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Observations of Three Stellar Occultations by Comet Hale–Bopp

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Abstract On June 12 1996 UT, three 11–12 R magnitude stars were occulted by comet Hale–Bopp. The passage of these stars through the cometary atmosphere was monitored at the Observatorio do Pico dos Dias (Brazil) using a 0.6 m telescope. We detected an absorption of starlight by the comet dust implying in a drop of $(6 \pm 1) \times 10^{-2}$ magnitude of occulted star XPM 152-0898466 at a minimum distance of $(4.3 \pm 0.2) \times 10^4$ km from the central condensation. This result, combined with magnitude variations of other stars, suggests the detection of a jet in the coma. From our measurement of extinction, we infer that the opacity of the nucleus surface was $\tau \sim 3$. The mean geometric albedo p of dust grains is $(4.5 \pm 0.7) \times 10^{-3}$. This low albedo may suggest a difference in the grain population associated to coma and jets.

1 Introduction

The comet C/1995 O1 (Hale–Bopp) was discovered when it was a 7.15 AU from the Sun on 23 July 1995, 21 months before the perihelion, and there was a brightness uncommon for comets at this distance. Later observations showed that the comet Hale–Bopp was at the

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time of its discovery possibly in an eruptive period covered by an explosive volatilization of CO deposits, similar to those shown by the comet 29P/Schwassmann-Wachmann-I (Sekanina 1996), causing a jump in brightness. Owing to its great brightness and its relatively short distance from the Earth, 1.3 AU on April 1st, 1997, extensive observations of this object were made in different spectral bands.

From these observations it was found that the comet Hale–Bopp is the most productive in terms of dust and gas, ever observed. Its gas and dust production rates are respectively 20 and 100 times greater than those of Halley (Schleicher et al. 1997).

The nucleus of Hale–Bopp was invisible due to the abundant presence of coma. Several techniques were used to determine the diameter of the nucleus. Weaver and Lamy (1997), Sekanina (1998) and Weaver et al. (1997) calculated a range between 40 and 80 km for the nuclear diameter by subtracting a modeled distribution of the coma from Hubble Space Telescope images.

Given the uniqueness of this object, the planetary sciences group of the Observatrio Nacional (Brazil) undertook a program of photometric observations of this object between 1995 and 1996. This period was characterized by the transition between the increase in the formation of radial structures near the nucleus to spiral jets (Schleicher et al. 2004) and a series of outbursts observed between September and November 1996 (Yan et al. 1999). On Jun 12, 1996 UT, three star of R magnitudes between 11 and 12 were occulted by coma of Hale–Bopp (see Fig. 1).

Data obtained from stellar occultations can be used in the study of the physical properties of cometary dust. In this method, the magnitude of a star is measured as the comet moves ahead on the line of sight of the observer. The extinction of the magnitude then provides a direct measure of the opacity of the coma region crossed by the star's light (a lower limit would be the absence of extinction). This allows us to infer the optical depth τ, the albedo of dust grains and its rate of emission (Combes et al. 1983; Lecacheux et al. 1984).

In this context, on October 5, 1996, the coma of comet Hale–Bopp occulted the star PPM 200723, while the object was 2.83 AU from the Sun (Fernández et al. 1999). This star

Fig. 1 Track of the comet (*circle*) relative to stars S1 (*square*), S2 (*diamond*) and S3 (*cross*). The center of the diagram is the equatorial coordinates of the comet Hale–Bopp in the mean time of our observational session (06:09–12/06/1996 UT). The minimum angular distances between the optocenter of comet and the stars were equal to 18.5 arcsec for S1 and 46.1 arcsec for S2 (05:44) and 16.4 arcsec to S3 (7:12). V is the comet's projected orbital velocity
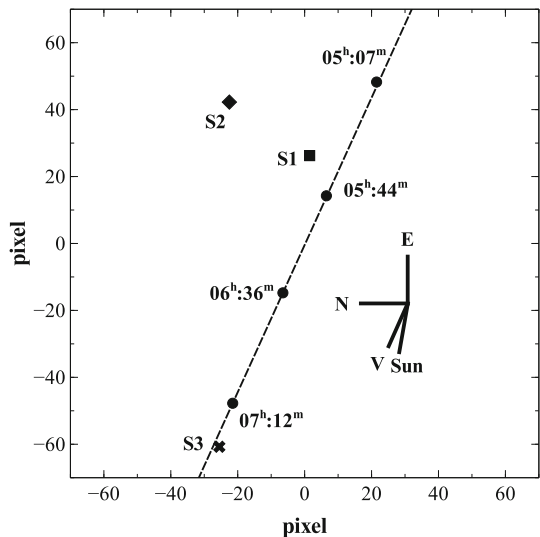
was observed in three strings, generating three light curves. One of these light curves suggested the detection of an occultation, which was observed by weak cirrus. These data were collected when the objects were at 25 degrees to the horizon. The collected data suggest an optical depth ≥ 1 to optocenter distances ρ between 20–70 km from the nucleus, which was assumed spherical. The dependence of the opacity of the coma on distance ρ was more intense than expected to the force-free, radial flow 100 km from the nucleus. Assuming that the coma dust originated from a point in the center of the nucleus and coma profile was higher than ρ^{-2}, the upper limit of the nuclear radius was estimated at 30 km.

