THE ANTI-TAIL OF COMET C/1995 O1 (HALE–BOPP) IN 1997/1998 *

HERMANN BOEHNHARDT
European Southern Observatory, Alonso de Cordova 3107, Santiago de Chile and Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

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Abstract. The large-scale post-perihelion evolution of the dust tail in Comet C/1995 O1 (Hale–Bopp) was monitored with Schmidt telescope exposures at the European Southern Observatory (ESO) La Silla in Chile. In early October 1997 signatures of a peculiar dust-tail appeared as straight, but diffuse extensions in the northern and southern coma hemisphere. With the approach of the Earth to the orbital plane of the comet a needle-like anti-tail with a similar, but much longer counterpart in the region of the normal dust tail formed. In early January 1998, i.e., close to the plane crossing, the anti-tail pointed towards position angle 190° and was at least 0.4° long, its counter part extended over more than 5° into opposite direction. During February and March 1998 the position angles of both features increased by more than 40° – while their appearance became shorter, wider and more diffuse again. The peculiar dust tail was last observed in April 1998. Modeling of the dust tail dynamics shows that the anti-tail and peculiar tail phenomenon observed is formed by a neck-line structure of heavy dust grains released around perihelion passage. Two scenarii are introduced to explain the extension of the anti-tail feature: (1) grains ejected about 20 days post-perihelion with a initial velocity of $\sim$ 170 m/s in radial direction towards the Sun and (2) grains released about 60–80 days before perihelion at a speed of $\sim$ 70m/s into the orbital plane and against the motion direction of the comet. The out-of-plane velocity component of the dust was less than $\sim$25 m/s. Both scenarios require dust of $\beta < 0.001$ to be involved, i.e., grains of at least mm-size. The rather symmetric shading of the neck-line structure before and after passage of the Earth through the orbital plane of the comet in early January 1998 supports the idea that dust of both scenarii may have contributed to the phenomenon.

Keywords: Comet C/1995 O1 Hale–Bopp, anti-tail, neck-line structure, mm-size dust

1. The Dust Tail of Comet Hale–Bopp

Since its discovery in July 1995 Comet C/1995O1 (Hale–Bopp) was observed showing a coma and dust tail all the time. During the immediate post-discovery period the comet was seen face-on from Earth, i.e., the observer was looking basically in the direction of the radius vector of the comet. In this viewing geometry the sunward coma appeared in the foreground for the observer on Earth. Beyond the coma, the dust tail was projected onto the sky, thus only a very short extension in the coma isophote pattern indicated its presence. In fact, at that time the dust tail

* Based on observations performed at the European Southern Observatory at Cerro La Silla in Chile

was pointing almost radially away from the Sun. During 1996 the dust tail of the comet was seen rather side-on and it appeared short and compact.

During the immediate pre- and post-perihelion period in spring 1997, C/1995O1 was viewed from Earth with a spread-out dust tail since the comet moved far above the Ecliptic plane and could thus be seen more top-on from Earth. Apart from many striae, also a bifurcation was noticed in the diffuse dust tail (Birkle et al., 1997) indicating a significant change in the dust properties and/or dust emission level during February 1997.

Between the end of December 1997 and early January 1998 another peculiar phenomenon was displayed in the dust tail of this comet: a needle-like straight anti-tail and its counterpart in the direction of the extended radius vector of the comet (Boehnhardt et al., 1998; see also section 3). The next visibility of the comet in 1998/99 showed a structureless and diffuse dust tail (Boehnhardt et al., 2002), now again – as during the discovery year – projected in the background of the extended coma.

In this paper we describe the anti-tail and its extension in the region of the normal dust tail of Comet Hale–Bopp as it was imaged between October 1997 and April 1998. Using Finson-Probstein type model calculations we interpret this phenomenon as a neck-line structure formed by old dust grains of mm size.

2. Anti-Tails in Comets: Projection and Neck-Line Structures

Anti-tails are rare phenomena in comets and are mostly observed in brighter objects. However, by nature their appearance is not restricted to bright comets, they are only much less apparent in the fainter representatives and may thus escape detection. In the past decades very prominent anti-tails were seen in: Comets C/1956 R1 (Arend-Roland), C/1973 E1 (Kohoutek), 1P/1982 U1 (Halley), and C/1969 Y1 (Bennett). A good example of a faint object with anti-tail was the comet-asteroid 133P/1996 N2 (Elst-Pizarro) in 1996. In most cases also a wide and diffuse "normal" dust tail, pointing away from the Sun, was observed together with the peculiar tail phenomenon.

Anti-tails show up in the sunward side of the comet head as seen from the observer on Earth. They appear to be very narrow and mostly structureless, peaking out of the sunward coma like a needle. In some cases their continuation on the tailward side is reported, i.e., an equally narrow structure appears in the region of the "normal" dust tail at a position angle exactly opposite to its sunward counterpart. Usually, the sunward spike is short (a few arcmins to half a degree) while the tailward feature can be much longer (several degrees). If the sunward and tailward spikes are weak and/or short, they are difficult to recognize on the bright background of the coma and of the "normal" dust tail. Hence, image scanning (Pansecchi et al. 1987; Cremonese and Fulle, 1989) and numerical contrast enhancement methods (Boehnhardt and Birkle, 1994) may be needed to better explore their geometry and extension.

In our general picture of cometary dust tails, the grains released by the nucleus are blown away from the comet into the tail region by solar radiation pressure. Their motion in the neighbourhood of the comet is described by means of the solution of the classical two-body problem, however for attenuated or even repulsive potentials depending on the sensitivity of the grains to the radiation pressure (Finson and Probstein, 1968a,b). The mathematical description makes use of the parameter β to describe the ratio of solar radiation pressure to gravity for dust grains.

The dust tail is a rather flat extended structure confined to the orbit plane of a comet. It points approximately radially away from the Sun most of the time except during perihelion passage. The dust in the tail can be mapped by the so called synchrone-syndyne grid, first introduced by Finson and Probstein (1968a): a synchrone defines the locations of dust grains with different solar radition pressure coefficient β that are released by the nucleus at the same moment; a syndyne defines the locations of the grains in the dust tail that are subject to the same radiation pressure force, but were released at different times.

