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IC 349: BARNARD'S MEROPE NEBULA[1]

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ABSTRACT

IC 349 is the brightest area in the Pleiades reflection nebulosity, by a factor of about 15. Discovered visually by Barnard in 1890, it is a difficult object because it is only about 30″ from 23 Tau, of $V=4.2$. It is fan-shaped with the axis pointing very nearly toward 23 Tau. Its blue color and the fact that its spectrum appears identical to that of the star shows that it also is a reflection nebula. The general Pleiades nebulosity is the result of a chance encounter between the cluster and a molecular cloud at a relative cross motion of about 12 km s^{-1}. It is proposed that the semistellar object at the head of IC 349 is part of that cloud and is being dissipated in the radiation field of 23 Tau as it approaches that star. The relative velocity vector is obtained from the proper motion and radial velocity of the cluster, and the CO radial velocity of the nearby Tau-Aur clouds; the proper motion of IC 349 is inferred from the proper motions of the cloud T Tauri stars. The shape of the fan of IC 349 is compatible with a model in which small dust particles ejected from the nucleus are being swept backward by the combined effects of radiation pressure from 23 Tau and drag exerted by intercluster gas. It is unknown whether the nucleus is a dust-shrouded pre-main-sequence star or a dense concentration of gas and dust several hundred A.U. in diameter.

1. HISTORY

In 1890, while examining the brighter stars in the Pleiades with the Lick 36 in. refractor, Barnard (1891a) "... discovered a new and comparatively bright round cometary nebula close south and following Merope (23 Tau) ... It is about 30″ in diameter, of the 13 (magnitude), gradually brighter in the middle, and very cometary in appearance." He measured the center, again visually, as 9.″0 east, 35.″7 south of 23 Tau, and commented: "it can be readily understood why this, the brightest of all the Pleiades Nebulae, has never been photographed. A sufficiently long exposure to secure an impression of the nebula, would so overexpose Merope that its light would coalesce with that of the nebula."

Shortly thereafter, Barnard was taken to task by Pritchard (1891), seemingly incensed at what he regarded as Barnard's affront to the power of photography. Pritchard said that he himself had already noted "this apparently insignificant fleck" on an Oxford Astrograph plate of 1889, and had dismissed it as no more than the brightest portion of the widespread Pleiades reflection nebulosity.

Barnard (1891b) responded at length. He admitted that the nebula was indeed photographable, and in fact appeared on some 36 in. refractor plates already in the Lick files. However, he stressed that it ought not to be regarded as "an insignificant fleck": it was really a remarkable object, distinctly brighter and different in form from the stripes and wisps characteristic of the ordinary Pleiades nebulosity. As will appear later, this is quite correct: the surface brightness of IC 349 in V is about 15 times higher than that of the brightest areas of the familiar Pleiades nebulosity.

Barnard's Merope nebula, subsequently catalogued as IC 349, was measured the following year, again with the 36 in. refractor, by Burnham (1892), with similar results. Without mentioning Pritchard, Burnham supported his colleague Barnard with the statement that "judging from its situation and appearance, (IC 349) is one of the most singular objects in the heavens." He anticipated a question that, a century later, has yet to be answered: "whether the new nebula is drifting in space with Merope and the other stars of this famous group." Barnard himself reported new visual measurements made in 1895 (Barnard 1895).

All these visual measures agreed in locating the center of the "round, bright nebula" at 36″ from 23 Tau in P.A. 166°. There was no suggestion of a nucleus or a stellar condensation being present. Burnham in fact commented upon the absence of any such structure.

So ended the visual history of IC 349, followed shortly thereafter by a note by Keeler (1898), describing IC 349 as it appeared on a series of exposures obtained with the Crossley 36 in. reflector at Lick. There are six such plates in the Lick files taken between 1898 and 1900, and two others obtained in 1914–1915, probably by S. B. Nicholson. All confirm Keeler's description of the nebula as roughly pentagonal in shape, "with the most salient angle pointing directly to Merope," and bounded by two wisps of nebulosity.