The analyzed string did not reveal the same structures at 100 km from the nucleus, which were suggested by low resolution images (700 km/pixel) obtained a few moments before the occultation. This could be derived from the space orientation of the string that crossed the region of acceleration of dust grains and/or the existence of a diversity in the azimuthal variation of coma between its inner and outer regions.

Unlike the occultation recorded in October 1996, our observations were not specifically designed for this purpose. The goal of our observational program was to determine the rotational state of the comet analyzing brightness variations of coma with time. In the observations of 12 June 1996 UT, when the object was 4.11 AU from the Sun, we obtained 18 CCD images of the comet with a telescope of 0.6 m for about 4 h. We found that 12 images had records of occultations three stars with V-band magnitudes between 11 and 12 (see Table 1). Analyzing the seeing over the observational period, we concluded that the observations were made in a photometric night. The observations occurred when the objects were between 75 and 50 degrees of elevation.

The aim of this article is to discuss the results obtained from our observations of these events, and their implications for the identification of structures in the coma and the physical characteristics of dust grains.

2 Observation and Reduction

On Jun 12, 1996, the comet Hale–Bopp crossed a dense stellar field and its coma occulted three stars listed on XPM Catalog of positions and proper motion (see Fedorov et al. 2011). Their characteristics are presented in Table 1. The term "Objetc" is the name of occultations stars in this work. RA and Dec are the J2000.0 equatorial coordinates and V is the magnitude in a near-Johnson V-band, with an error of 0.1–0.2 mag. None of the three stars are classified as variable according to The International Variable Star Index (http://www.aavso.org/vsx/index.php) of American Association of Variable Star Observers. The photometric observations reported here were performed at the Observatrio do Pico dos Dias (OPD, Brazil) using a 0.6 m telescope. The circumstances concerning the taking of images

Table 1 Characteristics of occulted stars in the XPM catalogue

Object	RA (J2000)	DEC (J2000)	V[a] ($\pm$0.1–0.2)
S1	19:17:59.969	−13:42:43.60	12.5
S2	19:18:01.165	−13:42:20.23	12.3
S3	19:17:53.786	−13:42:16.39	11.3

[a] Photometric magnitude in optical V-band

and geometric aspects of the comet in the solar system are summarized in Table 2. In the table, "Elev" is the angle between the object and the OPD's horizon, r and Δ are the heliocentric and geocentric distance respectively and α is the phase angle.

All the observations were made using a EEV-385 $\times$ 576 CCD in R band of Johnson-Cousins system with focal-plane reducing optics, giving a field of view of $6.6' \times 9.9'$ and yielding an image scale of 1.05 arcsec/pixel. The exposure time was 45 s.

The stability of the observational session was evaluated by a nonparametric Kruskal-Wallis H-test. The seeing of a unsaturated star, present in the field during the occultation of the three stars, was measured and the twelve estimates were separated into two groups of six estimates. Each group corresponds to occultation phase of stars S1 (XPM 152-0898466), S2 (XPM 152-0898537) and S3 (XPM 152-0898150), such that the group I (images 1 to 6), is associated with occultation of stars 1 and 2, and group II (images 7 to 12) correspond to occultation of star 3. The test showed that the distributions are indistinguishable at a $\sim 95\%$ or higher in confidence level. This result implies that the seeing remained almost constant throughout the observation period, with an mean full width half maximum equal to $2.6 \pm 0.3 \ (1\sigma)$ arcsec.

All frames were debiased and flat-fielded using dome flats. We used the IRAF/NOAO DAOPHOT package to compute the instrumental magnitudes of its stars and comet.