Obviously, dust can also move in the sunward direction due to its initial velocity and acceleration by the gas in the immediate vicinity of the nucleus. Actually, most of the emitted dust is expanding this way into the cometary coma giving rise to the frequently observed brightness asymmetry between the sunward and tailward coma hemispheres (C/1996 O1 (Hale–Bopp) 1–2 months before perihelion was a good example). Depending on the coefficient β the tracks of the micron-size dust grains (i.e., the ones that form the diffuse coma and dust tail seen in the visible wavelength region) are turned around from the Sun after some 10000–1000000km distance in the coma. The grains are moving “outwards” into the region of the dust tail.

Within this general concept for the dust motion in the vicinity of the comet two different explanations exist for the appearance of anti-tails in comets: (1) anti-tails due to projection and (2) so called neck-line structures.

(1) *The projection scenario (see for instance Sekanina 1976)*: during the passage of the Earth through the orbit plane of the comet the dust tail is seen side-on from Earth. With favourable viewing geometry parts of the dust tail, namely the older (a few weeks) dust grains in the tail, can appear – due to projection – on the sunward side of the nucleus in the sky (although in reality they are further away from the Sun than the comet). Since the thickness of the dust tail is very small, many dust grains fall along the line of sight of the observer and the light scattering cross section of the otherwise very extended and faint dust tail becomes high enough for detection from Earth. Since the velocity component of the dust out of the orbit plane of the comet is small and the sunward projected part of the tail is more distant from the observer than the foreground coma, the anti-tail gets a needle-like appearance.

This scenario can occur mostly close to perihelion (both before and after perihelion with higher probability for the post-perihelion geometry) because of the strong curvature of the dust tail in the orbit plane of the comet. Its visibility very much depends on the activity of the nucleus, i.e., whether enough dust was emitted into the sunward projected part of the tail. The dust grains seen in projection on the sunward side are typically released about 2 weeks to 2 months before the observations.

Classical cases for anti-tails by projection were seen in Comet C/1956 R1 (Arend-Roland) (Finson and Probstein, 1968b) in late April 1957 and in the comet-asteroid 133P/1996 N2 (Elst-Pizarro) (Boehnhardt et al., 1998) in autumn 1996. Comet Hale–Bopp as well had favorable projection geometries for anti-tails close to perihelion, i.e. in early January and in July 1997. However, during both occasions the comet was very close to the Sun (less than 30° elongation) and a faint anti-tail could have thus escaped detection because of the bright sky background when the comet had to be observed close to the horizon.

The neck-line structure (see for instance Kimura and Liu 1975): the neck-line structure in the tail is marked by grains that "collapsed" into the orbital plane of the comet at an angle π (or – more general – multiples of π) away in true anomaly from the point where they were ejected from the inner coma. Due to the radiation pressure the originally spherical dust cloud becomes ellipsoidal and, when passing the second (or later) node with the cometary orbit, that dust cloud is completely flat and only extends in the orbital plane of the comet. The overlap of all flat dust clouds of different size and different emission time that pass through their second (or later) nodes at a given time is called a neck-line structure.

The necessary – but not sufficient – criterion for neck-line formation, i.e., the true anomaly difference along the dust grains' orbit between observation and emission time to be a positive integer of π, in principle implies that neck-line structures in comets can be produced by dust repleased during a previous perihelion passage. Short-period comets in particular are potential candidates to look for $2\times\pi$ (or higher) neck-line structures. An indeed, there is a fair chance that the recently seen neck-line feature (own observations from spring 2003, unpublished) in the ROSETTA target comet, 67P/Churyumov-Gerasimenko, may be due to dust released during the previous perihelion passage. On the other side, the $1\times\pi$ neck-line scenario is still a valid interpretation, although it requires an unusually high dust emission activity during the aphelion arc of the comet. Observations and analysis of this rare phenomenon are still on-going.

The neck-line scenario requires dust released by the comet usually a long time ago (orders of many months to years), but still being in the close neighbourhood of the nucleus in order to become visible in the relatively small field of view of telescopes at the time of its occurence. Hence, one can conclude that the start velocities of the dust grains from the nucleus must be small and their sensitivity to radiation pressure must be low, i.e., the neck-line consists of heavy dust grains.

As for the projection scenario, the neck-line structure to become visible requires the Earth to be close to or passing through the orbital plane of the comet. The anti-tail is formed by dust particles that are physically located on the sunward side of the comet. Dynamically, this is only possible for very large dust grains that were released by the nucleus at considerable speed into the sunward coma hemisphere and that are rather insensitive to radiation pressure ($\beta \ll 0.1$). The tailward extension of the phenomenon contains less heavy dust.

Although to be considered as the same phenomenon, the sunward part of this phenomenon is called anti-tail (without distinguishing it from the anti-tail due to projection) while the tailward part is called neck-line. The so far interpreted $1\times\pi$ neck-line phenomenon occurs – usually – post-perihelion because it involves 'rather recently' emitted, thus less dispersed dust grain ensembles. The dust forming a neck-line, is released by the comet over a longer arc of the orbit that is only very approximately located an angle π (or multiples of π) in true anomaly away from the occurence of the narrow tail structure.

Classical examples for neck-line structures with anti-tails are Comet 1P/1982 U1 (Halley) (Cremonese and Fulle, 1989) in April to June 1986 and in Comet C/1969 Y1 (Bennett) (Pansecchi et al., 1987) in early May 1970.

3. The Peculiar Dust Tail of Comet Hale–Bopp from October 1997 to April 1998

The large-scale appearance of Comet Hale–Bopp that passed perihelion on 1 April 1997 was monitored post-perihelion by wide-field observations using the 1 m Schmidt telescope at the European Southern Observatory ESO in La Silla/Chile from August 1997 until November 1998 (thereafter this task was taken over by the Wide Field Imager camera at the 2.2 m telescope of the same site). The ESO Schmidt telescope provides a field of view of $5.2 \times 5.2°$ on photographic films or plates of 28×28 cm size. For our monitoring programme of Comet Hale–Bopp, Kodak 4215 film was used (hypersensitized with forming gas, developed with Kodak D19 developer).

From the archive of our Schmidt films of Comet Hale–Bopp we have selected 6 exposures which illustrate best the development of the peculiar dust tail from the beginning of October 1997 to the end of April 1998 (unfortunately, no Schmidt images of the comet were taken in November 1997 and in the second half of January 1998). In order to display the dust tail to its full extend and to detect faint details therein, the films were exposed for 3/4 to 2 h with the telescope following the motion of the comet in the dark sky. Because of the long integration times used, the comet head is overexposed. For the analysis of coma structures and their connection to tail features as well as for the better location of the nucleus position some shorter exposed images were also taken (not described here in greater detail).