More instructive, however, is a description by Trumpler (1922) of IC 349 on plates taken with the Allegheny 30 in. refractor, one of which is reproduced in his note. He de-

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[1] An expanded version of the Petrie Prize Lecture, given before the Canadian Astronomical Society in Penticton, B.C. in May 1995.

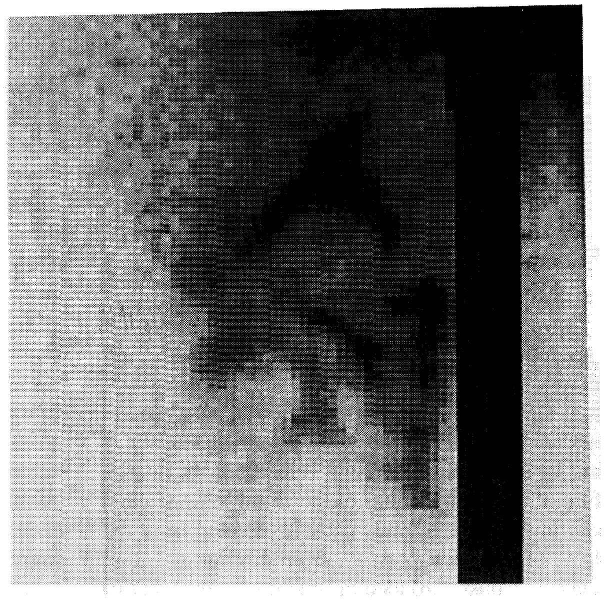

FIG. 2. IC 349: a 20 s exposure behind a B filter at the $f/10$ Cassegrain focus of the 88 in. telescope. The area shown is about 26″ square.

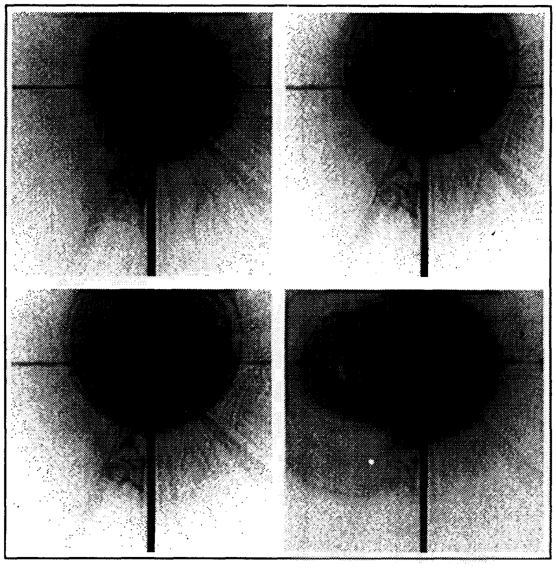

FIG. 3. Images of IC 349 behind a B filter (upper left), V (upper right), R (lower left), and I (lower right). The fact that there is no significant enhancement of the R-band brightness of IC 349 with respect to V and I is a crude indication that there is little contribution by Hα emission.

scribed the nebula as starting from "a marked round condensation (this was the first mention of any such feature in the nebula) from which two arms, about 10″ long, go out to the southeast and southwest forming nearly a right angle. Parallel to these and situated 7″ farther south are two similar lines also forming a right angle. The western edge of the nebula is well marked by a rather strong line running north-south." All this structure described by Trumpler is recognizable on modern images of IC 349 [see Figs. 1 (Plate 38) and 2].

More recently, in 1980–1981, several direct photographs of IC 349 were taken at the prime focus of the Lick 120 in. reflector. While setting up for these observations, the observer had to be struck by the brightness of IC 349: it is easily seen, particularly when the bright star was hidden behind a mask in the focal plane. Even better CCD images were obtained with the 88 in. reflector on Mauna Kea in 1993. Examples of these are shown in Figs. 1, 2, and 3. All this imagery confirmed the descriptions by Keeler and Trumpler, as far as they went. The nebula is pentagonal in outline, with its axis of symmetry pointing nearly but not exactly toward 23 Tau. At the apex is a semistellar knot, hereafter called the "nucleus." There is considerable structure within the pentagonal fan. There is a marginal suggestion of at least one wisp extending beyond the apex toward 23 Tau. The longer exposures show that IC 349 is superimposed upon a much fainter streak of the ordinary Merope nebulosity extending through the star toward about P.A. 157°; it can be seen dimly in Fig. 2.