To measure small changes in the magnitude of occulted stars, it was necessary to subtract the contribution from the sky and the coma of Hale–Bopp (see Figs. 2, 3). To remove these, we established the subtraction of a median image at the images in which the occultations were recorded (e.g. Lacerda and Jewitt 2012). Initially, we aligned the 12 images using as a reference the optocenter of the comet. The median images of coma were created using a set of six images, distinguished according to the same criteria used to define the quality of the night. Each median coma image was then subtracted from frames that recorded the occultation of stars S1, S2 and S3. Artifacts of imperfect subtraction coma may have been generated in the images due to seeing variations, problems with the telescope tracking system and/or imperfect alignment between the optocenters of the comet in the images.

We used circular aperture photometry to obtain the instrumental magnitudes of the stars S1, S2 and S3 in the images corresponding to the occultation period and those where there was no occultation. To measure the luminous flux, we use a aperture radius of 3 arcsec, corresponding to the mean seeing. After subtraction of the median images, the sky background is mostly canceled, with a slight variation of stochastic nature. This could suggest that the subtraction procedure of sky could have been unnecessary. However, this subtraction was intended to remove presumably minimum residual artifacts. The instrumental magnitudes were calibrated using absolute photometry. Three standard stars (PG1323-085B, 109 537 and 113 221) from Landolt (1992) were observed in an interval of

Table 2 Characteristics of comet Hale–Bopp on 1996 June 12

Time (UT)	RA (J2000)	Dec (J2000)	Elev[a] (°)	r[b] (AU)	Δ[c] (AU)	α[d] (°)
05:44	19:17:57.92	−13:42:57.4	75.7	4.118	3.198	6.809

[a] Object's elevation

[b] Heliocentric distance
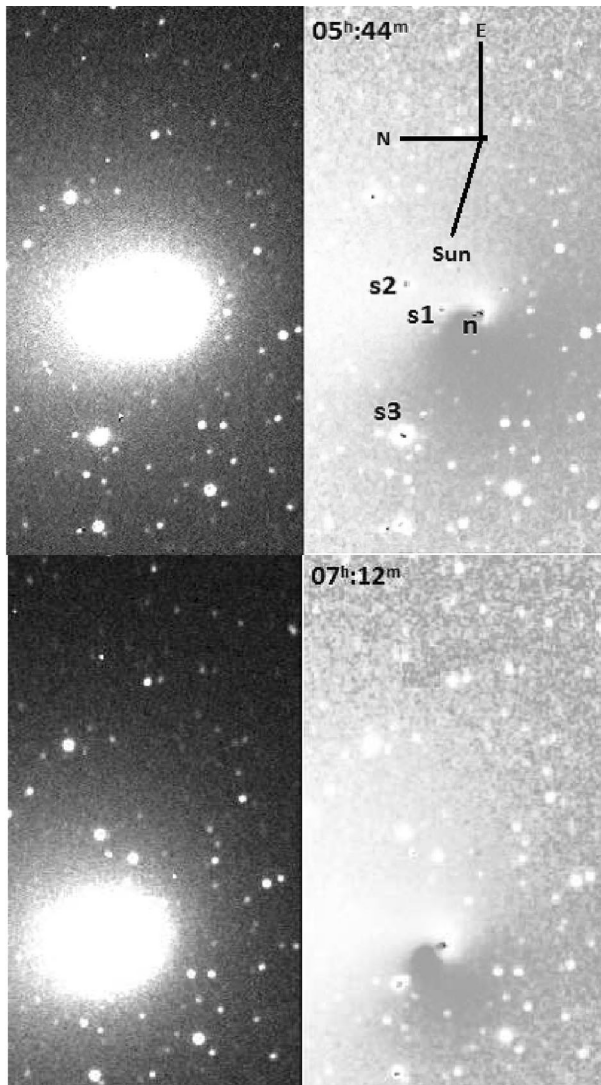
[c] Geocentric distance

[d] Phase angle

Fig. 2 CCD images of Hale–Bopp comet at 05:44 and 07:12 of 12/06/1996 UT. The field of view of all images is 6.6 × 9.9 arcmin. The images are aligned using the stars as reference. The occulted stars and the optocenter of the comet are defined by s1, s2, s3 and n. The *left images* in the upper and lower frames are the sum of three images of the comet, obtained sequentially to increase the SNR of any structures in the coma. The *right images* in the upper and lower frames are the result of dividing the previous images by the canonical profile $1/\rho$ (see Samarasinha et al. 2013)