In early October 1997 (see Figure 1) the normal tail appeared in the north-western quadrant with respect to the cometary head. It was diffuse with 2–3 jet extensions embedded in the region close to the coma. A second, narrower and diffuse dust tail is seen at a position angle PA $\sim 345°$. This tail continued straight

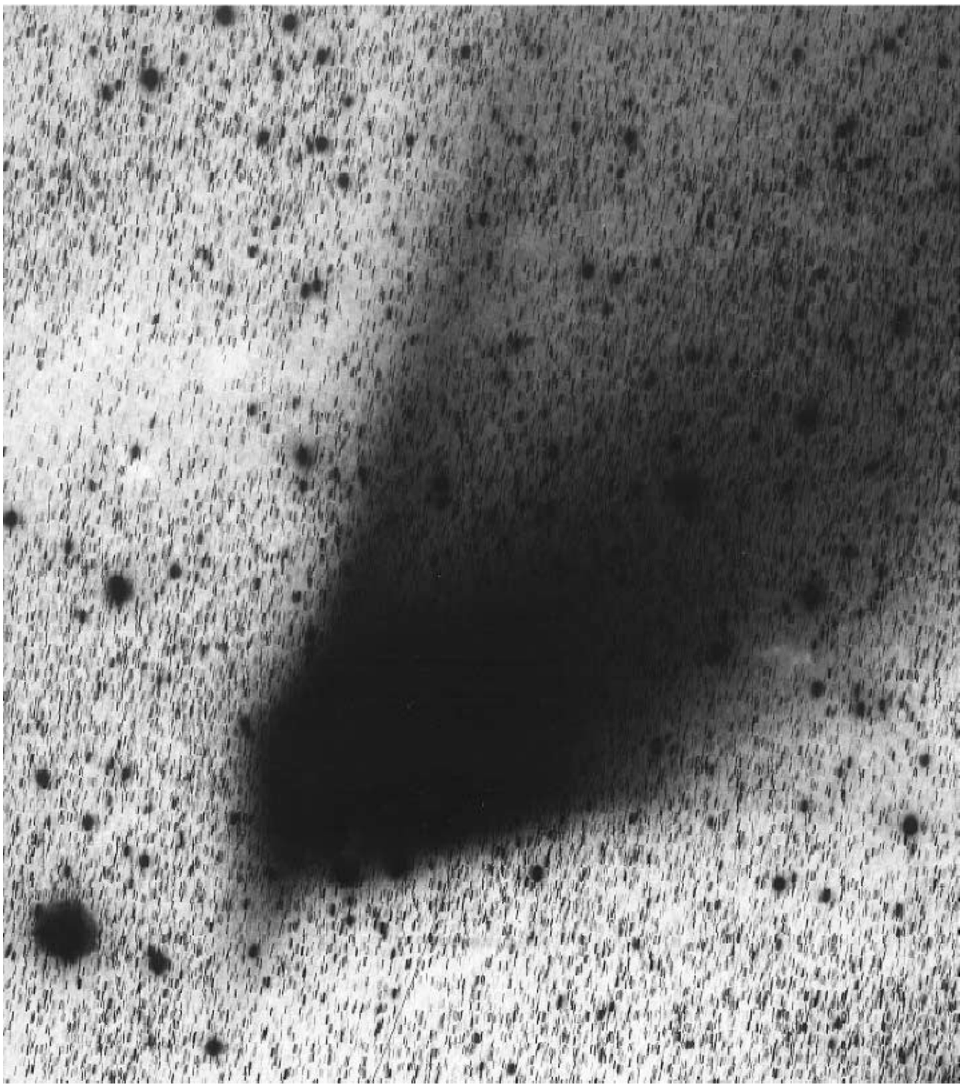

Figure 1. The dust tail of Comet C/1995O1 (Hale–Bopp) on 5 October 1997. Field of view is 1.5 × 1.6°, North is up and East is to the left. The anti-tail is peaking out of the comet head approximately towards the South, the neckline structure appears on the eastern edge of the normal dust tail in the northwestern quadrant of the image. A satellite trail is visible west of the comet head passing through the normal dust tail of the comet.

on the sunward side of the comet. During the last days of December 1997 and the beginning of January 1998 (see Figure 2) an at least half degree long, needle-like anti-tail popped out of the sunward coma at PA ∼ 190°. Its counterpart on the tailward side was equally narrow and straight, but longer (more than 5°) at PA ∼ 10° and it overlapped with the diffuse dust tail. Starting from late February 1998 (see Figure 3) the normal tail stayed in the northeastern quadrant of the comet

