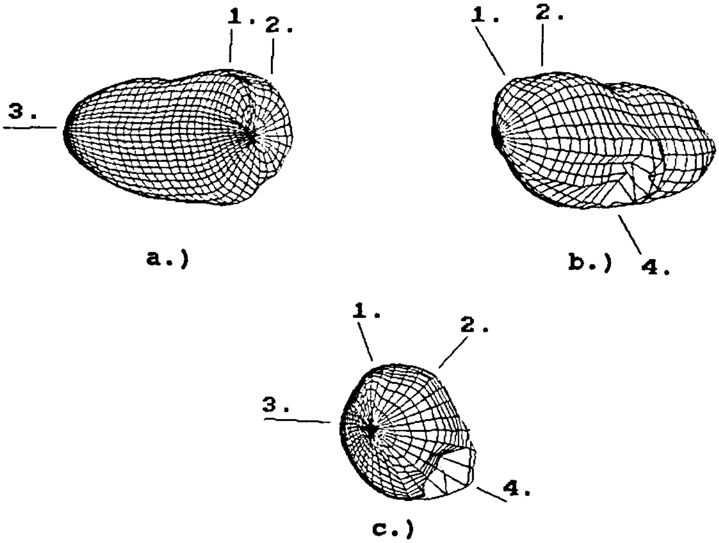

Figure 1. In this figure, the three-dimensional model of Halley's nucleus is exhibited from three viewing directions. In Figure 1c, the long axis points toward the reader, in Figure 1a, it is rotated 40° to the right, and in Figure 1b, it is rotated 40° to the left. Arrows identify the following features:

1. A protrusion, probably identical to the 'duck-tail' (the dark limb part in the upper right) in the Giotto frames.
2. An elevation.
3. A 'chain of hills,' probably identical to the terminator line in the Giotto frames.
4. A 'cave,' an 'S'-shaped concave-convex depression and elevation, the feature that produces the second brightness maximum in pre-encounter VEGA-1 images.

posed during different missions, we had to assume a certain rotation pattern of the nucleus. We used the rotation model of Sagdeev et al. (1989), but we admit that this model is still debated. We will come back to the problem of rotation later. The details of the reconstruction are published elsewhere (Merényi et al., 1989).

Because of the changing viewing directions, we have had to generate a three-dimensional model to visualize the nucleus and to identify surface features. Our computer-generated model nucleus consists of over 1000 surface points; the sizes of the smallest box (if its edges are parallel to the model axis) containing the model are 15.3, 7.2 and 7.22 km; the ratios of the inertial momenta of the model, assuming homogeneous mass distribution, are 3.4:3.3:1; its volume is 365 km^3. The shape is very irregular, not resembling any such simple body as a triaxial ellipsoid. The model is shown in Figure 1 from three different directions. When the model was constructed, a non-Lambertian scattering function $\cos^k \alpha_i \cos^{k-1} \alpha_e$ with k=0.7 was used, based on our earlier measurements (Sagdeev et al., 1985) for the surface scattering. We do not claim uniqueness for this model, though not much freedom has remained after reproducing the visual observations, with the exception of regions around the small end, which is not visible on the images.

Some of the bright features on the images can clearly be identified as jet activity. The rest of the brightness variations on the images are interpreted as slope variations; the most prominent are incorporated in our model. See the caption of Figure 1 for details. The size determination is not more accurate than $\pm$ 0.5 km. This is due to the dust surrounding the nucleus, which limits the accurate limb determination on the images to about 2 to 3 pixels. (The volume determination is more accurate than the size determination, unless all deviations go in the same direction.) Active and inactive surface regions cannot be distinguished visually on the VEGA images. This fact may have two different explanations: either a dust veil hides the visual differences or these differences are really not there. Based on the VEGA imaging results, we cannot take sides. Thus the conclusion in our model that no small-scale surface variation was observed and surface elevations are in the 100-m range without sharp cliffs, etc. also allows room for different interpretations. Hence, based on our experimental data, we do not know whether jet sources are permanent features on the nucleus or not. Reitsema et al. (1989) claimed that at least one source region is 50% brighter on the Giotto images. The simplest explanation for this is that the large phase angle of the Giotto images lowers the nuclear surface brightness to the point where the otherwise relatively weak jets show up quite clearly.