airmasses X compatible with those presented by the comet. With this procedure, we determined the magnitude zero point and the first order atmospheric extinction coefficient. By applying this correction, the calibrated R-band magnitudes presented an error $\lesssim 0.01$ mag.
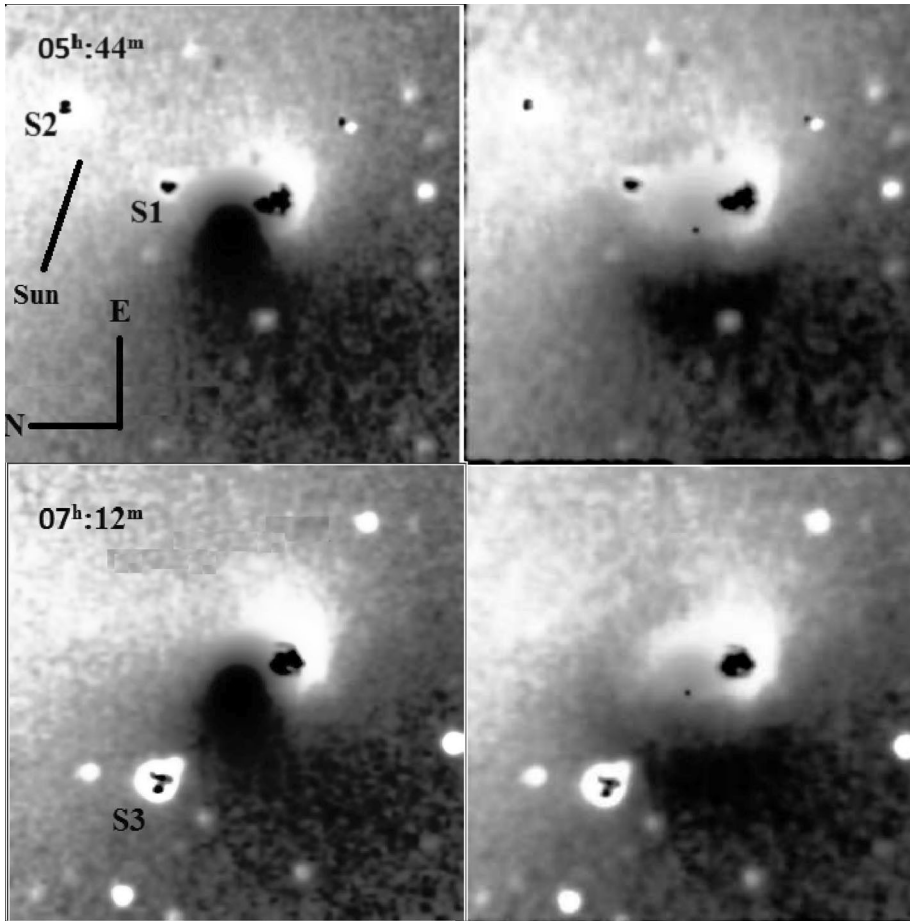
Fig. 3 Inner coma region of two images at 05:44 and 07:12 of 12/06/1996 UT. The *left images* are enhanced using division by a $1/\rho$ coma profile. The images on the right were generated by dividing an mean azimuthal profile. *Each panel* is approximately 240,000 km or 100 arcsec across with the nucleus located at the center. The bright feature in the upper quadrant is attributed to a spiral jet emitted from the nucleus. The discrepancy between the optocenter and the starting position of jet can be associated to an improper alignment between images which together generate the processed images above

For each object, there are 12 measures of magnitude, grouped in sets of three measures to construct a mean magnitude (see Table 3; Fig. 4). This grouping is justified, because these images were taken in sequence, and the time interval between three consecutive data points is equal to the time of download of the images. An analysis of this last table shows that the standard deviation of magnitudes σ is generally in the order of the error associated with the individual measurement. This reinforces the idea of the stability of the observational session. In Sect. 3, we use the mean magnitudes for obtaining the coma opacity.

Table 3 Mean R magnitudes of occulted stars on 1996 June 12

Time (UT)	S1	S2	S3
05:07	11.840 ± 0.005	11.943 ± 0.007	11.159 ± 0.001
05:44	11.846 ± 0.003	11.946 ± 0.003	11.145 ± 0.001
06:36	11.777 ± 0.003	11.881 ± 0.002	11.158 ± 0.003
07:12	11.800 ± 0.006	11.900 ± 0.008	11.147 ± 0.004

Each magnitude in the table is the mean of three consecutive measurements. The mean magnitude error is equal to one standard deviation
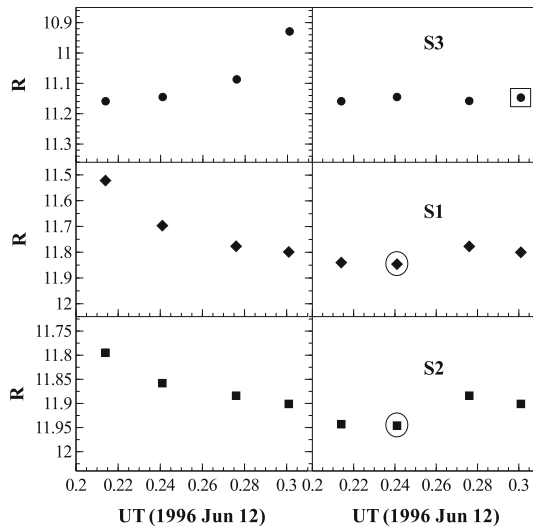

