Astron. Astrophys. 349, 985–995 (1999)

ASTRONOMY AND ASTROPHYSICS

Adaptive optics observations of the innermost coma of C/1995 O1*

Are there a"Hale" and a"Bopp" in comet Hale-Bopp?

F. Marchis[1,2], **H. Boehnhardt**[1], **O.R. Hainaut**[1], **and D. Le Mignant**[1]

[1] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[2] Institut d'Astrophysique spatiale, Université Paris Sud, Orsay, France

Received 1 February 1999 / Accepted 9 July 1999

Abstract. Comet C/1995 O1 Hale-Bopp was observed with the adaptive optics system ADONIS on the ESO 3.6 m telescope at La Silla, Chile, through the broadband J, H, K, SK (Short K) filters on 6 November 1997 and 15 January 1998. After processing of the images using different restoration techniques, the maximum brightness in the coma appeared as a double peak. The separation between the two components was 0.23″ in November 1997 and 0.36″ in January 1998. Furthermore, broad jet features were traced in our images of the inner coma. While lightshift effects could be excluded, dust knots in near-nucleus jets could explain the observed double peak. Nevertheless, an attractive scenario is that the comet actually has a double nucleus, which could even be gravitationally bound. The presence of jets with opposite curvatures, as observed in Hale-Bopp's coma on 22 January 1998 at optical wavelengths, provides additional support for the binary-nucleus interpretation. Indeed such features are difficult to explain by a single rotating nucleus, but they would be easily understood if two nuclei were involved. The pros and cons of the interpretations are discussed, but no final conclusion on the validity of either of them is possible on the basis of the observations available to our group.

Key words: comets: general – comets: individual: C/1995 O1 Hale-Bopp

1. Looking into the near-nucleus region of a comet

Since the resolution of ground-based telescopes is normally limited by seeing, our knowledge of the near-nucleus region of comets is based on observations of a handful of objects, namely, the spacecraft data from the Halley fly-bys, observations with the Hubble Space Telescope HST (for instance comets Faye, Borrelly, Hale-Bopp) and observations of comets that had a close approach to Earth (C/1996 B2 Hyakutake, see West et al., 1996). The scientific interest in such observations is multifold: direct measurement of the nucleus signal (for size estimates); a study of the collimation region of jets emanating from active areas on the nucleus; a detection of debris from the nucleus (like in Hyakutake) which could be used to estimate the total mass loss; assessment of the tensile strength (from nucleus splitting) and of the mass and bulk density of the central body. However, high resolution observations are either difficult or very expensive or both, as they rely on a comet's close approach to Earth, or on the availability of a dedicated spacecraft or the HST.

In this paper, we present results from an alternative approach using high resolution near-infrared (NIR) imaging performed with an adaptive optics system, which corrects in real time for effects of atmospheric turbulence.

The object of our study was comet Hale-Bopp (C/1995 O1), which offered an extraordinary insight into the evolution of cometary activity with heliocentric distance. The goal of our programme was to perform high spatial resolution imaging of the innermost coma of the comet to ascertain the morphology of dust jets close to the nucleus and possibly to detect the nucleus with the aim to determine its dimensions. We also wished to search for mini-comets (nucleus debris) in the circumnuclear region.

Hereafter, we outline the observing and data processing techniques applied in order to obtain the highest possible spatial resolution near the nucleus and we describe the results of our analysis.

After the description of the observing techniques in Sect. 2, we present the data processing of the NIR images. Sect. 3 also deals with the different restoration methods used to achieve the best resolution in the comet images and discusses the possibility for an artifact to explain the observed double peak. We describe the morphology of the inner coma and of the jets in Sect. 4 and finally discuss three different scenarios to explain the double peak in Sect. 5.

2. Observations

The observations of comet Hale-Bopp were performed with the ADONIS adaptive optics (AO) system (Beuzit et al., 1997) at the ESO-3.6 m telescope in La Silla, Chile. ADONIS is the first AO system available to the astronomical community since April

Send offprint requests to: F. Marchis

* based on observations (DDTC time) collected at the European Southern Observatory, La Silla, Chile.

Correspondence to: fmarchis@eso.org

Table 1. Condition of the comet Hale-Bopp observations.

Date (UT)	Observing Time (UT)	Weather	Airmass	seeing	comments
6/11/97	05:15–09:30	clear	1.7–1.1	$\simeq$1.0″[a]	rapid seeing variation
15/1/98	03:10–03:43	clear	1.2	$\simeq$0.6″	stable seeing
11/3/98	00:00–04:00	cloudy	1.2–1.6	-	observation impossible
4/4/98	00:45–02:11	clear & windy	1.4–1.9	0.8″	WFS analysis impossible
5/5/1998	23:00–00:30	clear	1.5–2.1	1.0″	WFS analysis impossible

[a] Measured by the atmospheric seeing monitor (DIMM) at La Silla

Table 2. Observing geometry, quality of observations and double peak geometry in the inner coma of comet Hale-Bopp (PA = position angle counted North over East).

Date	6 November 1997	15 January 1998
Sun Distance (AU)	3.31	4.07
Earth Distance (AU)	3.27	3.92
PA Radius vector (°)	288	29
PA Velocity vector (°)	198	185
Phase angle (°)	17	14
Filters	J, H, K, SK	SK
PSF star	HD 65748 (V=10.5, F0)	HD67196 (V=11, F2)
Strehl Ratio	4%	7%
FWHM (″)	0.35	0.18
Peaks separation (″)	0.23	0.36
Projected distance (km)	550	1025
PA secondary (°)	102±4	78±5
Intensity ratio (post processing)	0.37±0.08	0.56±0.04

1995. For the AO corrections the wavefront distortions of the incoming visible light are measured using one of the two 7×7 microlens array Shack-Hartmann wavefront sensors at a sampling rate up to 200 Hz. The analysis of the wavefront and the correction to apply to it (done via a 52 actuators deformable mirror and a tip-tilt mirror on the instrumental bench) are computed using a modal optimization with digital filter gain adjustment scheme (Gendron and Lena, 1995). Two NIR cameras permit imaging in the 1–5 μm range. For our observations of comet Hale-Bopp in the 1–2.4 μm range, we used the SHARP II+ camera (equipped with a 256×256 NICMOS3 detector) with a pixel resolution of 0.05″(Hofmann et al., 1995).

The observations were successfully performed on 6 November 1997 and on 15 January 1998; further attempts, made on 11 March, 4 April and 3 May 1998 were unsuccessful. Information on the atmospheric conditions at the time of observation (seeing, airmass, weather) can be found in Table 1. Table 2 lists the observing geometry for the comet together with the measurements from our successful observations (for a description, see Sects. 3 and 4).

In November 1997, we took images in J, H, SK, K broad band filters (see Table 3 for filter characteristics). In January 1998, because of the limited observing time available, only one data set was obtained through the SK filter.