The bigger than expected size of P/Halley compared with the observed non-gravitational forces led Rickman (1988) to conclude that the density of the nucleus is low. Dust density measurements also pointed in this direction. With regard to this question, our only contribution is the volume determination, which is 365 $km^3 \pm$ 15%, smaller than the assumption used by Rickman (1988). However, we emphasize that part of the nucleus was not seen, so there is some room to modify the model.

3. Jet Activity

3.1 JET SOURCES

The analysis of jet activity is an indispensable clue to an understanding of the physics of comets. Ground-based observations provide the greatest contributions, but the imaging experiments on the flyby missions have revealed facts and details not accessible from the ground.

In the remote images taken by the VEGA spacecraft, the coma dominated the images; however, in the near-encounter images, the extended coma disappeared in the background. The reason lies in the brightness difference between the prominent jets and the general coma. In the Giotto images, the coma background was seen, and this helped to actually identify the dark limb of the nucleus. We interpret this difference partly as a difference in sensitivity, but partly as phase angle effect. The Giotto camera observed the nucleus at a phase angle of 107°, whereas the VEGA's phase angle was always less than 90°. In case of the VEGA images, the brightest point was always in line with the nucleus; for the Giotto images, it was beyond the limb. This effect on tracking caused the Giotto camera to move away the dark part of the nucleus on the close-ups. For all observations, it was true that, as spacecraft approached the nucleus, jets were resolved into clusters of narrower jets. Hence our working hypothesis has been that all activity observed around the nucleus on the VEGA images is due to jets, either resolved or unresolved.

During the VEGA-2 encounter, large format (512 x 512 pixel size) images were transmitted back to the ground. The viewing direction of the 11 near-nucleus images covered more than a 150° range about the center. (The nucleus was overexposed on 8 of these.) This provided a good opportunity to reconstruct the spatial orientation of the jets and identify the sources on the nucleus (Sagdeev et al., 1986). It turned out that the most prominent jet sources form a long linear feature on a sphere centered on the nucleus. The width of the feature extended about 10° in longitude and 110° in latitude on the sphere in ecliptic coordinates; the subsolar point was within the feature, and all parts of the feature were closer than 30° in longitude to the subsolar point.

The small-format (128 x 128 pixel size) images transmitted during the VEGA-1 flyby do not allow full spatial jet reconstruction, as most of the image field is occupied by the nucleus itself and the jet cores are too short in the images to make unique identification. However, the general conclusions are similar to those in the VEGA-2 case. The most prominent jets were seen in the left-hand (solar) side of an image exposed 25° in longitude before the probe crossed the subsolar point, whereas all jets turned to the right after the probe passed the subsolar point 20° in longitude. The extension of the jets in latitude is uncertain, but in the far images, the opening angle of the jet cone is less than 60° relative to the solar direction.

The Giotto images provided basically two-dimensional information, since the camera viewing direction began to change only at the very end of the transmission. The observed opening angle of the jets as projected onto the imaging plane was less than 90° for the most prominent jets (Keller et al., 1987). Jets are colored and are redder than the nucleus (Thomas and Keller, 1989).

The source distribution described above certainly deviates from the activity of a homogeneous nucleus; hence, both active and inactive regions should be present on the surface. Deducing the possible active area from the overall gas production, the conclusion that about 30% to 50% of the illuminated surface is active still holds (Szegő, 1988). However, a large, extended, impervious crust is unlikely on the surface, and within the vicinity of the subsolar point, there are always active areas. This conclusion should also be examined in the context of ground-based observations. From those, it is clear that the number of prominent jets varies from none to five or six (S. Larson, private communication), and their duration is quite long in the case of P/Halley. So further information is required to model cometary surfaces, and an understanding of the rotational motion is indispensable.