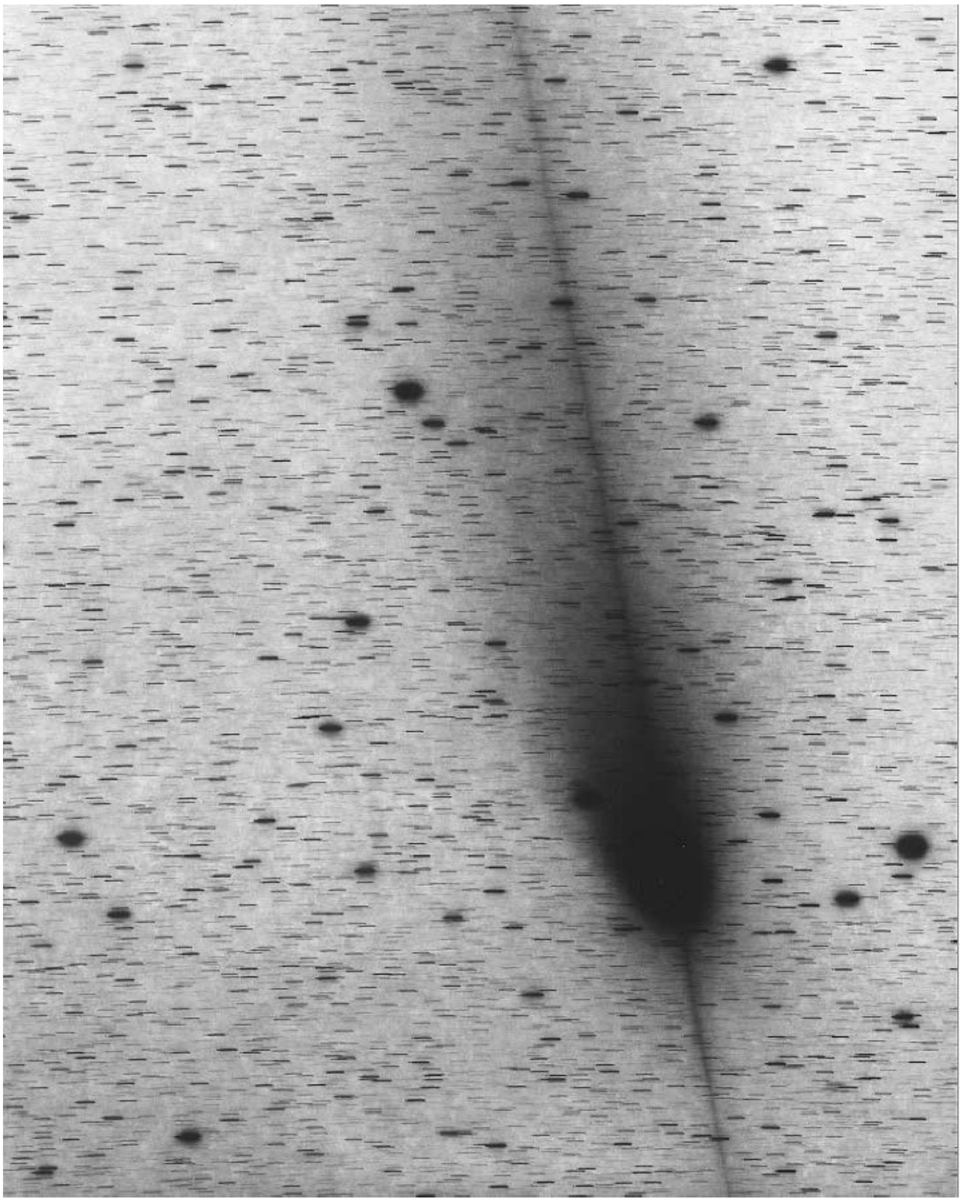

Figure 2. The dust tail of Comet C/1995O1 (Hale–Bopp) on 3 January 1998. Field of view is 0.9 × 1.3°, North is up and East is to the left. A very narrow anti-tail and neckline structure extends from the southern to the northern edge of the image.

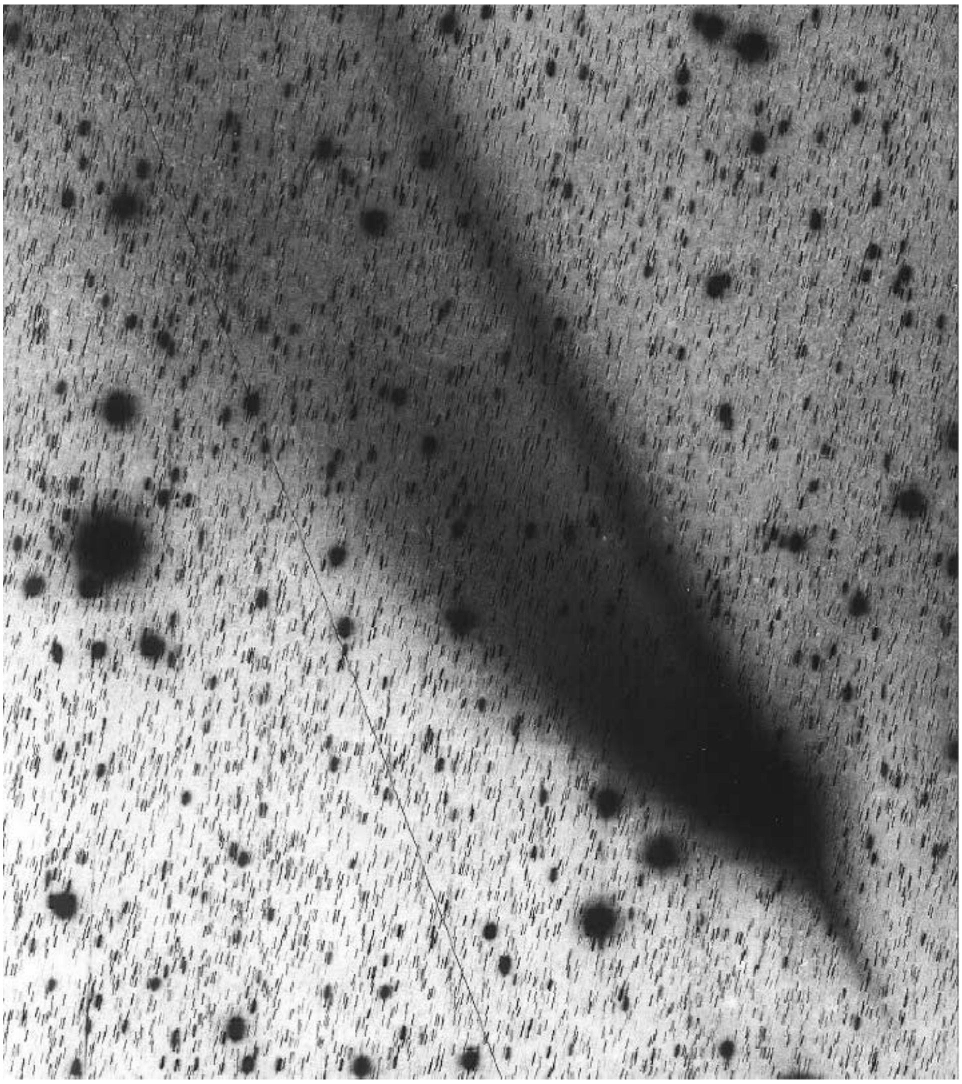

Figure 3. The dust tail of Comet C/1995O1 (Hale–Bopp) on 26 February 1998. Field of view is about 2.0 × 2.2°, North is up and East is to the left. The anti-tail is peaking out of the comet head approximately towards the South-West, the neckline structure appears on the western edge of the normal dust tail in the north-eastern quadrant of the image. A satellite is passing to the East of the comet head and across parts of the normal dust tail.

(again with 2–3 jet streamers). The second tail was still present on both sides of the coma (at PA ∼ 200–210° for the anti-tail and PA ∼ 20–30° for its tailward counterpart). It became more diffuse and wider and – during April 1998 – it also faded in brightness (see Figure 4).