The wavefront sensing (WFS) for the adaptive optics correction was performed at optical wavelengths (R band) using the comet itself, i.e., the central brightness maximum in the cometary coma, as a reference. We used the Electron Bombarded CCD (EBCCD) wavefront sensor at a sampling frequency of 25 Hz. Using the WFS flux, the magnitude of this peak was estimated to be around 11.5 mag (in November 1997), its width (less than 2″) did not compromise the accurate performance of the wavefront analysis.

Table 3. Characteristics of SHARP II+ broad band filters.

Filter	Central Wavelength (μm)	Bandwidth (μm)	Transmission
J	1.253	0.296	$\approx 75\%$
H	1.643	0.353	$\approx 77\%$ - Peak 82%
K	2.177	0.378	$\approx 72\%$ - Peak 76%
SK	2.154	0.323	$\approx 85\%$ - Peak 91%

With the adaptive correction being activated, we took several sets of images of the inner coma region of comet Hale-Bopp through a single filter band. The individual integration time per exposure was 60 s. The images were stored as data cubes, each of them containing 5 or 10 exposures. After each cube sequence, we changed the filter and repeated the series. During the observation, the comet was tracked at its predicted motion rate applying appropriate telescope offsets of about 1″ every minute. As the WFS image analyser was locked on the comet itself, the ADONIS tip-tilt mirror was able to fine correct for the comet's motion. After performing several sets of on-object exposures we stopped the adaptive correction loop, moved the telescope about 1° in the sunward direction and started an exposure of

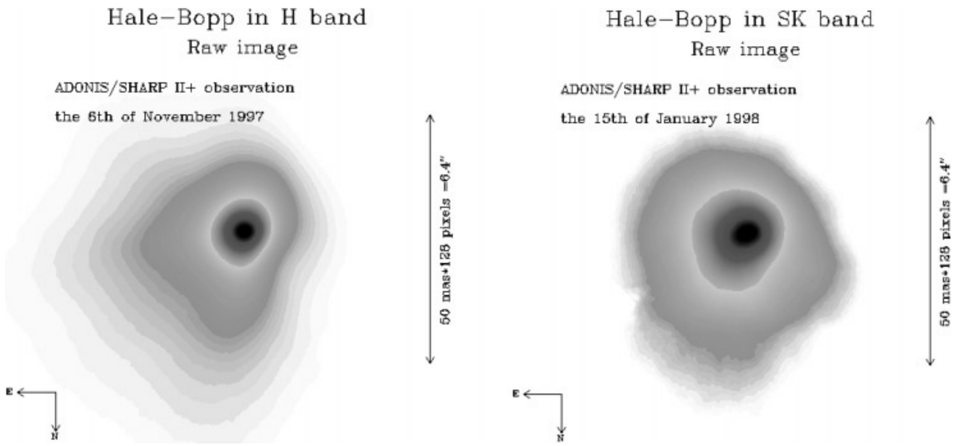

Fig. 1. Example images of comet Hale-Bopp after the basic data reduction and before deconvolution. In the H filter image of 6 November 1997 (*left*) jets are clearly visible as isophot extensions towards the east in the coma. In the SK image of 15 January 1998 (*right*) jets are less discernible. However, the near-nucleus coma shows an oval shape.

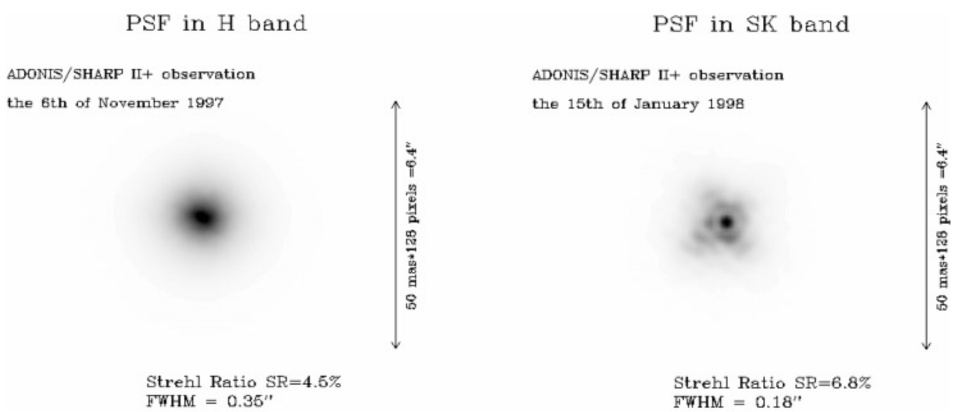

Fig. 2. Example images of the PSF stars used for the deconvolution methods: HD65748 through the H filter on 6 November 1997 (*left*) and HD67196 through the SK filter on 15 January 1998 (*right*). Due to the more favorable seeing conditions and a better alignment of the ADONIS instrument the PSF star image of January 1998 is of better quality, i.e. the Airy disc is visible and the full width at half maximum (FWHM) is smaller. The PSF star images shown here were used for the deconvolution methods described in Sect. 3.2.

the sky with the same filter setup. Thanks to the stability of the sky (variability in SK was typically 0.4% in 5 min) it was not necessary to take frequent sky measurements.

A star close to the comet (less than 3°) listed in Table 2, chosen for its similar spectral type and magnitude, was observed in the same passbands in order to estimate the quality of the adaptive optics correction and as a reference for the instrument's point spread function (PSF) in the deconvolution process of the images (see Sect. 3.2). To properly average atmospheric seeing variations, the total integration time of the PSF star must be at least equal to the integration time of the object frames, i.e. in our case 60 s.

Unfortunately, our follow-up observations of the comet later in 1998 remained unsuccessful. Attempts were made on 11 March, 4+15 April and 3 May 1998. Apart from adverse atmospheric conditions, the ADONIS wavefront sensing suffered from the fainter brightness of the comet (namely the reduced flux from the coma centre which became weaker than 13–14 mag). Therefore the surrounding coma caused a "confusion" to the WFS which did not lock on the coma peak for the tip-tilt corrections, but, instead, oscillated back and forth between the coma centre and another point in the coma some arcsec away. Furthermore, we could not find a reference star brighter than 13 mag in R and close enough to the comet ($< 30''$) that could be used as a reference for the adaptive optics system. The infrared images obtained were thus useless for our analysis.

3. Data processing

The data processing consisted of two steps: the basic data reduction and the image restoration.

3.1. Basic data reduction

For each frame we applied procedures for sky subtraction, flat-field correction and bad pixel removal, using ESO's infrared data reduction package **eclipse** (Devillard, 1997). Each data cube was transformed into a single frame by the `shift-and-add` process which aligned the images to the same point (the brightness maximum in the coma) and added them up. The image quality of the observations was determined by calculating the Strehl ratio of the PSF star as well as its full width at half maximum (FWHM) (see Table 2). With mediocre outside atmospheric seeing in November 1997, we reached a resolution of 0.35″ in our ADONIS images. In January 1998, the quality of observations was excellent thanks to very good and stable seeing, so the final image had a resolution of about 0.18″.

