THE SPIN AXIS POSITION OF C/1995 O1 (HALE–BOPP)

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Abstract. Monitoring of the near-nucleus activity of C/1995 O1 (Hale–Bopp) began in Teide Observatory in August 1995. During 1996 the comet was observed on 72 nights between March 26 and November 13. A permanent fan structure was observed towards the north during the whole period of observation. The position angle of the axis of this fan was measured and its variations with time were used to determine the position of the North Pole of the cometary nucleus.

Keywords: Comet Hale–Bopp (1995 O1), coma morphology, spin axis

1. Introduction

Hale–Bopp is one of the most important comets of the last few decades. It was discovered in July 1995 (Hale and Bopp, 1995) at the unprecedented distance of 7.2 AU from the sun. Its equivalent nuclear diameter has been determined to lie between 27 and 73 km (Weaver et al., 1997; Sekanina, 1997–1999). In addition, strong limits to the diameter (based on observational constraints) have been put ranging from 17 km (Schleicher et al., 1997) to 98 km (Matthews et al., 1997). The higher values would make Hale–Bopp the largest comet ever observed extensively with modern instrumentation.

The rotational state of the nucleus remains unknown, but the stability of the structures observed in the inner coma suggests a free rotation close to the lowest rotation energy state (Kidger et al., 1998; Jorda et al., 1997–1999; Licandro et al., 1998). In this scenario Hale–Bopp's rotation period is now well established to be 11.31–11.39 hours (Jorda et al., 1997–1999; Licandro et al., 1998).

Knowledge of the rotational state of a comet is crucial for the determination of the intrinsic physical properties of its nucleus and surface. In many cases, the morphological activity of a comet cannot be understood without estimates of the orientation, modulus and variability of its angular velocity vector. Given the large

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number of observations and long time-span of the coverage obtained for Hale–Bopp, we have an excellent opportunity to define the rotation mode of its nucleus.

In this paper we derive the position of the North Pole of Comet Hale–Bopp's nucleus from images obtained at Teide Observatory (OT) in 1996.

2. Observations and Reduction Procedure

Hale–Bopp has been monitored regularly at OT since August 1995 with the 82 cm IAC–80 Telescope. The comet was observed on 40 nights from March 26 to November 13 in 1996 by using a Thompson 1024 × 1024 chip and broad-band R Kron-Cousins filter. The comet was also observed on 32 nights, from 1996 July 16 to September 12, with the 51cm University of Mons Telescope at OT using an ST-8 CCD camera and broad-band R combination. Image scales are 0.435 arcsec/pixel in the IAC–80 (field $\sim$7.1 arcmin) and 0.74 arcsec/pixel in the Mons (field $\sim$3.4 arcmin).

Bias and flat-field corrections were applied to the images in the usual way. As no significant differences are observed between individual images for each night, all were recentered on the cometary nucleus and co–added in order to obtain a larger total exposure time. A Laplacian filter was applied to enhace the coma structures. For a detailed explanation of the precedure used and log of the observations see Kidger et al. (1998).

3. Coma Morphology

During 1996, a bright northern structure was present in almost all the images. It usually showed a fan shape whose position angle varied slowly westwards over the course of several months, from 20° in late March to 345° in mid November. Other straight structures (up to seven) were observed from June 1996 (see Figure 1a). The fan has some fine structure which might indicate that it was produced by more than one active region, or that there were large diurnal variation of the dust emission.

The continuous presence of the fan imposes tight constraints on the spin axis orientation. Indeed, the existence of a permanent fan can only be understood if Hale–Bopp's spin axis was almost perpendicular to the line of sight at the time. As pointed out by Sekanina (1987), the position angle (PA) of a fan axis lies close to the projected position of the nucleus spin axis. Hence, the fan observed during 1996 gives us a unique opportunity to determine the (projected) direction of Hale–Bopp's spin axis. Its variations with time will be used to infer the mean position of the North Pole assuming that variations due to precession, if they exist, are small.