3.2 INSIDE THE JETS

Before the flyby missions, in all models discussing cometary activity, it was assumed that most of dust particles leaving the surface remain intact, at least where physical size is concerned. The probability of dust-dust collision is negligibly small, and no other physical process was evident for disintegration in the vicinity of the nucleus. Nor were any experimental data available to suggest any other approach.

So it came somewhat as a surprise when both the VEGA and Giotto imaging teams pointed out that the brightness distribution along the jet cores close to the nucleus deviates from the expected $1/r$ behavior (Tóth et al., 1987; Thomas and Keller, 1987). The VEGA team, knowing exactly the spatial orientation of jets, were able to identify a 30- to 40-km range from the nucleus where the deviation is pronounced (Szegő et al., 1988) for several prominent jet features. Though unable to do spatial reconstruction, the Giotto team concluded that this deviation also occurs within the first 10 km (Thomas et al., 1988). The region in question is too small to be resolved in ground-based observations. To explain this phenomenon, it was evident that new material should appear in the field of view of the observer. Different mechanisms were suggested to provide it.

First it was pointed out that if the jet sources are extended, new material might appear due to the overlap of the jet cones associated with individual pointlike sources. Thomas et al. (1988) concluded that this effect gives the major influence on intensity profiles. This view was challenged by Szegő et al. (1988), based on the results of Huebner et al. (1988), pointing out that the geometrical overlap operates only much closer to the surface if a reasonable source extension (1.5 km) and jet opening angle (10°) are considered. Szegő et al. (1988) provided an alternative explanation based on grain fragmentation.

The physical mechanism of grain fragmentation is as follows: according to most models, the surface temperature of the active regions is not higher than 200 K. When grains leave the surface and direct heat transfer is no longer possible, their temperature almost immediately (in less than 1 sec) reaches 400 K. Due to this heat shock, the tensile strength of the grains diminishes considerably, and evaporation of the remaining volatiles decreases it still further. Thus, frequent collisions with gas molecules (10^8 to 10^9 collisions within the first 40 km) make grain disintegration likely. Acceptable parameters can be found to interpret the observations (Szegő et al., 1989).

There is another possible mechanism that may cause the observed effect: ice grain formation in flight. The dynamics of dusty gas streams has recently been reexamined by Crifo (1989). It was known that gas temperature falls quickly in the stream and, at around 10 R (where R is the radius of the nucleus), it reaches 10 K. Crifo, reanalyzing the probability of ice grain recondensation, was able to prove that at least 10% of the gas recondenses, forming clusters containing 500 to 1000 gas molecules, on the average. Grains are formed close to the nucleus (within a few kilometers) and reevaporate after a few hundred kilometers. Based on the calculation presented by Crifo (1989), we accept that ice grain formation actually takes place. Ground-based observations support this; Dollfus (1989) has pointed out that ice grain formation may explain the observed polarization of the coma within a 100-km sphere centered on the nucleus of P/Halley. The question is whether these grains are visible in the near-encounter images.

Dust grains scatter light via Mie (as opposed to Rayleigh) scattering. The geometrical cross-section and the light scattering efficiency more or less coincide for particles not smaller than 0.1 μ in diameter, which corresponds to about 10^{-16} g in mass. In the case of smaller particles, the scattering efficiency drops considerably. Water molecules are dipoles; hence the Rayleigh scattering law operates for them. However, if the particles are too small, their visibility is negligible. The probable size distribution of the ice grains and their scattering properties are currently being examined.

4. The Rotation of the Nucleus

4.1 EXPERIMENTAL DATA

The space missions to Halley have immediately revealed that it has a very irregular shape, and hence imply a complicated rotation pattern that can be described only as the rotation of an asymmetric top. The complete mathematical description of the motion of a free asymmetric top requires the knowledge of the inertial momenta Θ_i of the body, its rotational energy E, and the modulus of the total angular momentum J; or any equivalent data set. With these, the motion can completely be described in a coordinate system attached to the inertial axes of the body (a co-moving system). In this system, the motion is periodical. However, to interpret observations, the motion should be described in a coordinate system fixed in space (an inertial system), conveniently in the one attached to the angular momentum vector. In this system, however, the motion is aperiodic; strictly speaking, no point of the body returns to its previous position. This is because in the inertial system, a new period (incommensurable with the previous) appears that is characteristic of the variation of one of the Euler angles. All parameters and the initial phase of the motion should be derived from observational data, combining both ground-based and space-borne observations.