Examples of the comet and PSF star images resulting from the basic data processing are presented in Figs. 1 and 2.

3.2. Image restoration

The correction of the AO system is not perfect and some residual aberrations (like halo, trefoil) remain (see the image of the PSF

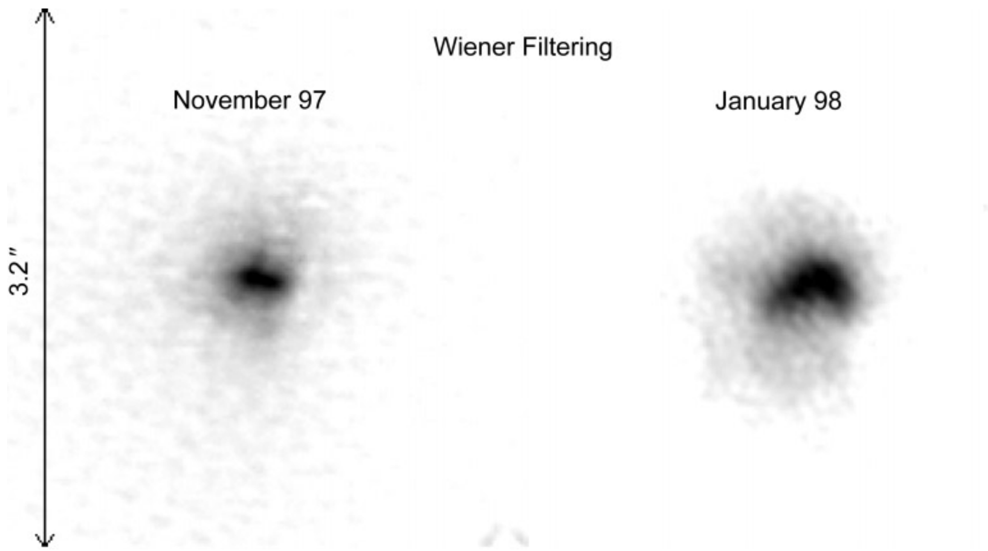

Fig. 3. Result images of the inner coma of comet Hale-Bopp using Wiener filtering with an estimated value of white noise.

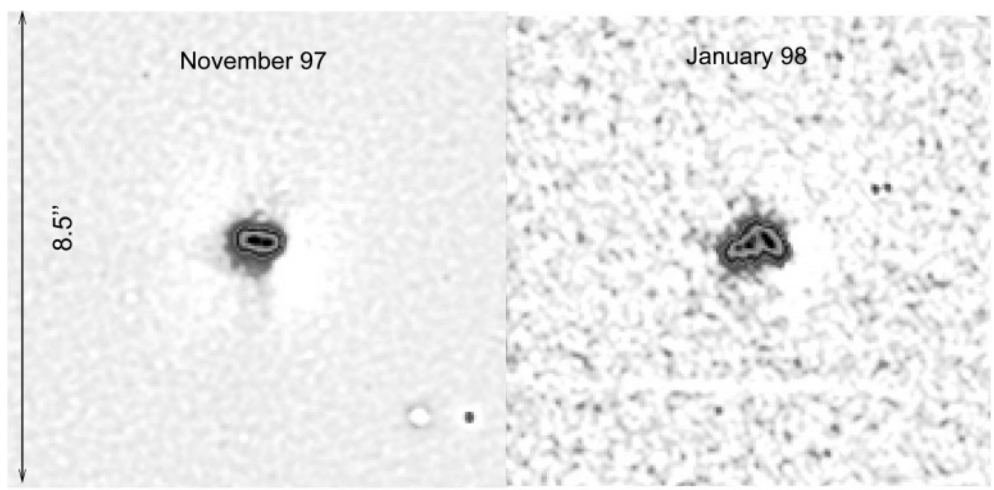

Fig. 4. Result images of the inner coma of comet Hale-Bopp using wavelet filtering

star in Fig. 2). The signal-to-noise ratios (S/N) of the PSF stars were very high, so the application of a deconvolution method is expected to improve sharpness and resolution of the images. We measured the correction quality of the AO system by computing the Strehl ratio (SR) on the star image. The SR quantifies the quality of the observed PSF image which is degraded by atmospheric turbulences and optic instruments deficiencies in comparison to the theoretical PSF given by the entrance pupil. A SR ratio of 100% means a perfect correction. ADONIS AO system gives SR up to 45% in K band. A non-corrected image will have a typical SR lower than 1% in K band. The SR also degrades with increasing zenith distance which accounts for the low SR values for our Hale-Bopp images since the comet was measured between 25 to 55° zenith distance during our observations.

For the image sharpening, we applied both iterative and non-iterative method. They are described below.

The **Wiener filtering** method (Press et al., 1986) is a non-iterative deconvolution procedure. We used the simplest option to obtain a restored image assuming a *white noise* in the signal and dividing the signal by this noise before inversion. The advantage of this method is the calculation speed. However, a part of the high frequency signal is lost in the final image (for the result see Fig. 3).

The images were also processed with a **wavelet filtering** technique (Stark, 1992) in its MIDAS version, which isolates a range of spatial frequencies from the data. For our comet images, only the spatial frequencies from 0.1 to 0.2″ were of interest, since we wanted to resolve the innermost coma. The advantage of the wavelet technique is that it does not use a PSF star as a reference, and therefore it cannot introduce artifacts through this additional PSF image, it is just a *filtering* of the image. Figure 4 shows a wavelet filtered image of the comet.

The iterative methods are more sophisticated and take more computer time, but give better results than the non-iterative ones. Two well-known methods were used in their IDL (Interactive Data Language) implementation.

The **Richardson-Lucy method (MRL)** (Lucy, 1974; Richardson, 1972) is based on the likelihood principle and the **Maximum Entropy Method (MEM)** (see Hollis et al., 1992) follows the Bayesian approach of the deconvolution problem.