In the October 1997 and February 1998 images a very weak and diffuse light bridge connects the normal and the peculiar dust tails on the tailward side of the

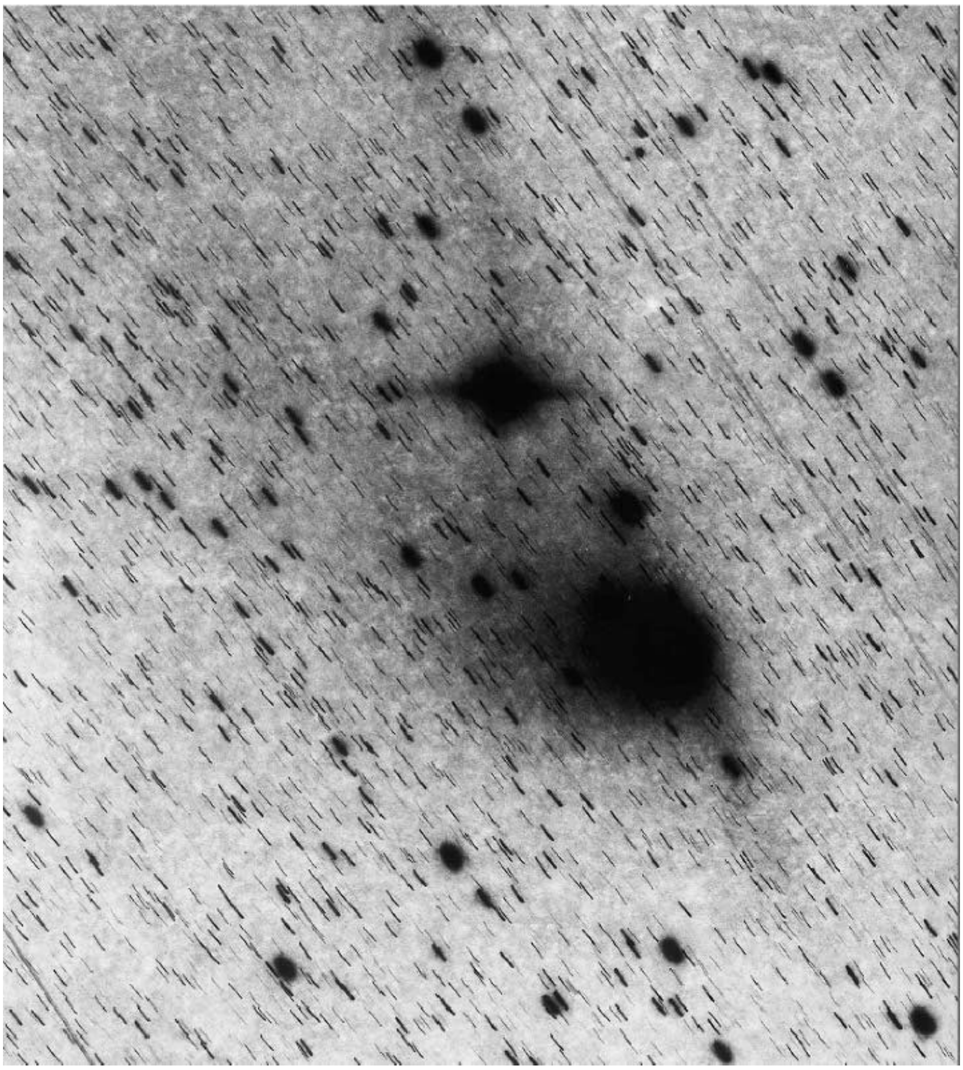

Figure 4. The dust tail of Comet C/1995O1 (Hale–Bopp) on 25 April 1998. Field of view is 1.2 × 1.1°, North is up and East is to the left. The anti-tail and neckline structure became very weak and smaller in extension on the sky. However, their orientation remained as seen in the end of February 1998. Satellite trails are visible in the southeastern and northwestern quadrants of the image.

comet. The width or opening angle (as measured at the nucleus position) of the peculiar tail remained below 5° with a minimum of less than 0.1° in early January 1998. Table I summarizes the geometric details of the peculiar dust tail in Comet Hale–Bopp as measured from our Schmidt exposures.

Close inspection under the microscope of the film negatives taken in early January 1998 revealed only very little substructure in the narrow dust tail: its width did not change along the tail axis and only a marginal brightness dip appeared at about

TABLE I

The anti-tail and neck-line structure in Comet Hale–Bopp. The table lists the observing date, the distance of the comet from the Sun and from Earth (in AU), the calculated position angle of the projected radius and velocity vectors of the comet (in degrees measured North over East), the measured length of the anti-tail and its tailward counterpart (neck-line; in degrees and km projected in the sky at the distance of the comet) and the position angle (in degrees) and width (in degrees) of the neck-line feature. Note: the position angle of the anti-tail was equal to the position angle of the neck-line plus 180°

Date [UT]	Distance Sun [AU] Earth [AU]	PA Vector Radius [deg] Veloc. [deg]	Length [deg/km] Neck-Line Anti-Tail	Neck-line PA [deg] Width [deg]
5 Oct. 1997	2.93	259	~1.7/~13.4 10^6	345
	3.07	175	~0.5/~4.0 10^6	<5
3 Jan. 1998	3.95	10	>5.0>49.5 10^6	10
	3.78	273	>0.4/>4.0 10^6	<0.1
26 Feb. 1998	4.51	81	~1.7/~20.0 10^6	34
	4.50	355	~0.5/~5.9 10^6	<3
22 Mar. 1998	4.75	104	~0.85/~10.6 10^6	28
	4.80	28	~0.35/~4.4 10^6	<2
2 Apr. 1998	4.86	114	~1.1/~14.2 10^6	30
	4.95	41	~0.4/~5.2 10^6	<3
25 Apr. 1998	5.08	140	~0.3/~4.1 10^6	23
	5.23	65	~0.1/~1.4 10^6	<2

84 arcmin on the tailward side of the comet. Apart from that, only a slow brightness decrease along the tailward part was found, while the sunward spike dropped faster in brightness.