Fig. 4 Light curve of stars S1 (*diamond*), S2 (*square*) and S3 (*circle*). The absolute magnitudes were obtained on the filter R. *Each point* represents the mean of three sequential observations, separated by less than 1 min (see Table 3). The photometric error is always less than the size of the dots on the graph (≤ 0.01 mag). The *right* frame shows the flux corrected light curve. This correction corresponds to subtracting a median image of coma in the images in which occultations were recorded. The minimum angular distances between the optocenter of comet and the stars were equal to 18.5 arcsec for S1 and 46.1 arcsec for S2 (*circular box*) and 16.4 arcsec to S3 (*rectangular box*)

3 Results and Discussion

3.1 Extinction and Optical Depth

We consider homogeneous spherical dust particles of radius a and introduce the cross section for extinction:

$$\sigma(\lambda) = \pi a^2 Q_{ext}(\lambda), \tag{1}$$

where $Q_{ext}(\lambda)$ is the efficiency factor for extinction. The optical depth along a line sight with volumetric dust density n_d is them

$$\tau_\lambda{}^{ext} = \int n_d \sigma_\lambda{}^{ext}\, ds = \sigma_\lambda{}^{ext} \int n_d\, ds = \pi a^2 Q_{ext}(\lambda) N(\rho), \qquad (2)$$

where $N(\rho)$ is the superficial column density at radial projected distance ρ from the nucleus.

The extinction in magnitude A_λ is defined in terms of the reduction in the intensity cause by the presence of the dust:

$$I(\lambda) = I_0(\lambda) \exp\left[-\tau_\lambda{}^{ext}\right], \qquad (3)$$

such that

$$A_\lambda = -2.5 \log_{10}[I(\lambda)/I_0] = 2.5 \log_{10}(e)\tau_\lambda{}^{ext} = 1.086\tau_\lambda{}^{ext}. \qquad (4)$$

Applying the Eq. (4) in the mean magnitudes of the stars S1, S2 and S3, we see that S1 and S2 undergo considerable extinction in nuclear distance in the order of 10^5 km (see Tables 4, 5). The value of $\tau_\lambda{}^{ext}$ is ten times smaller than that to that obtained by Fernández et al. (1999) in a ρ equal to 100 km. To investigate the reason for this discrepancy, we applied the optical depth model for the coma of Müller et al. (2002):

$$\tau(r^*) = Q_{ext}\frac{C}{r^*}, \qquad (5)$$

where Q_{ext} is the efficiency factor for extinction and r^* is the distance from the nucleus center if the point is over the nucleus day side. If the point is over the nucleus night side r^* is the distance from symmetry axis. For our study, we consider that $r^* \cong \rho$ in both situations, as ρ is much larger than the nuclear radius estimated for Hale–Bopp. We estimate the Q_{ext} value assuming that the grain released by Hale–Bopp is a highly irregular agglomerate. To do this, we used Fig. 10 of Ivanova et al. (2016), that correlates $Q_{ext} \times X$ to cometary grains with different imaginary parts of refractive index. The size parameter X (Bohren and Huffman 1983) is defined as $x = 2\pi r_{ad}/\lambda$, where r_{ad} is the radius of a sphere circumscribing a grain cluster. As the peak of the distribution of grain size released by Hale–Bopp was near constant during the pre and post-perihelion phases, with a $r_p = 0.2\,\mu m$ (Harker et al. 2002) and our observations were made through the R filter with $\lambda = 0.65\,\mu m$, we concluded that $X = 1.9$. Using the data, we estimate $Q_{ext} \simeq 0.3$.