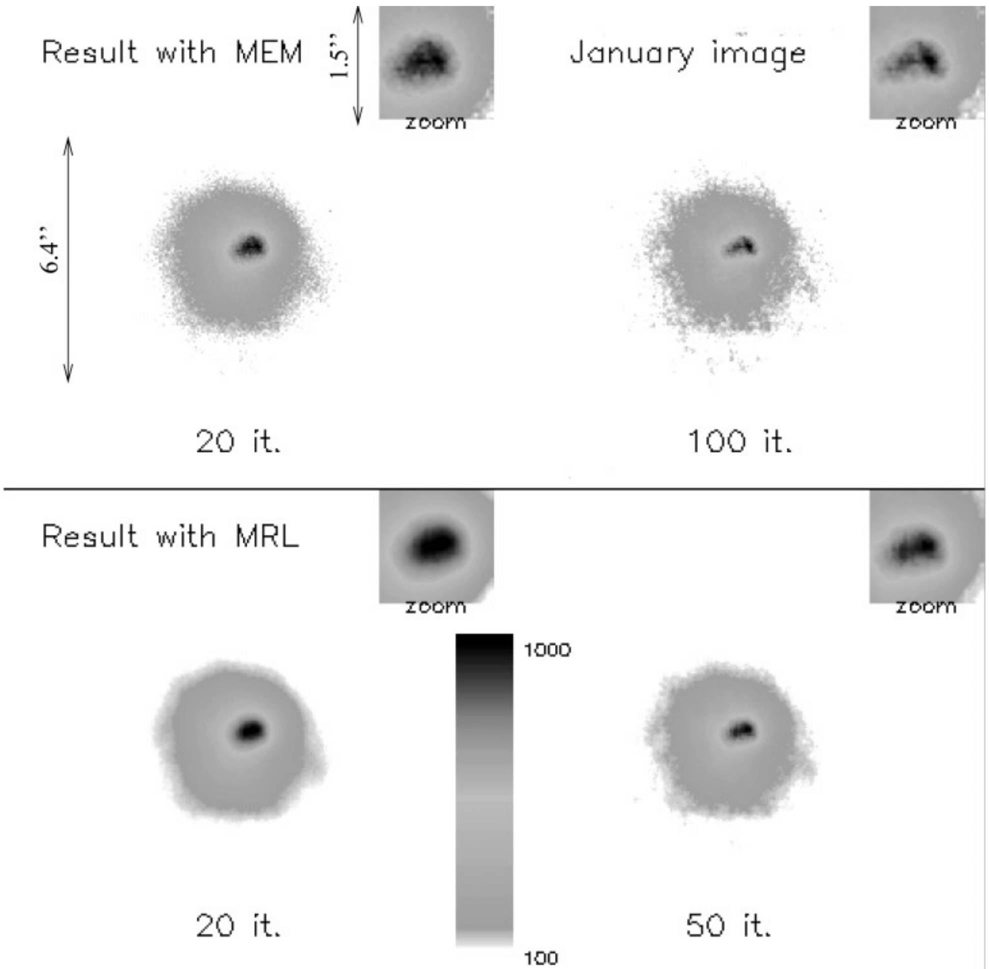

Fig. 5. Result images of the inner coma of comet Hale-Bopp on 15 January 1997 using MEM (*up*) and MRL (*down*) deconvolution. The double peak in the coma center is clearly apparent with both deconvolution methods after 30 iterations.

Both methods use PSF information from the star image for deconvolution and they typically need several 10 to 100 iteration steps to get convergence in the final result. Increasing the number of iterations does not yield better results in the restored images (there is even a higher chance of creating artifacts). We used an accelerated version of the MRL method (see Adorf et al., 1992). As expected for this extended object, the MEM gives better results. Examples of the deconvolution results using both methods for the November 1997 and January 1998 images of comet Hale-Bopp are shown in Fig. 5.

3.3. *Discussion of image deconvolution methods*

The different restoration techniques lead to similar result for our Hale-Bopp images, which are described in Sect. 4. The most striking result is that the central brightness peak in the coma appears double. In this section, we will discuss the reality of this feature from the technical point of view, its physical interpretation is discussed in Sect. 4.

During the November 1997 run, because of some technical problems, we got only one series of PSF star exposures in the J, H, K, SK bands. The first comet image was taken about 2 h earlier than the PSF star. The time delay between object and PSF measurement is important, since – and this is relevant for the image deconvolution – one cannot assume that the same atmospheric conditions apply to the PSF star as to the object after a certain period of time (airmass and seeing having changed as shown in Table 1). Although all images were processed in the same way, we concentrated in our analysis on the deconvolution results which used comet exposures taken within 30 min from those of the PSF star. In our data set the H band images (see Fig. 1) fulfil this requirement and gave thus the best results for the image sharpening. In January 1998, the PSF star images were taken a few minutes before the comet images (in the respective passband).

All the deconvolution processes gave basically the same result in the restored image, namely, a double brightness peak in the coma (see Figs. 3 to 5).

The double peak – and also the general coma geometry – was the same in the images taken through different broadband filters, excluding the possibility of an artifact caused by the filters. More generally, the reference stars (and all the other objects observed with ADONIS during our observing nights) do not present this double structure, excluding an artifact caused by the optics. Moreover, such a double peak feature has never been reported as an ADONIS artifact (Le Mignant et al., 1999)

We also got this double peak in the coma by deconvolving the comet exposures with a PSF star image which was rotated by

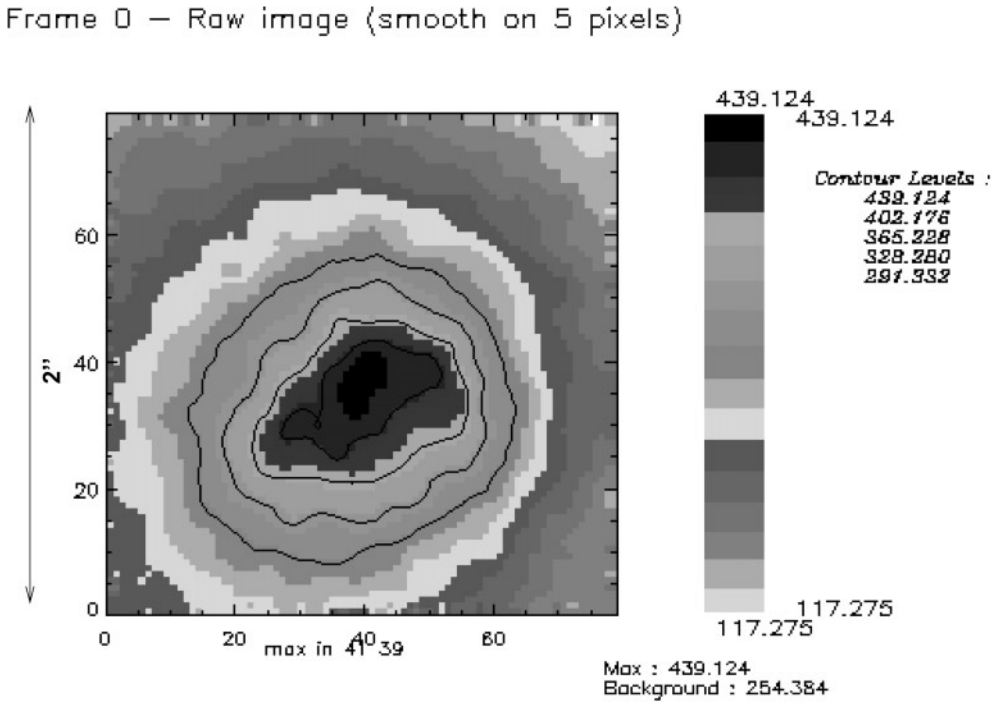

Fig. 6. Close view of the very inner coma of comet Hale-Bopp from 60 sec SK filter image of 15 January 1998. Basic data reduction, but no deconvolution processing is applied. The central brightness maximum in the coma has an oval halo and is almost resolved in its double peak seen after deconvolution.