We group ground-based observations according to the observed features. The first group contains brightness measurements. If the observation time is long enough and cometary outbursts are properly treated, these brightness measurements are very reliable. Though the nucleus generally is not resolved, it is safe to assume that periodic brightness variations should be connected with the rotation. Two different periods have been reported by different groups, one close to 2.2 d, and the second close to 7.4 d. Some of the analyses recently have been strongly criticized by Belton (1989). The list of references can be found there and also in Sagdeev et al. (1989). We know only about one measurement (West and Jorgensen, 1989) in which the brightness variation of the nucleus may have been observed directly, but a brightness change identifiable with the rotation has not been obtained.

The second group contains the analysis of the jet curvature. Though it is clear that the curvature is related to the rotation, much care is needed here. The curvature depends on the escape velocity vector, radiation pressure, and instantaneous spin vector. The latter does not generally coincide with the angular momentum vector, and its position changes in time. If this variation is big during the flight time of the observed jet particles (as generally is the case for P/Halley), the derivation of the position of the instantaneous spin vector is impossible or misleading. However, if there is a dominant characteristic period of the rotation, this can be recovered from the data. No new systematic analysis has been published that we know of, but curvatures probably confirm a period near 2 days (S. Larson, private communication).

The third group is the observations of jet activity, when recurrence of certain jet patterns is searched for. The aperiodicity of the rotation of P/Halley seemingly does not exclude recurrences that occur for both dust (Larson, 1989) and gas jets (Hoban et al., 1989). Most of the published period of recurrences is about 7.4 d, but Schulz and Schlosser (1989), examining CN shell structures, reported a spin period near 7.4 d superimposed by a nutation period near 2.2 d.

The fourth group contains any other observed periodicity that may or may not be connected to the rotation, such as plasma phenomena. We do not discuss them here.

The observations made during the flyby mission are put into two groups. The first contains imaging data, and the second any other observations relevant to the rotation of the nucleus. Space observations are indispensable to an understanding of the rotation. Ground-based data can reveal periods, and in some exceptional cases, the projection of the instantaneous spin vector can be derived, but generally the amount of information is not enough to fix all the parameters of the motion.

The imaging data were provided by the experiments aboard the two VEGA and the Giotto spacecraft. As we discussed already in Section 2, only these made it possible to derive the inertial momenta of the body. Using the VEGA images, the orientation of the long axis of the body during the encounters could be deduced. As is shown by Sagdeev et al. (1989), the long axis in ecliptic coordinates pointed to $b = 15^\circ$, $l = 79^\circ$ during the VEGA-1 encounter and to $b = 9^\circ$, $l = 310^\circ$ during the VEGA-2 flyby. As the Giotto imaging experiment provided only a two-dimensional view of the nucleus, the orientation of the long axis cannot be obtained directly. The projected length of the nucleus was 14.7 km, and the angle between the Sun and the long axis was $-32^\circ \pm 10^\circ$ (Keller et al., 1987). No characteristic surface features can be identified uniquely on images taken during different encounters, at least not without making assumptions about the rotation. This is partly due to dust seen on the images, but partly to the uncharacteristic shape of the features identified.

Other experiments aboard the missions have also revealed periodic events. The best known is the Lyman-α breathing of the nucleus; this breathing exhibits a 52-h periodicity (Kaneda et al., 1986). Dust experiments, exploiting the dust velocity spread, also can reveal information concerning the rotation state of the nucleus (Pankiewicz et al., 1989). However, as these results are very much specific to P/Halley, we do not go into further details here.

4.2 THEORETICAL MODELS

During the early stages of the analysis of the rotation, many people modeled the nucleus as a symmetric top, since visual observations, within measured errors, allowed them to make the two shorter axes of the nucleus equal. However, it was overlooked that an asymmetric top also has such a rotation mode, which has no analogue in the case of a symmetric one. As Halley's nucleus is rotating in this mode, the early models are not applicable.