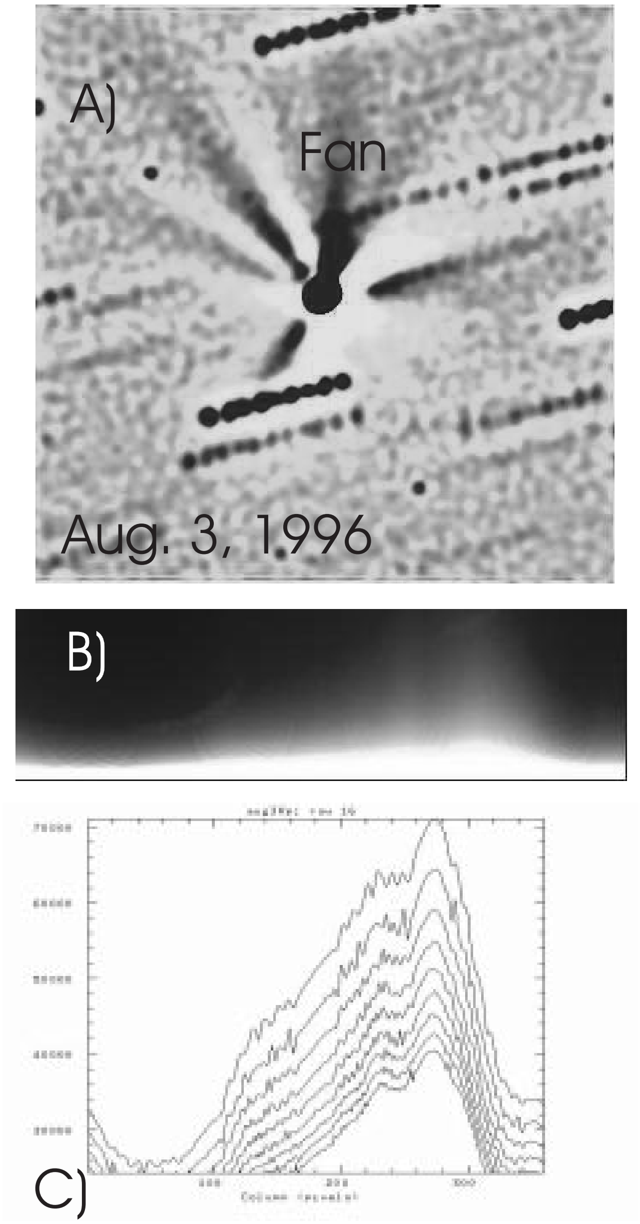

Figure 1. (A) Image of Hale–Bopp coma obtained on Aug 3, 1996 with the Mons Telescope. It was procesed with a Laplacian filter. North is up, West is right. The fan structure pointing to the North at $PA \sim 355°$ is indicated in the image. (B) The non-filtered image transformed to polar coordinates. The x-axis represents azimuthal angles (ψ), with $PA = 270 - \psi$, and the y-axis radial distances (ρ) measured in pixels. (C) Plot of the azimuthal profiles obtained from (B). Now, the x-axis indicates azimuthal angle and the y-axis intensity in ADUs. The largest peaks around $\psi = 275°$ correspond to the fan structure indicated in (A). Gaussian fits make it possible to obtain the PA of the fan from these maxima (see text for details).

4. Determination of the Spin Axis Position Angle

In order to determine the PA of the fan axis structure the unfiltered images were transformed to polar coordinates (ρ, ψ) with their origin at the coma optocenter (see Figure 1b). In the polar representation, the rows correspond to concentric circles around the center of the comet, so azimuthal profiles can be easily extracted by plotting rows. The fan (and also the other structures observed after June) appear as a vertical column in the polar representation. To determine the PA of the fan we analyzed the azimuthal profiles at radial distances from 10 to 32 pixels (Figure 1c) for all the 1996 images. The PA of the fan axis at each distance from the optocenter is assumed to be defined by the maximum of the corresponding azimuthal profile. For each curve, the maximum was found by means of a gaussian fit as it turns out that the central part of a gaussian curve provides an accurate fit to the peak of the observed fan profiles. The PA of the fan at the comet nucleus (i.e., at zero radial distance) was determined from these maxima by linear regression.

This method has allowed us to accurately determine the temporal evolution of the PA of the fan axis or, according to Sekanina (1987), the temporal evolution of the projected direction of the spin axis onto the sky plane, with errors usually smaller than one degree. We point out, however, that the asumption that the PA of the fan coincides with the projected direction of the spin axis might be just a rough approximation. For example, if the region is active only during a small fraction of the rotation period, or if it has large variation of dust release, the fan can be located at one side of the spin axis. For this analysis we will assume the simple case that both directions are equivalent.