90° and with an artificial PSF (same Strehl ratio, same FWHM). These experiments were performed in order to check that the double peak is not introduced by the PSF itself. The deconvolution with the 90° rotated PSF would rotate its artifact by 90° and the artificial PSF does not include the high frequency features of the PSF exposures that could have caused the artifact. In all cases, the geometry and structure of the innermost coma region remained unaffected and thus we consider it as real and intrinsic to the object. In the case of the January 1998 images this structure can even be suspected from some raw frames (see Fig. 6).

We also speculated that this double peak feature might be due to an unexplained ADONIS behaviour. However, it was not the first time that ADONIS was used for comet observations: comet Hyakutake was successfully observed by Marco et al. (1998) and also comet Hale-Bopp was imaged with ADONIS before (see Hale-Bopp summary by R. West on ESO web site, `http://www.hq.eso.org`).

During our observations of comet Hale-Bopp, we carefully monitored the behaviour of the WFS, but we could not detect any special or unusual behaviour of this unit (for instance, oscillations of the tip-tilt corrections as seen in our later attempts in April 98). Because of the separation of the two peaks, which was clearly below the pixel size of the wavefront sensor CCD (0.8″) and the seeing resolution, the coma centre gave a good reference for the wavefront sensing in the visible wavelength range and - at least for the November 1997 and January 1998 observations - the contrast between the centre and the surrounding coma was high enough to close the adaptive correction loop on the central brightness peak.

Therefore, we are confident that the double peaks observed are real and are not due to artifacts in the optomechanics of the instrument nor due to data processing.

4. The description of the inner coma

After careful image deconvolution of our data (described in Sect. 3), we obtained an effective spatial resolution of the result frames of about 0.2″ in November 1997 and about 0.1″ in January 1998. Evidently, the appearance of the inner coma (the innermost 6″ around the central brightness maximum) was different in those two months. This is easily recognisable from the isophote patterns in our images (see Figs. 7 and 8).

While on 6 November 1997 the inner coma isophotes extended widest into the northeastern quadrant with a somewhat shorter "bump" towards the southeast and to the west, they are more circular on 15 January 1998. The asymmetries in November 1997 are related to the presence of jets and fans originating from the nucleus. At least 3 – and possibly 5 – jet and fan structures are anticipated in the position angle (PA, counted North over East) range 0–145° (the jets are between PA = 0–30, 75–95, 115–135, 240–260° and a fan of complex substructure between PA= 165–230°; the reality of these coma structures is also supported by the results from computer processing of our ADONIS images using adaptive Laplace filtering as described by Boehnhardt and Birkle (1994). In general, the jets were very broad and pointed radially away from the brightness peak in the coma. In January 1998 clear signatures of jets/fans are much less apparent (wide fan structures at PA = 0–40 and 90–130°), although the isophotes appeared to be elongated in the same PA range as in November 1997.

In the deconvolved (and also in some of the raw) ADONIS images the central coma peak is resolved into two maxima of

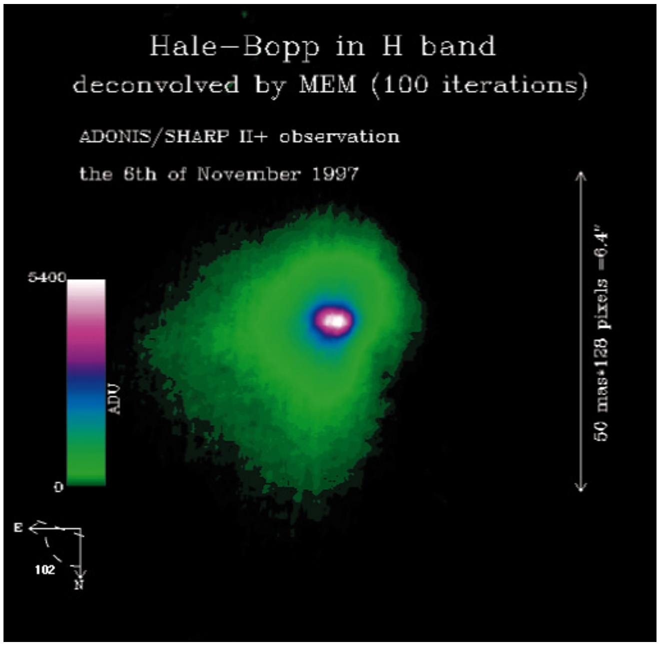

Fig. 7. Close view of the very inner coma of comet Hale-Bopp on 6 November 1997 after MEM deconvolution

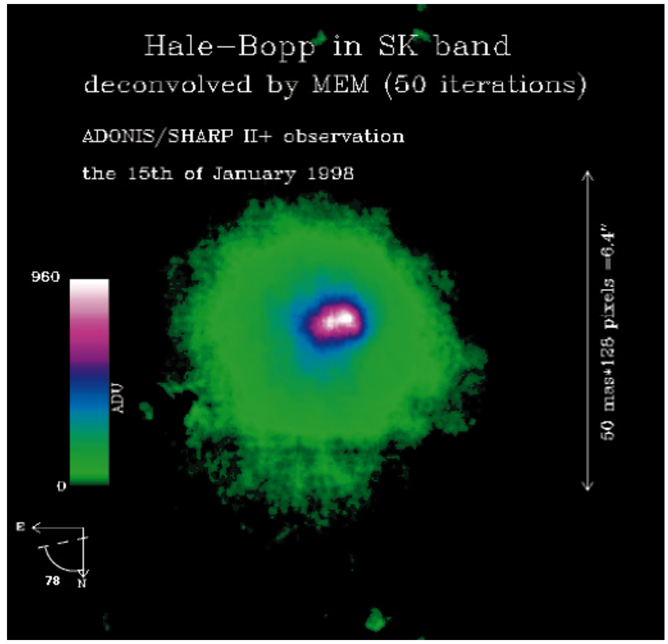

Fig. 8. Close view of the very inner coma of comet Hale-Bopp on 15 January 1998 after MEM deconvolution

different brightness (see Figs. 7 and 8). The reality of this feature was discussed in the previous section.

The PAs and separations of the secondary with respect to the primary maximum (i.e. the brighter one) are listed in Table 2. Within our measurement uncertainty (see Table 2) the relative orientation of the two features did not change during the observing windows of 4 h in November 1997 and 0.5 h in January 1998, respectively. A third much weaker maximum is marginally detected to the northwest of and very close (less than 0.1″) to the primary in January 1998. This detection, however, is uncertain.

The separation between the peaks is larger than the intrinsic resolution limit of the images (after restoration), they are present in the filters J, H, K and SK (when used for the observations). We consider both maxima as real and intrinsic to the comet. Since the J,H,K and SK passbands do not contain prominent gas emissions, we attribute the observed features in the coma to solid cometary material, i.e. to dust and/or the nucleus.