There appears to be no important structure of IC 349 hidden by the bright vertical bar in Figs. 1 and 2 (a CCD artifact), nor is there any significant structure still nearer 23 Tau. This is demonstrated by conventional photographs taken with the Allegheny (Trumpler 1922) and Lick refractors, which have no such instrumental structure, and with the Lick 120 in. reflector, whose diffraction spikes are oriented at 45° to the meridian. This result was confirmed more recently by a CCD image taken with a coronagraphic device at the 88 in. telescope by Mr. Paul Kalas.

The resemblance of IC 349 to the well-known "cometary" nebulae at R Mon, HK Ori, and LkHα-208 is striking, but aside from it clearly being unipolar, it will be argued that IC 349 has a quite different explanation.

23 Tau itself is type B6 IVe. Its absorption lines are broad and shallow, a consequence of the large $v \sin i = 280$ km s^{-1} (Slettebak *et al.* 1992). Emission cores are present in the Balmer lines, and vary in intensity on a time scale of years (Slettebak 1982). The star is also slightly variable in light, with a period of 11.8 h (McNamara 1987).

2. PHOTOMETRY AND SPECTROSCOPY

A series of CCD frames centered on 23 Tau were obtained at the $f/10$ focus of the 88 in. telescope on 1993 November 23, under only fair photometric conditions. The detector was a Tektronix 2048^2 CCD behind *BVRI* filters; the field was about 7′ on a side. Exposures ranging from 5 to 60 s on the IC 349 field were matched with similar series on a standard region from Landolt (1991). The transformations from the instrumental to the Landolt *BVRI* system were defined adequately from those observations, but sky conditions deteriorated before an equally satisfactory solution for the extinction coefficients was possible, so coefficients determined on a good night earlier in the year with the same equipment had to be used instead. Consequently the present photometric results are of only fair quality. The reductions were carried out with the APPHOT package of IRAF, and with aperture diameters of 2.1, 3.8, and 5.0 arcsec; the seeing disk had a FWHM of 0.8 arcsec throughout.

TABLE 1. Magnitudes and surface brightnesses in IC 349.

Region	Δx (arcsec)	Δy (arcsec)	Aperture (arcsec)	V	$B-V$	S_V
nucleus	+6.5	−24.	2.1	16.14	−0.16	17.49
nucleus	–	–	3.8	15.36	−0.20	17.99
nucleus	–	–	5.0	15.02	−0.21	18.27
A	+2.	−29.	2.1	16.42	−0.19	17.77
B	+3.	−35.	3.8	15.74	−0.19	18.36
D	+7.	−30.	3.8	15.90	−0.31	18.52
F	+9.5	−26.	3.8	15.91	−0.38:	18.53
C	+5.5	−32.	3.8	15.66	−0.26	18.28
E	+7.5	−35.	3.8	16.39	−0.28:	19.01
G	+12.	−32.	3.8	16.38	−0.50:	19.00

TABLE 2. Surface brightnesses and colors of Pleiades nebulosity.

Region	Δx (arcsec)	Δy (arcsec)	O'Dell $S_{V'}$	O'Dell $B'-V'$	This paper S_V	This paper $B-V$
O'Dell I	−91.	−88.	21.11	−0.39	20.70	−0.22
O'Dell II	−91.	−189.	21.39	−0.31	20.98	−0.27
1	−47.	−172.	–	–	20.76	−0.10
2	+144.	−113.	–	–	21.18	−0.45
3	+148.	+161.	–	–	21.83	−0.5:

The nucleus of IC 349 is symmetric but nonstellar. It is nearly superimposed upon the narrow filament that defines the eastern edge of the fan, and so appears to be elongated in about P.A. 318°. One-dimensional Gaussians were fitted to the images of stars on all the CCD frames (except in I) in order to define the instrumental profile, and then subtracted quadratically from that of the core of the nucleus. The weighted mean FWHM of all the stars on all the frames was $0\farcs82$, and that of the core, following removal of the stellar profile, was $1\farcs32\pm0\farcs10$. There was no obvious dependence upon color.