4. The Interpretation of the Observed Peculiar Dust Tail Phenomena

The passage of the Earth through the orbital plane of Comet Hale–Bopp happened on 2 January 1998. At the same time the prominent narrow anti-tail appeared in our Schmidt exposures of the comet. Although necessary, it is not the only requirement for the formation of an anti-tail as seen from Earth – see section 2. Since this phenomenon appeared post-perihelion, no firm a-priori conclusion about its nature can be made from simple considerations. Therefore, the dynamical structure and viewing geometry of the anti-tail in Comet Hale–Bopp was analysed by means of dust tail simulation software (Beisser, 1987, 1990, 1991, 1992).

In the first approach described here, we tried to identify the correct interpretation of the phenomena and to constrain the relevant dust parameters (β ratio, grain sizes and emission properties).

Anti-tail by projection: the attempt to simulate the observed anti-tail structure and its straight continuation in the normal tail as a projection phenomenon failed completely. All the micron-size dust released over about months before the observations, that typically forms the visible dust tail in comets, was either in the coma (if just a few days old) or in the region of the normal tail. The main tail axis was not curved and inclined enough with respect to Earth direction as seen from the comet to cause the projection of parts of the tail into the sunward side of the comet head.

Anti-tail as neck-line phenomenon: hence, we investigated the possibility to explain the observed tail features as neck-line structure. The anti-tail should then consist of old and heavy grains released into the sunward hemisphere. Since C/1995 O1 is a long-period comet, dust from previous apparitions is practically excluded to explain the neck-line feature observed. Thus, we focus in our analysis on grains from the most recent (1997) perihelion passage, i.e., we consider the dust with true anomaly difference of π between observations and emission. From this true anomaly condition one can get a very rough estimate for the time when the heavy grains were emitted from the inner coma of the comet at the earliest: around the beginning of February 1997, i.e., a few weeks before perihelion of the comet.

Thus, in our modelling the time interval for the emission of the dust grains observed in the anti-tail was set to ± 80 days around perihelion. A series of test runs were performed each with a fixed quartet of the parameters β and the three components of the initial velocity of the dust grains released by the comet. The solar radiation pressure factor β was varied from 0.0001 to 0.01, i.e., representing dust grains of typically 5.0 to 0.05 mm radius (see for instance Crifo, 1987). The initial velocity was assumed to vary from 0 to 250 m/s. The main criterion for the test calculations was to reproduce the extension of the anti-tail observed on 3 Jan. 1998 ($>4 \times 10^6$ km). Furthermore, we checked also the overall temporal evolution of the tail geometry formed by heavy dust grains around the comet and how it could match with the available large scale observations.

Two parameter ranges for β and the initial velocity were found to “feed” dust into the very end of the observed anti-tail of Comet Hale–Bopp:

- option 1 (see Figure 6): grains with $\beta < 0.001$ and initial velocity of about 170 m/s into anti-sunward direction (-x direction in Figure 5) and
- option 2 (see Figure 7): grains with $\beta < 0.001$ and initial velocity of about 70 m/s perpendicular to radial direction in the orbital plane and oriented against the orbital motion of the comet (-y direction in Figure 5).

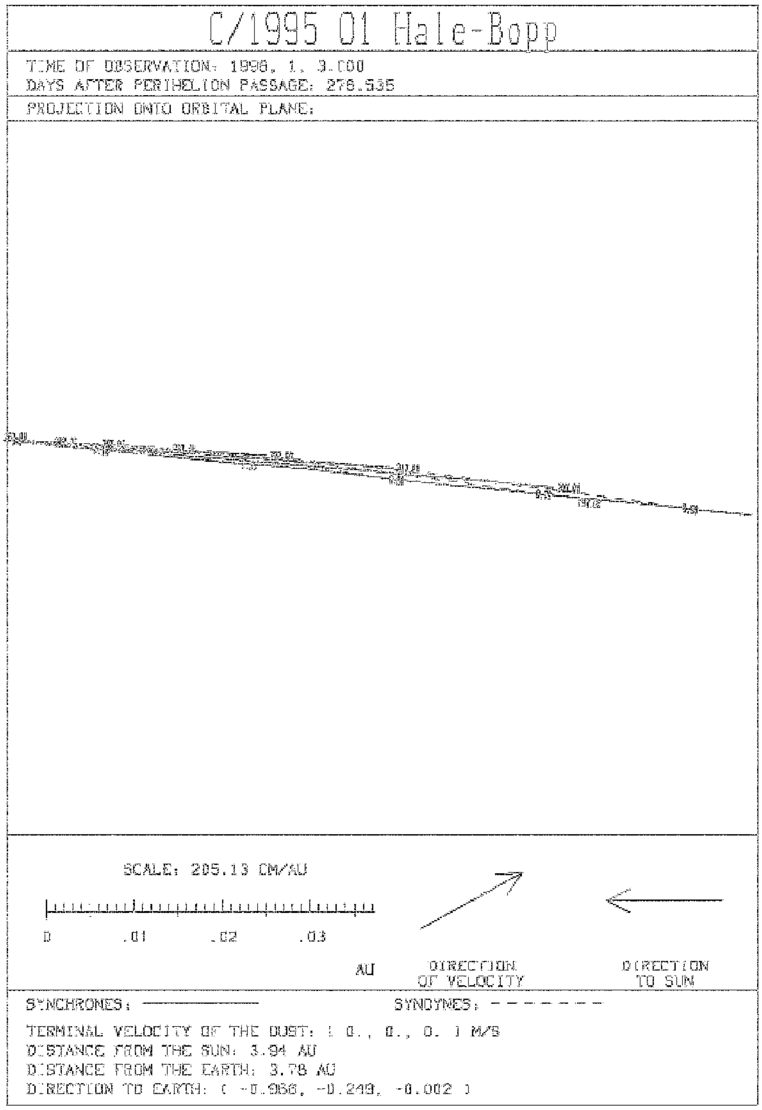

Figure 5. Synchrone-syndyne pattern of the normal dust tail of Comet Hale–Bopp on 3 January 1998 as seen in projection onto the orbital plane of the comet. The synchrones (continuous lines) cover ~80 days time interval of dust emission before the date of observation. The syndynes (broken lines) show dust of β between 0.1 and 0.9, i.e., micron-size dust that makes up the normal dust tail. Emission times in days and β ratio are given as labels to synchrones and syndynes. The position of the cometary nucleus is indicated by a star symbol. The x axis of the plot is given by the radius vector of the comet (arrow "Direction to Sun" in plot), the y axis lies in the orbital plane and points into the same hemisphere as the velocity vector of the comet (arrow "Direction of Velocity" in plot). The direction to Earth (given as unit vector in the last line of the plot) has an angle of 165.5° with the radius vector of the comet and about 155° with the main axis of the dust tail. The dust tail and the Sun are on different sides of the direction to Earth which implies that the tail is pointing away from the Sun as seen projected onto the terrestrial sky.