It is important to decide to what extent the rotation can be considered as a free motion. This is certainly an approximation, since dust and gas emission exert force and consequently torque on the body. Both Rickman (1989) and Wilhelm (1987) estimated its effect. However, based on the 13-month-long observation of Festou et al. (1986), during which no change was detected in the characteristic period, we assume that the torque can be neglected and the rotation can be considered as a free motion.

We are aware of two papers that consider the problem in its full complexity. The first has already been published, and the second is in press. Sagdeev et al. (1989) assume that $J^2 \sim 2E\Theta_3$, where **J** is the angular momentum, E is the rotational energy, Θ_i are the inertial momenta of the body, and $\Theta_3 > \Theta_2 > \Theta_1$. In this case, ω_3 is almost constant, and the equations of motion can be simplified considerably. To solve those, the following inputs were assumed:

- The major and minor dimensions of the nucleus were 16 and 7 km.
- The two characteristic periods were 2.2 d and 7.4 d.
- The long axis orientations during the VEGA-1 and VEGA-2 encounters were as cited before.
- The projected length in Giotto images was 14.7 km.
- During the Giotto encounter, b = -32° in ecliptic coordinates for the long axis orientation.

Tacitly, it was also assumed that the observed long axis was close to the appropriate inertial axis and that the internal mass distribution was homogeneous.

Watanabe (1989) solved the true set of equations of motion and he used approximations only in the last steps when that was unavoidable. His input data set was different:

- He used the ratio 16:8:7.5 for the overall dimensions, though he also considered other ratios.
- He used about 15 d for the long period.
- He used b = -17° for the Giotto orientation. The rest of the assumptions were identical to those of Sagdeev et al. (1989).

The rotation axes derived from the above calculations - within the given errors - coincide. Watanabe (1989) also investigated how the observed jet activity pattern of a 7.4-d period can be explained in his model. The important factor was the large amplitude motion of the intermediate inertial axis. It was assumed that the active areas were located at the end of the long and short axes. Though there are deviations from the observations, it is important to emphasize that a full, complex description of the rotation is needed for an understanding of the observational data.

5. Conclusions

After the successful imaging of comet P/Halley, we are sure that there is a consolidated body at the very heart of comets, the nucleus. Nuclei are probably all irregular in shape, their albedo is low (2% to 5%), and so their volume is bigger than it was thought before the flyby missions. The surface is dark reddish, and the jets are redder than the nucleus.

The nuclear surface does not exhibit small-scale horizontal variations on the images (i.e., variations close to the resolution limit). Either these do not exist or even a fairly transparent dust veil can hide them. Images revealed surface elevations, with heights on the order of 100 m and with linear extensions on the order of 1 km. Active and inactive regions are not recognizable visually. During all the three flyby missions, there were active regions close to the subsolar point, within 20° in latitude. This probably excludes the existence of large areas, many kilometers in size, of crust on the surface. We think, however, that the surface in general is fairly evolved; the identified features, protrusions are probably already depleted of volatiles. On the other hand, at jet sources, fresh, pristine material should be present; otherwise, the total activity cannot be accounted for. The variety of jets (different gas and dust) points to an inhomogeneous internal structure, such as that invoked in fractal models.

The prominent jet activity always pointed sunward. Ground-based observations have revealed recurring jet patterns. From on-board imaging data, we cannot infer whether jet sources are temporary or permanent features on the surface.

Jets leaving the surface undergo changes. Dust grains are probably disintegrating. Ice grains might be formed in the coma. All these lead to a deviation from the 1/r brightness distribution along jet cores closer than 40 km to the nucleus; then the variation becomes smoother.

Due to the irregular shape, the rotation pattern is complicated. Generally, two different time periods are exhibited in different processes; some are dominated by the first, others by the second.

It is not clear whether nongravitational forces generate negligible torque only in case of P/Halley, or if this holds in general.

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