The V and $B-V$ results are given in Table 1 for the nucleus, as measured through the three apertures, and for 7 points within the IC 349 nebulosity. The points measured are identified in Table 1 by their rectangular coordinates (in arcsec, x being positive to the east, y positive to the north) with respect to 23 Tau. The surface brightness S_V in mag arcsec^{-2} is simply the V magnitude corrected for aperture area.

The largest source of error in the data of Table 1 is the uncertainty in the correction for the background of scattered light from 23 Tau upon which IC 349 lies. The falloff with distance from the star was mapped by measuring on every CCD frame the flux at many points along radii extending from the star on either side of IC 349. The background level used in the reductions was then the flux read off smooth curves drawn through those points. This ignores, of course, the rays and streaks which issue irregularly from the star image; some can be seen in Figs. 1 and 3.

It is important to determine whether there is any significant color difference between IC 349 and the general reflection nebulosity illuminated by 23 Tau. The surface brightness was measured at two points in the field where the general nebulosity was quite bright, by the procedures and apertures just described. As a check, they were chosen to coincide with two of the areas in the Merope nebulosity that had been measured by O'Dell (1965). Some uncertainty arises from the fact that there is no area in these small CCD frames that is completely free of some trace of the general nebulosity. Three points of minimum brightness were found by inspection of POSS prints where the surface brightness was low, and the background level at these low points was used in the reductions. Some confidence in these background levels was provided by their agreement with measures of sky brightness on frames of nebula-free fields elsewhere in the sky that were taken the same night.

The two data sets are not closely comparable, however: O'Dell's measures were made through a 63″ diaphragm, while the present ones are the means of the fluxes through the three much smaller apertures. Furthermore, two of O'Dell's filter band passes were at 4110 and 4630 Å, on either side of the effective wavelength of the Johnson B filter near 4400 Å. It was assumed for the present purpose that the mean of the 4110 and 4630 Å fluxes is not far from B. Another of O'Dell's pass bands fell at 5620 Å, not far from the V passband near 5500 Å (no details of the filter characteristics were published), so again it could only be assumed that the 5620 Å passband is almost equivalent to V. Since O'Dell's measures were differential with respect to 23 Tau, they can then be converted to magnitudes arcsec^{-2} and colors ($S_{V'}$ and $B'-V'$), and are shown in Table 2. The S_V, $B-V$ results from the present observations are given in the last two columns. The last three entries refer to bright areas in filaments of the ordinary Pleiades nebulosity.

The present V surface brightnesses seem to be about 0.4 mag brighter than O'Dell's, although that may be only a consequence of the systematic differences between the two sets of data mentioned above.

Surface photometry of the Pleiades nebulosity has also been published by Johnson (1960), who measured UBV for three regions about 3′ from 23 Tau. His observations were made through a 150″ diaphragm and thus average over considerable structure in the filamentary nebulosity. Johnson's area 3′ south of the star includes O'Dell's II and region 1 of his Table 2(b), and for this area he measured $S_V=20.9$, $B-V=-0.13$. These are in reasonable agreement with the values in Table 2.

No effort was made to reproduce the photometry of Witt (1977) because his surface brightnesses were measured in the cardinal directions from 23 Tau, where CCD bleeding along columns and diffraction spikes is significant on these frames.

The conclusion is, however, that the $B-V$ colors of IC 349 and of the general Merope nebulosity, as measured here, are the same within their uncertainties. (The results from the R and I images are not reproduced here because of the difficulty of allowing adequately for the particularly complex scattered light background on those frames.) Furthermore, the present photometry does not differ significantly, as a system, from those of O'Dell and Johnson.

Comparison of Tables 1 and 2 shows that the surface brightnesses of the brighter areas in IC 349 are about 3 mag brighter than the brightest regions of the general nebulosity near 23 Tau, which according to O'Dell, are themselves the brightest points in the entire Pleiades.