For option (1), dust emitted at about 20 days post-perihelion could have reached the maximum distance in the observed anti-tail. For option (2), the peak distance in the anti-tail is defined by particles emitted about 60–80 days (the latter value from calculations not presented in the figures) before perihelion. In both cases the the maximum distance does not depend very much on the sensitivity of the grains to radiation pressure (as long as β is smaller than 0.001), but it scales – almost linearily – with the initial speed of the grains when emitted from the inner coma. It is noteworthy that for option (2) the location of heavy dust grains in the anti-tail region changes from the eastern to the western edge of the neck-line structure during the passage of the Earth through the orbital plane of the comet, while the opposite trend is found for option (1). The estimated width of the anti-tail of 0.1° provides a constraint for the maximum initial out-of-plane velocity of the dust: the model calculations indicate an upper limit of 25 m/s (in $\pm$ z direction, i.e., perpendicular to the orbital plane of the comet). The tailward side of the neckline structure is obviously formed by the smaller and lighter dust population that is more sensitive to radiation pressure ($\beta > 0.005$ to 0.01).

5. Discussion and Conclusions

Schmidt telescope observations have revealed a peculiar large-scale dust tail phenomenon in Comet Hale–Bopp between October 1997 and April 1998. A secondary dust tail with extension into the sunward side of the comet head (length from 0.1 to more than 5° in the sky) appeared detached – though still connected through a light bridge of faint dust – from the normal diffuse dust tail of the comet. In early January 1998 a very narrow tail appeared superimposed on a wider dust tail and the anti-tail became about 0.4° long.

Model calculations of the dust grain dynamics indicate that the detached dust tail and its connected anti-tail are formed by a neck-line structure of old and relatively heavy dust grains emitted from the inner coma within about 2 months around perihelion. More specifically, two scenarios could be identified to explain the position, length and width of the observed anti-tail: dust grains ejected about 20 days after perihelion with $\beta < 0.001$ and velocity of $\sim$170 m/s towards Sun direction (option 1) and those released about 2 months before perihelion with $\beta < 0.001$ and ejection velocity of $\sim$ 70 m/s in the orbital plane against the motion direction of the nucleus (option 2). The initial out-of-plane speed of the dust should be <25 m/s in both scenarios. Also in both scenarios, the exact position of the grains in the observed anti-tail depends mostly on the emission time and speed as long as β is below 0.001.

The dust emission period in question of having produced the dust in the anti-tail was the high activity phase of the perihelion passage of the comet. Measurements of the dust shells seen in the coma of the comet during February and March 1997 revealed expansion velocities of the typically micron-size grains therein of at least

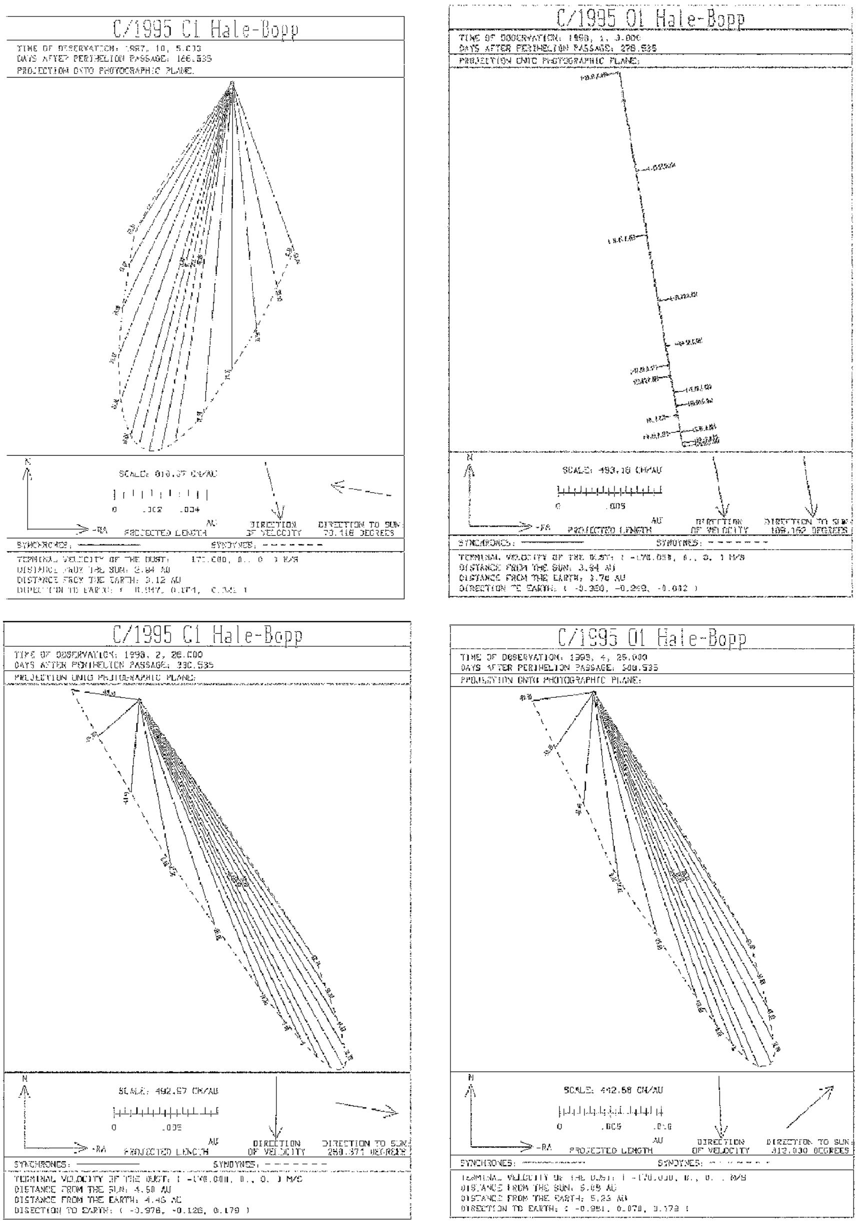

Figure 6. Synchrone-syndyne pattern of the dust anti-tail of Comet Hale–Bopp in late 1997 and early 1998 as seen in projection onto the sky of the observer. The synchrones (continuous lines) cover ±60 days around perihelion. The calculations are made for dust with $\beta = 0.0001$ (broken line) and initial velocity of 170 m/s in anti-solar direction (-x direction in Figure 5). The labels at the synchrones indicate the release time of the dust in days before (−) and after (+) perihelion passage of the comet (0.00 in the labels stands for $\beta = 0.0001$). The comet nucleus is indicated by a star symbol. The four subpanels show the location of the dust as projected into the sky for the observing dates in Figures 1 to 4.