5. Determination of the North Pole Position

Let Ω be the angular velocity vector of the nucleus. By convention, Ω defines the North Pole position. In the comet reference frame, the coordinates of Ω/Ω are determined by the Euler angles ε_1 and ε_3 (cf. Landau and Lifschitz, 1976). Expressed in the equatorial reference frame, Ω/Ω has coordinates α_p and δ_p given by

$$\begin{aligned}
\cos\delta_\mathrm{p}\ \cos\alpha_\mathrm{p} &= \sin\varepsilon_3\ \sin\varepsilon_1\\
\cos\delta_\mathrm{p}\ \sin\alpha_\mathrm{p} &= -\sin\varepsilon_3\ \cos\varepsilon_1\\
\sin\delta_\mathrm{p} &= \cos\varepsilon_3.
\end{aligned}$$

Observed from the Earth, the spin axis Ω/Ω projects onto the sky plane with position angle Π. The relationships between Π, the equatorial coordinates of the comet α and δ, and the angle subtended by Ω to the comet-Earth vector θ are

$$\sin\Pi\ \sin\theta\ =\ -\sin\varepsilon_3\ [\sin\alpha\ \sin\varepsilon_1 + \cos\alpha\cos\varepsilon_1],$$

$$\begin{aligned}\cos\Pi\ \sin\theta &= -\sin\delta\ \sin\varepsilon_3\,[\cos\alpha\ \sin\varepsilon_1 - \cos\varepsilon_1\ \sin\alpha] + \cos\delta\ \cos\varepsilon_3,\\ \cos\theta &= \cos\delta\ \sin\varepsilon_3\ [\cos\alpha\ \ \sin\varepsilon_1 - \sin\alpha\ \ \cos\varepsilon_1] + \sin\delta\ \ \cos\varepsilon_3.\end{aligned}$$

Thus, knowledge of the variation of Π with time (i.e., with α and δ) makes it possible to derive the Euler angles ε_1 and ε_3.

We have applied Powell's method (Press et al., 1986) to our series of PAs in order to find the values of ε_1 and ε_3 that best reproduce the observations. It is necessary, however, to keep in mind that we do *not* measure the position angle Π of the spin axis, but rather the position angle of the fan axis (PA). As PA may take on one of the two values Π or $\Pi + 180°$ (depending on whether θ or $\theta + 180°$ is employed in the above equations), two sets of Euler angles will result from the analysis. This indetermination is solved by considering the sense of rotation of the curved jets observed during April 1997, because it determines the correct value of θ (and hence whether PA $= \Pi$ or PA $= \Pi + 180°$). The counterclockwise rotation of the jets (Licandro et al., 1998) implies that the North Pole was pointing approximately to the Earth at this time (i.e., $\theta \simeq 0°$ instead of $\theta \simeq 180°$).

The best fit to the temporal evolution of PA is obtained with $\varepsilon_1 = 5°$ and $\varepsilon_3 = 140°$. This is shown in Figure 2, where the observed PAs of the spin axis and the best fit are plotted. Accordingly, the equatorial coordinates of the North Pole turn out to be $\alpha_{\mathrm{p}} = 275° \pm 5°$, $\delta_{\mathrm{p}} = -50° \pm 5°$. The obliquity of the spin axis with respect to the orbital plane is $\omega = 83°$.