Spectroscopy of IC 349 is difficult because of the scattered light background from 23 Tau. A photographic-region spectrogram obtained by Arny (1977) appears to be much like that of 23 Tau itself, although it is not clear what precaution was taken to exclude scattered light from the star. A Lick coude spectrogram ($R=6700$) of IC 349 in the red region, obtained in 1986 with a CCD and hence more readily corrected for background, shows only a weak continuum and a broad Hα absorption line with some noisy central emission structure. A properly exposed spectrum of 23 Tau itself, obtained at the same time, reveals that the latter is in fact the centrally reversed Hα core of the stellar spectrum. The entire Hα structure is very similar to that observed in 23 Tau in 1982 by Hanuschik *et al.* (1988). There is no sign in the IC 349 spectrum of narrow H or [S II] emission lines as might be expected if shocked gas were present.

Low-resolution ($R=760$) spectra of IC 349 were obtained in 1995 with the $f/31$ Cassegrain Faint Object Spectrograph on the 88 in. telescope at Mauna Kea. These showed that the Hα emission in the field around IC 349, much of it instrumentally scattered light from 23 Tau, was much stronger than it had been in 1986. The Hα emission in the nucleus of IC 349, and in the fan where the slit crossed it 7″.5 south of the nucleus, was stronger in the same proportion.

These observations indicate that IC 349, both nucleus and fan, are pure reflection nebulae that in color and spectrum do not differ detectably from the general Pleiades nebulosity. Furthermore, the 1986 and 1995 spectroscopy proves that IC 349 is indeed illuminated by 23 Tau, and responds to changes in the spectrum of that star.

3. THE BRIGHTNESS OF THE NUCLEUS

The question then arises: if it is seen entirely in scattered light from 23 Tau, what albedo would be required to explain the remarkable brightness of the nucleus of IC 349? Consider a perfectly white Lambertian disk illuminated by 23 Tau, and having in projection a circular outline of diameter D. Although in projection it appears only d_0 from the star, it can lie either in front of or behind the plane of the sky; assume that the star-nucleus line is actually inclined at an angle α to the sky plane, α being positive if the object is behind. If the illumination arrives at an angle i to the disk normal, and leaves at angle ϵ, then for simplicity assume that the disk normal bisects the angle between star and Sun, so $i=\epsilon=(\pi/2-\alpha)/2$. The actual area of the disk is $\pi D^2/4 \cos \epsilon$, so if F_* is the stellar flux at unit distance, the total amount of light scattered from the disk and received cm^{-2} at the Sun is

$$\frac{F_* \cos^2\alpha}{4\pi d_0^2} \frac{D^2 \cos \epsilon}{4} \frac{1}{r^2}, \tag{1}$$

where r is the distance from the Sun. The star itself contributes $F_*/4\pi r^2$ at the Sun, so the observed magnitude difference between nucleus and star is

$$V_{\text{nuc}}-V_* = -2.5 \log\left(\frac{\cos^2\alpha \cos[(\pi/2-\alpha)/2]}{4}\right) - 5 \log\left(\frac{D}{d_0}\right). \tag{2}$$

TABLE 3. Calculated V magnitudes and Bond Albedo for a Lambertian Disk illuminated by 23 Tauri.

α (°)	V_{nuc}	A
−60	14.69	0.17
−30	12.79	0.03
0	12.10	0.015
30	12.19	0.02
60	13.26	0.04

The nucleus has a FWHM of 1″.54 or about 210 A.U. on the V frames, before allowance for seeing. Table 2 contains its V magnitude as measured through several larger apertures; extrapolated to an aperture of 1″.54, then $V=16.63$, and since $V_*=4.17$ and $D=210$ A.U., the ideal "white Lambertian scatterer" magnitudes V_{nuc} of Table 3 follow. The last column contains the Bond albedo A that would have to be assigned to the nucleus to account for the fact that it is $V-V_{\text{nuc}}$ magnitudes fainter than this calculation predicts.

Clearly, at this resolution the non-stellar nucleus of IC 349 resembles a dark, dusty surface. The result is much the same if the calculation is carried out for the V's and larger apertures in Table 3.