Table 4 Coma and grains parameters obtained from the occultation of S1 star

Time (UT)	05:07	05:44
ρ[a] (km) ($\times 10^4$)	10.3 ± 0.2	4.3 ± 0.2
A_λ[b] ($\times 10^{-2}$)	5 ± 2	6 ± 1
τ[c] ($\times 10^{-2}$)	5 ± 2	5 ± 1
A[d] ($\times 10^{-2}$)	1.7 ± 0.7	2.4 ± 0.5
p[e] ($\times 10^{-3}$)	4 ± 2	6 ± 1

[a] Optocentric distance

[b] Magnitude extinction

[c] $\tau = \tau_\lambda{}^{ext} = $ optical depth

[d] Dust albedo

[e] Geometric albedo

Table 5 Coma and grains parameters obtained from the occultation of S2 star

Time (UT)	05:07	05:44
ρ (km) ($\times 10^5$)	1.22 ± 0.02	1.13 ± 0.02
A_λ ($\times 10^{-2}$)	5 ± 2	6 ± 1
τ ($\times 10^{-2}$)	5 ± 2	5 ± 1
A ($\times 10^{-2}$)	1.6 ± 0.6	1.6 ± 0.3
p ($\times 10^{-3}$)	4 ± 2	4.0 ± 0.8

The constant C of Eq. 5 is defined as:

$$C = \frac{Af\rho_0(0)}{8p}, \tag{6}$$

where p is the geometric albedo. The parameter $Af\rho_0(0)$ is a function of $Af\rho_0$, which was defined by A'Hearn et al. (1984) as:

$$Af\rho_0 = \frac{(2\Delta r)^2}{\rho_0} \frac{F_c}{F_\odot}, \tag{7}$$

where $F_\odot$ is the solar flux at Earth, and F_c is the comets flux measured in the aperture radius ρ_0, A is the dust albedo at the considered phase angle and f is the filling factor. The parameter $Af\rho_0$ depend on the phase angle α. This is due to the non-isotropic function of grains and the effect of the geometric projection in the image plane. The correction of the effect of the phase angle was taken using the relationship Which allows, finally, to define $Af\rho_0(0)$ as:

$$Af\rho_0(0) = \frac{Af\rho_0}{\phi(\alpha)}, \tag{8}$$

with

$$2.5 \log_{10} \phi(\alpha) = -\alpha\beta, \tag{9}$$

where β is the phase coefficient of 0.025 mag/degree (see Meech and Jewitt 1987). Using the mean R magnitude of the Hale–Bopp of 11.15 ± 0.01, $Af\rho_0(0) = (1.96 \pm 0.03) \times 10^5$ cm for $\rho_0 = 3$ arcsec. As the occultations of stars S1 and S2 occurred about 16 to 50 arcsec from the central condensation, we cannot say that the parameter $Af\rho_0(0)$ is independent of ρ_0, assuming a steady-state, force-free, radially flowing dust coma.

To calculate $Af\rho_0(0)$ to the arbitrary value of $\rho_0 = 150$ arcsec, we estimated the magnitude M corresponding to this aperture, using a expression proposed by Betzler et al. (2016):

$$M = 2.5(m-2) \log_{10}(\rho_0) + C_0, \tag{10}$$

with m the exponent of the model for the surface brightness of the coma ($B(\rho_0)$ proportional to $1/\rho^m$) (see Jewitt and Meech 1987) and C_0 is a constant depending on the combination of instrumental parameters and seeing. For our observations, $C_0 = 12.58 \pm 0.01$ and $m = 0.8 \pm 0.2$ to $\rho_0 > 4$ arcsec. A slope smaller than 1 indicates that the dust is pushed in the tail by the solar radiation, replenishing the antisolar regions (Ivanova et al. 2015). For $\rho_0 = 150$ arcsec and the previous values applied in the Eq. (10) imply

$M = 6.05 \pm 0.01$, which is compatible with visual magnitudes estimates available in the International Cometary Quarterly. The value of M, applied in Eqs. (7) and (8), generates $Af\rho = (2.49 \pm 0.02) \times 10^5$ cm and $Af\rho_0(0) = (3.72 \pm 0.03) \times 10^5$ cm. Considering the geometric albedo p of grains of Hale–Bopp equal to 0.05 (Fernández et al. 1999), $Q_{ext} = 0.3$ and the previous value of $Af\rho_0(0)$, Eq. (5) provides $\tau(r^*) = 6.5 \times 10^{-5}$ for $r^* = 4.27 \times 10^4$ km corresponding to the occultation of star S1. This result suggests that the occultations were observed beyond the possible detection capability of our observational session. In fact, the occultation of S3 generated a $\tau_\lambda^{ext} = 0.007(\pm 0.01)$ at 06:36 and was undetectable at 07:12 UT. As the uncertainty is greater than the measure itself, this first result can be classified as ambiguous and the occultation was probably not detected. Its occultation was not detected although this star has been separated from 16.4 arcsec or 3.8×10^4 km from the comet optocenter at 7:12 UT, smaller than the distance reached by the star S1 at 05:44 UT (see Table 4). The value of τ_{ext} corresponding the occultation S1 and S2 are at least 770 times higher than that suggested by the model and is virtually constant at an optocentric distance ranging between $\sim (0.4 - 1) \times 10^5$ km. As the night was considered photometric, we think that the measured opacity was due to the passage of starlight by a jet. Events of this nature were identified soon after the discovery of comet Hale–Bopp: Offutt (1995) reported the development and decay of spiral structure in the coma,interpreted as a jet by Kidger et al. (1996).