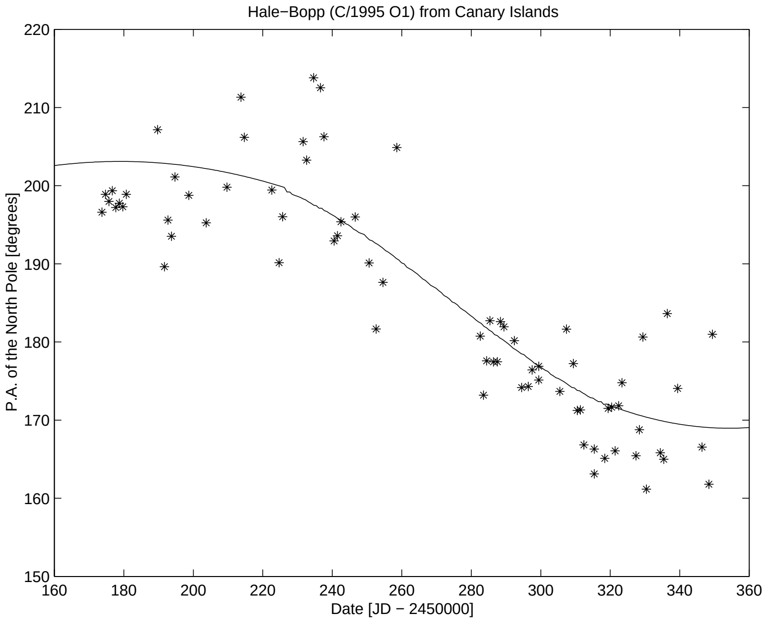

Figure 2. Plot of the position angle of the North Pole (Π) vs time. Full line indicates the best fit to our observations.

6. Discussion

The method we employ to determine the pole position of Hale–Bopp's nucleus strongly depends on two factors: the nucleus should be a free rotator close to the lowest rotational energy state; and the correct identification of the fan structure.

A strong precession of the spin axis would imply large variations of the position of the North Pole, thus preventing the use of the method described above. However, the stability of the structures observed in the inner coma during 1996 and the beginning of 1997 favoures a free rotation close to the lowest rotation energy state (Kidger et al., 1998; Jorda et al., 1997–1999; Licandro et al., 1998), and so the angle between the spin axis and the angular momentum remains small.

Regarding the correct identification of the fan, the daily frequency of our observations over several months and the homogeneity of the data have allowed us to monitor the evolution of the fan (see Kidger et al., 1998) even when several other straight jets appeared in the inner coma after June 1996. As an alternative approach, Sekanina and Boehnhardt (1997–1999) modelled all the observed structures on CCD images obtained between May 11 and November 2, 1996, by assuming no diurnal variations of the dust production of the active regions, and obtained pole positions rather distant from ours (see Figure 3 of Sekanina and Boehnhardt, 1997–1999). In their model, the straight jets are interpreted as boundaries of fan-shaped structures. Each active region produces a pair of jets symmetrically distributed with respect to the spin axis. To obtain this distribution, they identify the dark straight structure observed at PA$\sim$ 40° in Figure 1a as the actual fan.

Although we did not consider the straight jets in our analysis, thus running the risk of incorrectly identifying the fan, the jets observed at the beginning of 1997 lend support to our pole determination. Jorda et al. (1997–1999) obtained a very similar pole solution ($\alpha_{\mathrm{p}} = 275°$, $\delta_{\mathrm{p}} = -57°$) by modelling the jets observed between February and March 1997. Sekanina (1998) came to a similar result modelling the diurnal evolution of a bright jet observed on February 28, 1997 ($\alpha_{\mathrm{p}} = 257°$, $\delta_{\mathrm{p}} = -61°$). Using numerical simulations to reproduce the jets observed in 1996 and 1997, Samarashina et al. (1997–1999) also report a very similar pole position ($\alpha_{\mathrm{p}} = 270°$, $\delta_{\mathrm{p}} = -43°$) for the case of a nucleus in a complex rotational state with small precessional angle (corresponding to our most likely solution). Allowing the dust from the active regions to be ejected during a limited period of time between sunrise and sunset in their model, Sekanina and Boehnhardt (1997–1999) obtained another solution which is closer to ours for the 1996 images ($\alpha_{\mathrm{p}} = 240°$, $\delta_{\mathrm{p}} = -57°$).

Finally, the curved jets observed in 1995 (see Kidger et al., 1996, 1998) and in April 1997 are also consistent with a spin direction that lies close to the line of sight, while the fan and straight jets observed during 1996 and the last part of 1997 are consistent with a spin direction nearly perpendicular to the line of sight. In both cases, this is what our pole position predicts. Although the complete explanation of the observed jets will certainlly require careful numerical treatments, the qualitative picture presented in this paper gives additional support to our pole determination.

7. Conclusions

A permanent fan structure was observed in Hale–Bopp on 72 nights from 1996 March 26 to November 13, in CCD images obtained at Teide Observatory. By measuring the PA of this fan, the direction of the spin axis projected onto the sky plane was determined. Considering the sense of rotation of the jet structures observed during April 1997, we have determined the position of the North Pole of the cometary nucleus to be $\alpha_{\rm p} = 275°$ and $\delta_{\rm p} = -50°$. The position of the spin axis relative to the Earth, as deduced from our pole determination, is compatible with the structures observed in 1995, 1996, and 1997.

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