4. THE MOTION OF IC 349

It is now generally recognized that the reflection nebulosity in the Pleiades is the result of a chance encounter between the star cluster and a molecular cloud, very probably an outlying fragment of the extensive Tau-Aur dark nebulae which lie to the east and south of the Pleiades. Arny (1977) was apparently the first to point this out in print, when he suggested that some of the filamentary structure of the Pleiades nebulosity could be caused by the movement of the cluster stars with respect to the nebulosity. The same view was made more specific by Jones & Herbig (1979), Gordon & Arny (1984), White (1984), Breger (1987), and in greatest detail by White & Bally (1993).

Despite all the photographic plates, some of them over a century old, which lie in observatory archives and contain images of IC 349, there is as yet no astrometric information on the relative motion of that nebula with respect to the Pleiades stars. As a consequence, there is no proof that IC 349 is not a dynamical member of that cluster. That seems improbable, however, because (a) the nucleus of IC 349 is not stellar, (b) its color is not that expected of a stellar member of the cluster having $M_V \approx +10$, (c) nor is there any indication in the optical spectrum of the presence of a K- or M-type dwarf (as would be expected at that luminosity).

Since its color is in fact comparable to the bluish colors of the Pleiades reflection nebulae, we pursue the assumption that the nucleus of IC 349 is a dust condensation or a dusty star belonging to the Tau-Aur clouds, that it is being carried toward 23 Tau by the relative motion of cluster and cloud, and that it is now in the process of being dissipated in the radiation field of that star.

If the nucleus of IC 349 is moving with the Tau-Aur clouds, whose main structures lie about 5° to the east, then the relative motion of IC 349 and 23 Tau can be estimated because the proper motion of the clouds can be inferred from that of the T Tauri stars imbedded within them. The nearest concentration of TTS lies between $l=168°$ and 170°, $b=-15°$ and $-17°$. The mean proper motion for the 17 TTS in this subcloud as determined by Jones & Herbig (1979) is: $\mu_\alpha=+0\farcs61\pm0\farcs91$ cent^{-1}, $\mu_\delta=-2\farcs77\pm0\farcs71$ cent^{-1}, where the second figures are the standard deviations of an observation of unit weight. Reduced to the position of the Pleiades, these become $+0\farcs91\pm0\farcs91$, $-2\farcs64\pm0\farcs71$.

According to Ungerechts & Thaddeus (1987) and Fukui & Mizuno (1991), the CO radial velocity of this subcloud, referred to the LSR, is $+7.5\pm1$ km s^{-1}. The mean radial velocity of the Pleiades is -3.0 ± 0.2 km s^{-1} (Morse *et al.* 1991; Liu *et al.* 1991; Rosvick *et al.* 1992). The proper motion of the Pleiades is well determined; Olano & Pöppel (1987) give it as $\mu_\alpha=2\farcs0\pm0\farcs1$ cent^{-1}, $\mu_\delta=-4\farcs2\pm0\farcs1$ cent^{-1}.

It must be noted, however, that these two motions are not precisely on the same system: that of the Pleiades is near the FK4 (Jones 1973), while the T Tauri motions were referred to a network of AGK-3 stars (Jones & Herbig 1979). The difference is not believed to be large, but the matter will be clarified when *Hipparcos* results become available.

If these proper motions are taken literally, then the relative cross motion of the clouds with respect to the cluster is 12 km s^{-1}, and at the Pleiades, the clouds and IC 349 are moving at $1\farcs9$ cent^{-1} toward P.A. $325^{+30°}_{-32}$ with respect to the cluster mean. (The uncertainties on the position angle are the outer dimensions of the error box defined by the uncertainties and dispersions in all the proper motions and radial velocities.)

If these calculations are carried through instead with the mean proper motions of all 75 TTS in the entire Tau-Aur cloud complex, and with the overall average CO velocity, the results are not significantly different. The relative velocity vector is then $2\farcs3$ cent^{-1} toward P.A. $334^{+22°}_{-26}$, which is now 15 km s^{-1}.

The nucleus is currently 25″ from 23 Tau in P.A. 164°, which means that in either case, in projection it is moving in the general direction of the star; see Fig. 4.

As will be shown later, this result is consistent with the fact that the dust fan of IC 349 is symmetric with respect to the direction of 23 Tau. That is, if the nucleus was instead moving across that direction, radiation-pressure driven dust particles would define a strongly curved banner, convex in the direction of motion, contrary to what is observed at IC 349.