5. Double peak in the coma

5.1. Possible interpretations

Three potential scenarios are considered for the double brightness peak in the coma of comet Hale-Bopp: a lightshift effect, near-nucleus footprints of coma jets and multiple nuclei (or nucleus fragments). In all three scenarios the brighter peak is attributed to the main nucleus of the comet, although strictly speaking this is an arbitrary assumption.

Lightshift effects in the coma. Based on unexplained, but systematic residuals between the measured and calculated positions of comets, it was speculated that the centre of gravity and the centre of light do not coincide, at least in bright comets. 1P/Halley displayed this effect prominently (see Röser et al., 1986, for its description and critical assessment of this so–called lightshift effect). The centre of light would be offset due to dust, which is predominantly emitted into the sunward hemisphere and may thus have a high spatial density within a few hundred to thousand kilometers from the nucleus. A secondary brightness peak separated from the primary one (which should contain the nucleus) could appear in the coma or, in extreme cases, the nucleus may be hidden in dust and only the peak from the sunward dust region may be detectable. Due to insufficient spatial resolution of normal ground-based telescopes, the effective brightness peak in the coma may be offset radially. This effect is modelled in cometary orbit calculations by a radial sunward offset between the centre of light and the centre of gravity in the coma. This offset is dependent on the distance of the comet from the Sun and should be largest when the comet is at, or close to, perihelion (although it is modulated by the Earth distance to the comet for the angular offset value measured). However, despite of all efforts made, this effect was so far never directly observed. It is inferred from cometary orbit calculations only and in the case of 1P/Halley even the images from the GIOTTO and VEGA spacecraft did not confirm the existence of the offsets between the nucleus and the light centre in the coma (see Röser et al., 1986, for an interesting alternative explanation of this effect).

Comparison with our imaging results of comet Hale-Bopp led us to the following conclusions: in principle, the two brightness peaks in our Hale-Bopp images could represent the centre of gravity and the centre of light and a radial offset towards the Sun direction would be expected between both of them. Due to the increased distances of the comet from the Sun and Earth and due to the reduced phase angle of the comet, the offset should be larger in November 1997 than in January 1998.

While in November 1997 the offset between the two brightness peaks in Hale-Bopp's coma was approximately radial in Sun direction (the primary peak would represent the centre of gravity, the secondary one the lightshift peak), it was clearly non-radial in January 1998. Moreover, the distance between both peaks increased significantly from November 1997 to January 1998, which is in contradiction to the model prediction. Hence, our conclusion is that the lightshift effect as modelled in cometary orbit calculations does not match our observations of comet Hale-Bopp. To our knowledge, such effect was never reported for this comet neither by other observations nor by modelling.

Near-nucleus footprints of coma jets. This scenario is somehow similar to the lightshift explanation: at least one of the brightness peaks represents a dense and well confined dust cloud (knot) produced by an active region on the rotating nucleus (for instance, produced by brief ejections of dust, or puffs, see Sekanina and Boehnhardt, 1999). The other peak could host the nucleus, or else it is another jet cloud. The knots could either be real clouds of spatially confined assemblages of dust grains in the jets or could be due to projection effects (although the latter option requires rather extreme and next to impossible viewing geometries of strongly curved coma jets very close to the nucleus). Such jet knots were observed in the coma of comet Hale-Bopp during late January to March 1997 when it changed its appearance from a steady straight-jet (porcupine-like) pattern into a mixture of straight jets and curved jet envelopes. The latter can be considered as clear indications for the presence of active regions on the rotating nucleus (with the rotation period determined accurately from these dust envelopes; for details, see Jewitt, 1998, and references therein). Since the activity of the nucleus with its dust emitting regions is mostly confined to the sunward hemisphere, this scenario would require the brightness peaks to be on the sunward side of the nucleus, but not necessarily placed along the radius vector. In principle, the distance between the jet knots should decrease with increasing distance from Sun and Earth (although this effect may be insignificant for our observing dates of comet Hale-Bopp and could be counteracted by changes due the expansion of the knots and due to projection effects). Experience from the observations of jet knots and envelopes in the coma of comet Hale-Bopp near perihelion would argue for the presence of more than one dust envelope and/or for the alignment of a straight jet with knot(s).

Since a priori we do not know which one of the brightness peaks in our Hale-Bopp images could host the nucleus, the orientation of the two peaks is not very diagnostic for this scenario. Again, the November 1997 image seems to fit better: peak separation almost in the Sun direction, quasi alignment with a broad, straight jet emission cone (for instance, the one with PA = 115–135), with only a single knot (or two if one considers both peaks as dust clouds) observed, but no correlation with a jet envelope is found. In January 1998 the peaks are further away from the radial direction towards the Sun and, moreover, no alignment with a straight jet nor with a curved jet envelope in the coma can be found. However, the increased separation of two peaks could be explained by larger distances of the jet footprints in January 1998 due to a different rotation phase and/or by different foreshortening due to projection. Some nucleus rotation models have been published (see for example Sekanina, 1998; Licandro et al., 1998), however they cannot be used for reliable predictions of the jet patterns at our observing dates (because of insufficient information on the rotation axis position with time and because of the time dependent behaviour of active regions - switch on/off, extinction of existing regions, outburst of new ones). Therefore, one cannot predict the PAs of dust jets ejected from active regions for our observing dates which could be used to verify whether the peaks could be produced by one or two of these emission areas.

Split cometary nuclei: More than 30 split comets are known from the literature (for reviews, see Sekanina, 1982, 1997). For these cases, two or more fragments are normally detected of which one (in all analysed cases the brightest one) seems to be the primary nucleus. It is this subnucleus which typically survives the comet splitting while the other secondary subnuclei were only of temporary nature and always disappeared (i.e., they are no longer detectable) within weeks to years after the splitting. While the primary peak can typically be considered as the host of the nucleus, there are indications that at least in some cases, secondaries may have been dust clouds only (see Sekanina, 1982). All known split comets were "open" systems, i.e. the fragments were not gravitationally bound and departed from each other over time. At least in an early phase after separation the mother-daughter chain is approximately spread out along the radial direction away from the Sun. The fragments have their own comae which can vary in intensity over time. In many, but not all cases the fragmentation process itself is found to be associated with a brightness outburst of the comet.