In order to enhance this jet, we align and stack three images obtained sequentially, corresponding to the occultation of stars S1, S2 (images 4,5 and 6) and S3 (images 10,11 and 12), to increase the SNR of any structures in the coma. These resulting images were processed with the routines "Division by $1/\rho$ profile" and "Division by Azimuthal mean" provided by "Cometary coma image enhancement facility" (Samarasinha et al. 2013). The use of two methods can be justified by the possible introduction of artifacts or modification of the position of actual structures in the resulting images, because of the particular characteristics of each enhancement method. In both methods, we use the default values proposed for the routines. In the first routine, the previous images were divided by a canonical profile $1/\rho$. We consider this procedure quite reasonable since, during our observations, the coma of Hale–Bopp had this approximate profile on a large scale ($\simeq 2 \times 10^3$ km/pixel). The "Division by Azimuthal mean" converts the input image into polar coordinates relative to the optocenter. The routine finds the mean value of all azimuths for a given radial distance, excluding outliers, and divides each azimuthal value by that mean.

The application of these two methods resulted in suppression details near to the nucleus and enhancement structures on the outer coma region in which the three occultation were observed (Schleicher and Farnham 2004). In the resulting images (Figs. 2, 3), asymmetric dust emissions released into the solar direction can be identified by bright or tenuous areas. Regions associated with the gas phase of the coma would present with flatter spatial profiles (Samarasinha and Larson 2014). From the application of the two methods, a jet was revealed in Hale–Bopp's coma during our observations. Analyzing the images obtained by the first method, the jet appears to be spiral and, considering the distance between the nucleus and the point of inflection where it is thrown back by the solar wind, it is 11.8 arcsec or 2.8×10^4 km in length (The angular and linear extent refer to the distance between the nucleus and the point of inflection where the jet is swept back by the solar wind).

Considering the sequence of images in which S1 and S2 stars are occulted, the position angle of visible end of the jet coincides with the equivalent presented by these two stars.

The position angles PA are respectively near ~ 0 degrees. This similarity is not observed between the end of the jet and the star S3 at 06:36 UT (PA ~ 225 degrees). We can conclude that the value of the optical depth corresponding to passage of starlight S1 and S2 by jet with density $N(\rho)$ approximately constant along its radial direction.

Hadamcik and Levasseur-Regourd (2003) made CCD imaging polarimetric observations about 4 h before our observations. These observations revealed that the coma around the nucleus had an elongated shape, with two high polarization regions in the solar and antisolar directions, composed of five small radial jets, and dimensions $\approx 1.5 \times 10^5$ km. A structure perpendicular to the solar direction, not visible in polarimetric images, was brighter than the elongated structure in the images processed with rotational gradient method. This seems to indicate a different population of dust in this region than in the other bright structures.

We believe that the stars S1 and S2 intercepted the elongated region. The star S3 was occulted within the limits of perpendicular structure. Presumably, as there is a differentiation in the population of the grains in these two regions, opacity levels of coma may have been different, justifying the failure to detect the extinction in the observations of star S3.

Fernández et al. (1999) found an optical depth equal to 0.48 to ρ equal to 100 km, we recalculated the constant C of Eq. (5). With a nuclear radius $R_n = 35$ km, we estimate that the optical depth in the surface of the nucleus of Hale–Bopp is ~ 1.4 in 1996 October. Assuming that the $\tau(r^*)$ values estimated by the model are 40 times smaller and that this proportion remains constant in time, ~ 3.2 for our data. This result suggests that Hale–Bopp has the largest opacity near to the nucleus observed, and the increase or decrease in this parameter may be associated with the manifestation of jets.