On the other hand, it has to be pointed out that the direction of relative motion inferred in this way conflicts severely with that deduced by White & Bally (1993) from the cavity extending east and south of the Pleiades that can be seen in *IRAS* images. White & Bally interpret this feature as the wake of the cluster as it moves through the ambient interstellar medium. If so, then it indicates that the medium is moving with respect to the cluster towards about P.A. 95°. This is not the direction inferred from the TTS, P.A. 325°. There is no obvious explanation of this disagreement if the layer of interstellar material seen by *IRAS* belongs to the Tau-Aur clouds which contain the TTS. This issue will be considered again in Sec. 6, below.

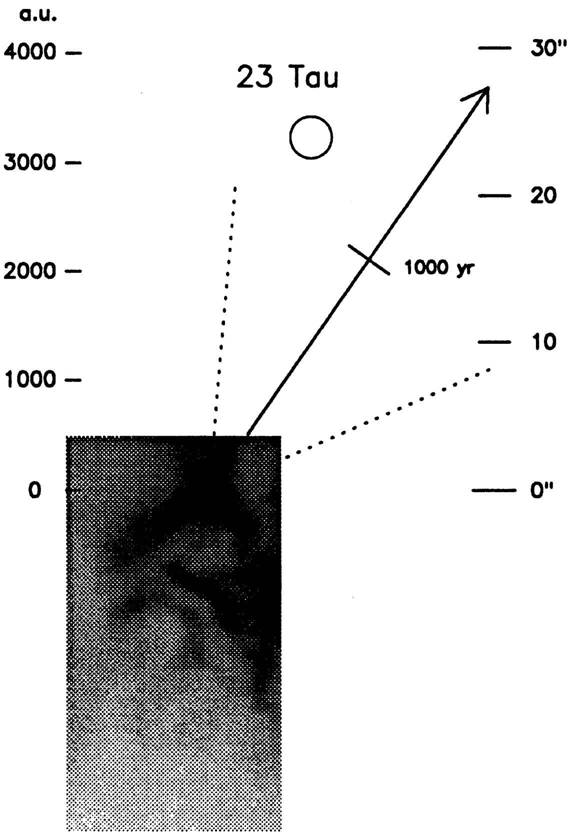

FIG. 4. The velocity vector of the nucleus of IC 349, projected on the plane of the sky (solid line). The dashed lines indicate the uncertainty in direction of the vector that results when the errors and dispersions of all the quantities involved combine to maximum effect. The motion in the next 1000 years assumes the values of the proper motion of IC 349 with respect to the Pleiades that are derived in the text.

5. THE TEMPERATURE OF THE NEBULAR DUST

The ejection of dust from a nonstellar object in the neighborhood of a star is reminiscent of the situation of a comet near the Sun, where the comet's nucleus is warmed to the point that frozen volatiles evaporate, and in escaping carry dust with them. This analogy will be pursued here as far as it remains instructive.

The temperature of the nucleus of IC 349 is not known. IC 349 is not apparent on the coadded *IRAS* images, possibly because of their low angular resolution. However, the temperature that the dust will assume in the radiation field of 23 Tau can be estimated. That would establish whether the dust is at least warm enough for frozen materials such as CO to evaporate.

TABLE 4. Predicted dust grain temperatures.

Separation (au)	T (K) $a = 10^{-6}$ cm	T (K) $a = 10^{-5}$ cm
3400.	98	82
3700.	95	80
4000.	92	78
5500.	83	70
7000.	77	65

The temperature of a particle illuminated by 23 Tau can be obtained from the expression which equates the heating by absorption with the cooling by thermal emission:

$$\int_0^\infty Q_{\rm abs}(a,\lambda)\pi a^2 F_*(\lambda)d\lambda = \int_0^\infty Q_{\rm abs}(a,\lambda)4\pi a^2 \pi B(\lambda,T)d\lambda, \tag{3}$$

where $F_*(\lambda)$ represents the flux received by the particle.