Based on this description, one could consider the two brightness peaks in the innermost coma of Hale-Bopp as two subnuclei of the comet. Their projected distance at the comet was about 550 km on 6 November 1997 and 1025 km on 15 January 1998, respectively. The intensity ratio (measured within an aperture of $0.2''$ around the peak position) was between 0.37 and 0.56 (see Table 2), although these values may be influenced by the image processing technique (i.e. most likely over-estimated). The two subnuclei of comet Hale-Bopp would be closer than ever observed before in a split comet. The question whether the objects are bound or unbound cannot be answered from our observations. As a matter of fact, their distance increased with time, although very little. However, if projection effects are not too large, the fragments could even be at a distance to be considered as gravitationally bound: assuming a 50 km diameter nucleus (Lamy and Weaver, 1999) and a bulk density of 0.2–0.5 g/cm^3, the radius of the gravitational domain of the comet Hale-Bopp is about 920–1320 km in November 1997 and 1120–1620 km in January 1998 (see in Sekanina, 1999, Eqs. (1) and (2)). The measured separations of the subnuclei can be used to derive very approximate values for the revolution period assuming that the satellite nucleus was in a circular orbit around the primary one: 20–30 days for 6 November 1997 and 50–80 days for 15 January 1998. Therefore, in this scenario one would not expect to see a motion of the peaks during our observing windows, which is in agreement with what we found. More recent estimates of the nucleus density (Rickman H., private communication to the referee) put it in the 0.5–1.2 g/cm^3 range. Using these values, the radius of the gravitation domain of the nucleus is increased by a factor ∼2.5, further supporting the possibility of the secondary nucleus being a bound object. Unfortunately, we could not confirm the presence of the two coma peaks and their relative motion by additional observations (see Sects. 2 and 3.3). Also three HST images of the comet taken on 27 August 1997, 11 November 1997 and 10 February 1998 did not show duplicity according to the conclusion of Weaver et al. (1999). Furthermore, a prominent outburst of comet Hale-Bopp which could have indicated the splitting of the comet is not reported.

In conclusion, the dataset presented in this paper does not allow us to unequivocally determine whether Hale-Bopp had or still has a double nucleus.

5.2. Additional evidence for a double nucleus

Comet Hale-Bopp showed pronounced and stable coma jets when it was far from the Sun pre-perihelion (for an explanation, see Sekanina and Boehnhardt, 1999) and time-variable shell and jet knots close to perihelion (for a review of the nucleus rotation state, see Jewitt, 1998). The observed structures in our images within 3″ from the coma centre do not correlate with features in the more distant coma regions; in particular, there is no obvious link between the double peak centre and the coma jets.

The breakup scenario is controversial since it is not supported by more independent observations. If the subnuclei were longlived and unbound, they would have been detected at larger separations later. As this is not the case, it implies that one of the subnuclei did not survive for long, or that they are bound.

The confirmation of the satellite scenario requires high resolution imaging and becomes more and more difficult from the ground (as described in Sect. 2). The HST imaging on 27 August 1997, 11 November 1997 and 19 February 1998 (Weaver et al., 1999) does not give immediate evidence for a double nucleus in comet Hale-Bopp. It is noteworthy that the second HST observation happened just 5 days after our first ADONIS detection of the double peak structure in the coma centre. The HST investigators attribute a secondary peak in a jet region seen in processed images of 11 February 1998 to a not further specified “temporal variation”. Their analysis of the coma is based on STIS acquisition images for spectroscopy which were processed by means of the radial renormalization method using azimutally (averaged) profiles of the images. This technique enhances the broader coma feature. For instance, the image of Fig. 1 in Weaver et al. (1999) shows two jets and a fan structure. On the other side, the ADONIS image processing aimed at enhancement of small and faint structures in the coma. It resulted not only in the detection of the double nucleus, but also revealed the presence of several (more than 2) jets on the ADONIS images that were obtained only 5 days before the HST images. These jets appear as assymetries in the isophot profiles, and were further confirmed by an adaptive Laplacien filtering of the images.

The possible discrepancy of the HST and ADONIS images could potentially be explained by the movement of the nuclei and by activity changes on the time-scale of a few days, but it may also need a critical reassessment of the image processing methods which seem to aim for coma features of different scale-length and sensitivity level (with advantages and disadvantages on both sides). In this context, we refer also to the work of Sekanina (1999), who reported the detection of one or more satellites near the comet's nucleus on the HST images from 1996 by applying a deconvolution technique different from ours and the one used by Weaver et al. (1999).

On 30 September 1996, during the commissionning of PUEO, another adaptive optics system mounted on the Canada-France Hawaii telescope (CFHT) at Mauna Kea, Hawaii, comet Hale-Bopp was one of the targets chosen to test the capabilities of this system. Images have been processed in a similar way as ours (see the images on the PUEO web site, Rigaut, 1996). Besides the straight jets (Boehnhardt et al., 1999), a double peak (separation of 0.15″) was found in the coma centre (after image deconvolution). The projected distance of the two maxima was 340 km. If interpreted as a double nuclei, the PUEO observations are also consistent with a bound satellite (300 km separation would be well inside the gravitational domain of the primary nucleus of about 50 km in diameter). It is interesting to note that the position of this secondary nucleus is roughly consistent with those derived by Sekanina (1999) for the 23 September and 11 October HST images (position angle of about 10°, 0 and 55° respectively). The separation, however, is observed to be about twice as large as at the CFHT than with HST.

Finally, we would like to mention results from optical imaging of comet Hale-Bopp taken on 22 January 1998 with the DFOSC instrument at the DANISH 1.5 m, telescope at La Silla (see Fig. 9). Just 7 days after our last successful ADONIS observations of this comet, the coma exhibited a rather complex appearance of jets, fans and clouds of dust while in the ADONIS images of 15 January 1998 the coma isophotes were remarkably round. In particular two phenomena were not seen before in this comet and could become important for the scenario of mini-comets or companions in the neighboundhood of the nucleus of this comet: the presence of jets with opposite curvatures and the appearance of an isolated dust cloud about 200 000 km away from the coma centre (see Fig. 9). The latter phenomenon suggest unusual activity by the nucleus (a major puff from an active region) but could also indicate the desintegration of a major piece of cometary matter. The opposite curvature of the coma jets is most intriguing, because it is hard to understand in the framework of a single nucleus in a simple rotation state: either this body underwent a complex precession motion (not detected near perihelion) or the nucleus was not single. In this context we would like to refer also to the work of Sekanina (1998) where he concludes the presence of two nuclei based upon a model analysis of a system of two spiralling halos in the coma of comet Hale-Bopp.