3.2 Albedo of the Grains

According to Eqs. (1) and (2), the product of the particle column density and cross-section is given by:

$$N(\rho)\sigma \le \tau_{ext}. \tag{11}$$

Given a superficial brightness of the coma, the following section canonical relation ρ^{-1}, the filling factor of Eq. (7) is equal to:

$$f = 2N(\rho)\sigma, \tag{12}$$

combining Eqs. (9), (11), and (12) and using the four values of τ_{ext} (Tables 4, 5), we determined that the mean dust albedo is $A = (3 \pm 1) \times 10^{-4}(1\sigma)$. We assume that the cometary dust does not have such a small albedo and that the material is sufficiently porous that a typical photon must reflect twice on the surface before escaping (Larson and A'Hearn 1984). Thus, $A = (1.8 \pm 0.3) \times 10^{-2}$ and considering that the relation between A and the geometric albedo p is $A = 4p$, then $p = (4.5 \pm 0.7) \times 10^{-3}$.

Applying the procedure of Fernández et al. (1999) on our data, $A = (2.6 \pm 0.4) \times 10^{-2}$ and $p = (6 \pm 1) \times 10^{-3}$. This suggests that the albedo of the grains was intrinsically low during our observations.

To test the consistency of our estimates of albedo, we used an alternative model of optical depth used by Ivanova et al. (2016). Mishchenko (2015) defined the optical depth as:

$$\tau = n \times Q_{ext} \times G, \tag{13}$$

in which, n is the number of particles in a column with projected area of 1 m^2 and G is the efficiency for extinction [dimensionless] and ensemble-averaged geometric cross section of agglomerated debris particle [in m^2]. We admit that grain with $r_{ad} \approx 0.2 \mu m$. As the projected area of the agglomerated debris particles is for a factor of 0.61 smaller than that in the circumscribing sphere, so than what in the circumscribing sphere, so, $G \approx 8 \times 10^{-14}$ m^2. We using Eq. 13 to determine n, with $\tau = (5 \pm 1) \times 10^{-2}$ obtained from the occultation of S1 at 05:44, $Q_{ext} \approx 0.3$ and the previous value of G. Taking into account the τ error, $n = (2.2 \pm 0.4) \times 10^{12}$ grains/m^2. Alternatively, we estimate n by $Af\rho$. Considering $Af\rho = (1.97 \pm 0.02) \times 10^5$ cm and $\rho = 4.3 \times 10^4$ km, $Af \approx 4.6 \times 10^{-5}$. Assuming grains with typical dust albedo $A = 0.03$–0.07, the filling factor ranges between $(0.7$–$1.5) \times 10^{-3}$. This interval of f implies $n = (0.9 - 2) \times 10^{10}$ particules/m^2, two orders of magnitude lower than the initial estimate of n given by a Eq. 13. On the other hand, if we use the dust albedo $A \approx 3.4 \times 10^{-4}$, the filling factor is $f \approx 1.3 \times 10^{-1}$ and $n \approx 2 \times 10^{12}$ grains/m^2, which is consistent with the initial estimate. This result implies in an extremely low albedo for the dust grains emitted by comet Hale–Bopp, which is not an unusual result. Low albedo have been estimated by observing stellar occultations (Larson and A'Hearn 1984; Lacerda and Jewitt 2012) and measures *in situ* on the surface of the nucleus of comet 19P/Borrely (Oberst et al. 2004). As the analyzed grains are presumably in a jet region, some of its physical properties may be different from those found in the coma, such as increased porosity/diameter or the presence of grains composed of less absorbent materials (see Giese et al. 1986; Hage and Greenberg 1990).

IR polarimetric observations of Hale–Bopp, made by Jones and Gehrz (2000) in 1996 April and August and 1997 April, suggest a non-uniform polarization in the coma. The polarization peaks were detected in jet structure extremes, which is most easily explained by a population of small grains present in the jet that are continuing to break up several hours after release from the nucleus.

4 Conclusions

We have reported photometric observations of three stellar occultations by the coma of comet C/1995 01 (Hale–Bopp). Our findings can be summarized as follows:

1. We detected an extinction which was almost equal to 0.06 distance ranging between $(0.4 - 1) \times 10^5$ km, implying an optical depth $\tau \simeq 0.05$. This value of τ is extremely high for this optocentric distance if compared to results available in the literature or inferred by models.
2. The value of τ in this optocentric distance can be explained by the presence of a jet in a coma. Thus, the unusual depth optical values can serve to identify structures in a coma.
3. Applying a model of optical depth of Müller et al. (2002), we inferred that the $\tau \sim 3$ for the comet Hale–Bopp nucleus surface in June 1996. As result its nucleus surface is the most opaque observed until now.
4. The albedo of grains in this jet are respectively equal to $A = (1.8 \pm 0.3) \times 10^{-2} (1\sigma)$ and $p = (4.5 \pm 0.7) \times 10^{-3}$. These values are lower the the A=0.21 and p=0.05 found by Fernández et al. (1999), which may suggest a difference in the grain population associated to coma and jets.

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