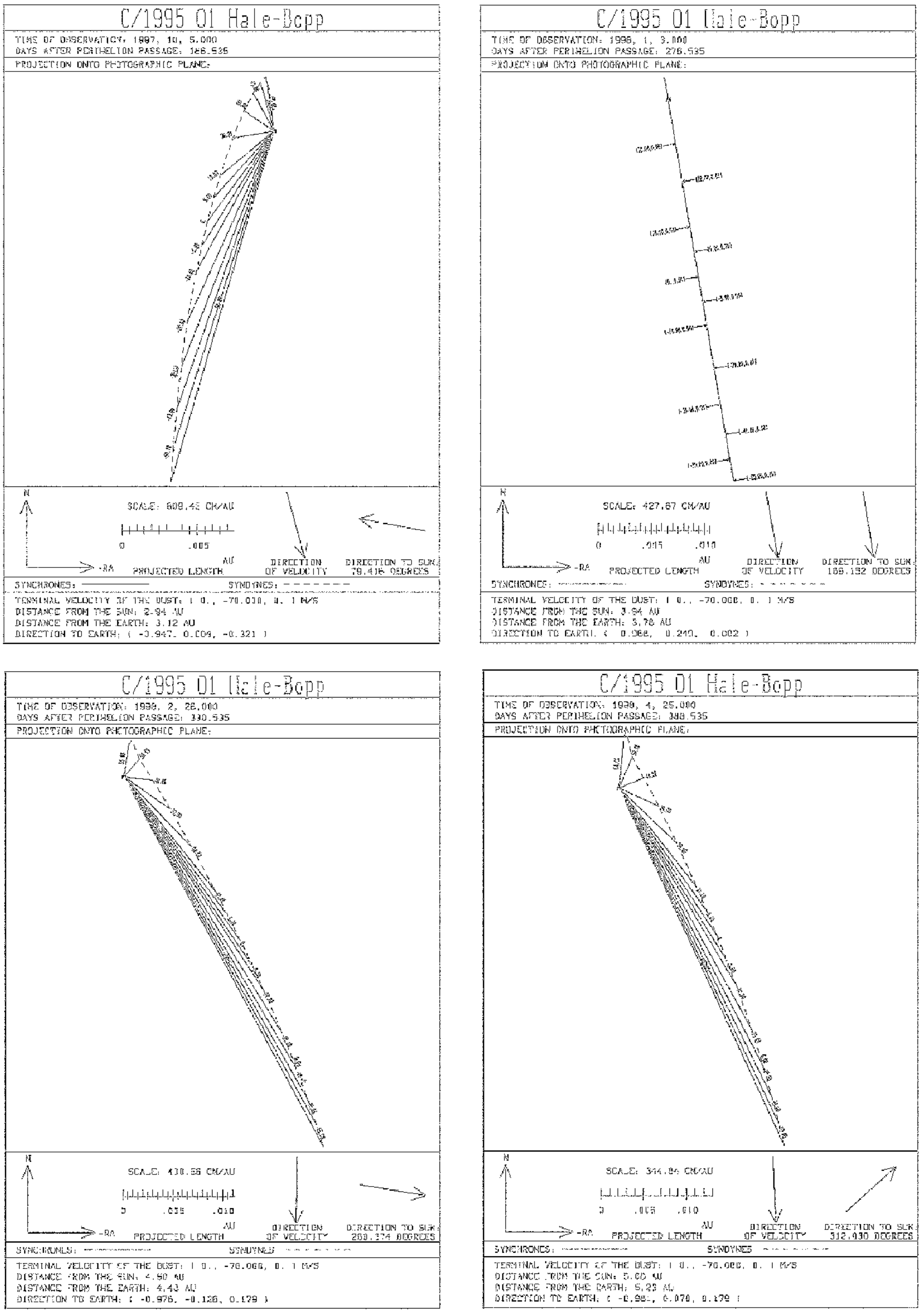

Figure 7. Synchrone-syndyne pattern of the dust anti-tail of Comet Hale–Bopp in late 1997 and early 1998 as seen in projection onto the sky of the observer. The synchrones (continuous lines) cover ±60 days around perihelion. The calculations are made for dust with $\beta = 0.0001$ (broken line) and initial velocity of 70 m/s in the orbital plane perpendicular to the radial direction and against the motion of the comet (-y direction in Figure 5). More explanations in caption of Figure 6.

500 m/s (Schütz 1997). Using results (Crifo, 1987) from hydrodynamic modeling of the dust expansion in the coma, one can expect terminal velocities between $\sim$150 m/s for 10^{-4} g particles ($\beta \sim 0.001$) and $\sim$30 m/s for 10^{-1} g particles ($\beta \sim 0.0001$), respectively.

Considering the inherent modeling and measurement uncertainties, it is difficult to exclude one of the two scenarii as being unlikely. Taking the results of Crifo (1987) as a reference, option (1) requires somewhat (but not unrealistically) higher dust expansion velocities, while option (2) needs a specific orientation of the dust ejection (assuming a similar total amplitude of the emission velocity at an inclination to sunward direction of about $\sim 30°$ for $\beta \sim 0.001$ grains) in order to produce the relatively high initial grain velocities against the orbital motion direction of the comet. The rather symmetric shading of the sunward neckline structure before and after perihelion passage would even argue that both scenarios may contribute to the populations of the dust in the neck-line structure of Comet Hale–Bopp (meaning that the period of heavy grain release lasted over the several months around perihelion).

The presented results combine geometric measurements and dynamical modeling of the peculiar dust tail of the comet and conclude that the observed anti-tail phenomenon requires the presence of particles of mm-size. The quantitative estimation of the size distribution of the dust population and the amount of dust actually necessary to explain the neck-line structure will require photometric calibration and numerical processing of the Schmidt plates on one side and modeling of the optical appearance of the dust on the other side.

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