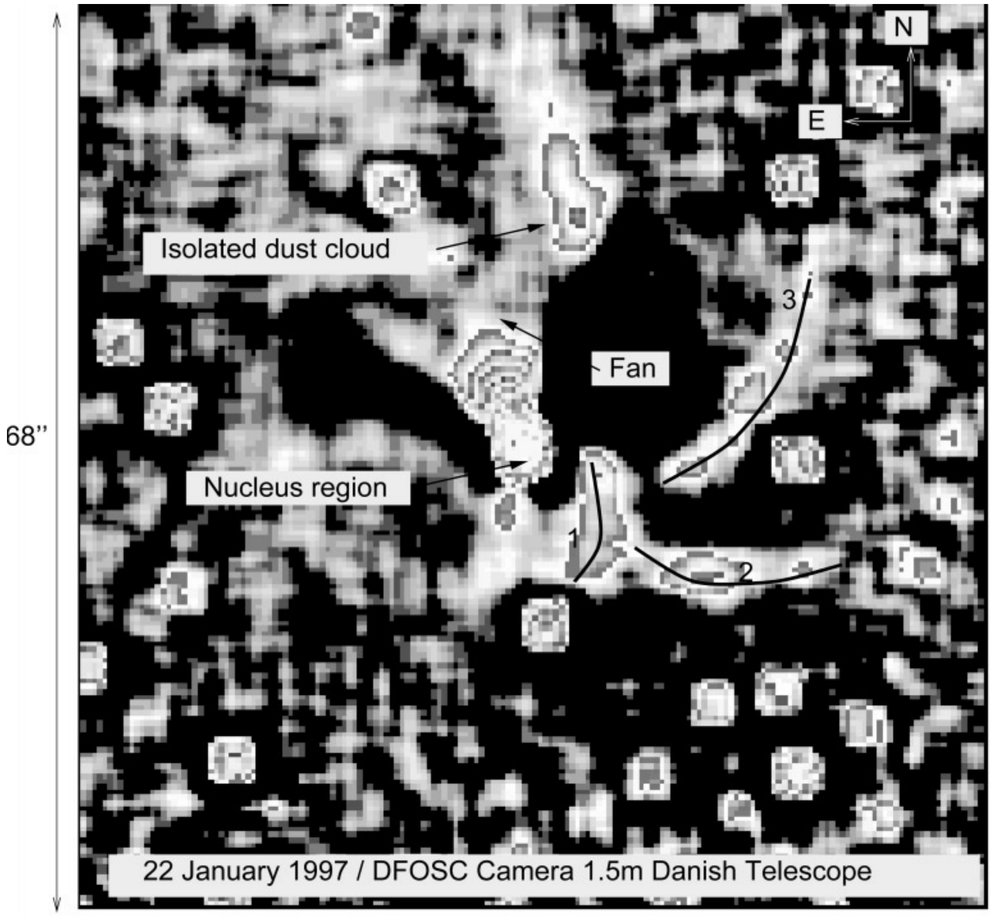

Fig. 9. Processed CCD image of the overall coma of comet Hale-Bopp on 22 January 1998. The original image was taken with the DFOSC instrument in the R filterband at the Danish 1.5 m telescope in La Silla. For the enhancement of inherent jet structures in the coma adaptive Laplace filtering (see Boehnhardt and Birkle, 1994, and references therein) was applied. North is up and east to the right, the field of view is 68×68″. Various coma features are indicated by arrows in the image. Three jets (indicates by numbers 1, 2, 3 and with their main axis drawn in a line) can be seen in the western coma hemisphere. Jets 2 and 3 show the same curvature, while Jet 1 displays an opposite one.

6. Conclusion

High-resolution near-infrared imaging with the adaptive optics system ADONIS mounted on the ESO–La Silla 3.6m telescope was used to inspect the innermost coma of comet Hale-Bopp. While jet features were very broad and pointed almost radially away from the coma centre, a narrow double peak was found at the brightness maximum. Careful analysis of the data convinced us of the reality of this feature. The known observational facts clearly rule out lightshift effects as an explanation for this finding, but scenarios involving near-nucleus footprints of jets and split subnuclei seem to be possible. The discussion of the observational facts does not permit the conclusion of the most likely explanation.

With regard to additional observations from our and other groups, the attractive scenario of a double nucleus imaging seems to be the most likely. Combining the various detections of the secondary peak near the nucleus (which cover more than 1.5 years) one could start simulating potential orbit solutions for a bound double nucleus in comet Hale-Bopp. The fragments found in our and other data have one feature in common: their projected distances are close enough to allow an interpretation as bound objects. If one would be able to determine an orbit for such objects, one could hope to obtain for the first time ever the mass of a comet without any assumptions.

Acknowledgements. We are very grateful to J.L. Beuzit and D. Mouillet, from Canada France Hawaii Telescope (Hawaii) and Laboratoire d'Astrophysique de l'Observatoire de Grenoble (France), who allowed us to use part of their observing time for the January 1998 imaging of comet Hale-Bopp. We also thank our A&A referee J. Crovisier and our internal "auditor" Z. Sekanina for their very helpful comments.

References

Adorf H.M., Hook R.N., Lucy L.B., Murtagh F.D., 1992, In: Grosbol P., Ruijsscher R. (eds.) Data Analysis Workshop, ESO conference and workshop proceedings 41, p. 99
Beuzit J.L., Demailly L., Gendron E., et al., 1997, Experimental Astronomy 7, 285
Boehnhardt H., Birkle K., 1994, A&AS 107, 101
Boehnhardt H., Birkle K., Fiedler A., et al., 1999, Earth Moon and Planets. in press
Devillard N., 1997, The Messenger 87, 119
Gendron E., Lena P., 1995, A&AS 111, 153
Hofmann R., Brandl B., Eckart A., et al., 1995, Proc. SPIE 2475, 192
Hollis J.M., Dorband J.E., Yusef-Zadeh F., 1992, ApJ 386, 293
Jewitt D., 1998, Earth Moon and Planets. in press
Lamy,P., Weaver H., 1999, Earth Moon and Planets. in press
Le Mignant D., Marchis F., Bonaccini D., et al., 1999, In: Bonaccini D. (ed.) ESO-OSA Topical Meeting on Astronomy with

Adaptive Optics. Present Results and Future Programs. ESO conference and workshop proceedings 56, p. 287

Licandro J., Bellot Rubio L.R., Boehnhardt, et al., 1998, ApJ 501, L221

Lucy L.B., 1974, AJ 79, 745

Marco O., Encrenaz T., Gendron E., 1998, Planet Space Sci. 46, 547

Press W., Flannery B., Teukolsky S., Vetterling W.T., 1986, Numerical recipes: The Art of Scientific Computing. Cambridge University Press, p. 417

Richardson W.H., 1972, Optical Society of America Journal 62, 55

Rigaut F., 1996, (http://hplyot.obspm.fr/pueo/best_pictures.html)

Röser S., Bastian U., Birkle K., Klare G., 1986, In: Battrick B., Rolfe E.J., Reinhard R. (eds.) Proc. 20th ESLAB Symposium on the Exploration of Halley's Comet. Heidelberg, 27–31 October 1986; ESA SP-250, Noordwijk, Vol. 3, p. 283

Sekanina Z., 1982, In: Wilkening L. (ed.) Comets. Tucson, AZ, University of Arizona Press, p. 251

Sekanina Z., 1997, A&A 318, L5

Sekanina Z., 1998, ApJ 509, L133

Sekanina Z., 1999, Earth Moon and Planets. in press

Sekanina Z., Boehnhardt H., 1999, Earth Moon and Planets. in press

Stark J., 1992, Ph.D. Thesis, Observatoire de la Cote d'Azur

Weaver H., Feldman P., A'Hearn M., et al., 1999, Icarus, submitted

West R.M., Hainaut O., Scotti J.V., et al., 1996, IAU Circ. 6343, 1