The Mie efficiency factors $Q_{\rm abs}$ for "astronomical silicate" particles can be calculated from the optical constants tabulated by Draine (1985). An estimate of the flux received by the particle from 23 Tau was assembled from that measured between 0.12 and 0.32 μm for the unreddened B6 V star HD 90994 by *IUE* (Wu *et al.* 1983). The fluxes between 0.33 and 1.08 μm as compiled by Breger (1976) and as measured by O'Connell (1973), and the flux densities at 2.3, 3.6, and 4.9 μm given by Gehrz *et al.* (1974) were joined to the *IUE* data. Below 0.12 μm, the surface fluxes for $T_e = 14\,500$ K and $\log g = 4.0$ as tabulated by Kurucz (1979) were adjusted for the radius of a normal B6 V according to Andersen (1991), the distance of HD 90994, and for compatibility with the *IUE* fluxes in the region of overlap. Finally, these fluxes were corrected for the difference in absolute magnitude between 23 Tau (B6 IV) and HD 90994 (B6 V), and reduced to a standard distance of 1 A.U. The total flux of 6.1×10^8 ergs cm^{-2} s^{-1} thus obtained is comparable with that inferred from Schmidt-Kaler's mean M_V's for B6 V and B6 IV and Andersen's $L/L_\odot$ for B6 V (7.0×10^8).

The expression (3) can be solved for T when d, the distance from 23 Tau is specified. At the distance of the Pleiades (135 pc), the projected distance of the nucleus from 23 Tau of 25″ corresponds to about 3400 A.U. Table 4 gives the calculated T's for the two particle sizes for that and several larger values of the separation, it being unlikely that the nebula lies precisely in the plane of the sky. These temperatures are significantly higher than the blackbody equivalent of Eq. (3). This can be seen if $Q_{\rm abs}$ is set to unity in Eq. (3); the resulting T at 3400 A.U. is 30 K, independent of particle size.

Of course all this assumes that there is no internal source of heat within the nucleus, as, for example, from a central star or as the result of viscous heating.

According to the review by Rickman (1992), a substantial fraction of the CO in a CO:water ice mixture would evaporate at 50–100 K. Presumably CO frost on the surface of silicate grains would evaporate at still lower temperatures, so it could be, given the temperatures in Table 4, that the outflow of dust in IC 349 is driven by evaporating CO. However, since we are ignorant of conditions at the surface of the nucleus of IC 349, and entirely so of what lies inside, this is no more than a plausible place to start.

6. MODELING THE NEBULA

The motion of very small silicate particles launched from the nucleus of IC 349 will be controlled by the radiation pressure from 23 Tau, by the gravitation of both the nucleus and 23 Tau, and by drag from the material of the ambient Pleiades nebulosity. It is possible to compute the motion of such a particle under simplifying assumptions.

For the calculations of particle trajectories to follow, $M_{\rm nuc}$ has been taken to be 0.1 $M_\odot$. In that case, the velocity of escape at the $r_0 = 90$ A.U. level (half of the measured FWHM) is 1.4 km s^{-1}. However, a particle propelled upward with a velocity of only $0.7v_{\rm esc}$ will ascend to a peak altitude of r_0, but it will usually not fall back because by that time it will have been caught up and swept away by the radiation pressure of 23 Tau. Whatever $M_{\rm nuc}$, under this circumstance, ejection velocities of about $0.7v_{\rm esc}$ and greater will be sufficient to remove the particle from the gravitational domain of the nucleus.

The most serious conceptual assumptions that are imbedded in the following calculations of particle trajectories are:

(a) It is assumed that the particle is composed of Draine's "astronomical silicate," that those optical properties hold through the spectrum, and that the grain is nearly enough spherical that conventional Mie Q's are meaningful.

(b) No account is taken of the likelihood that a range in particle sizes is present.

(c) It is assumed that except for deceleration due to collisions with the ambient gas, the particle properties do not change during flight: they experience no mass change due to sputtering or accretion, and they interact with the medium with a drag coefficient of unity.

(d) It is assumed that the particle's motion, once it is free of the nucleus, is thereafter not influenced by any gas released at the same time.

(e) The possibility that radiation pressure could be reinforced by a wind from 23 Tau has been ignored.

Numerical assumptions are:

(f) That the mass of the nucleus itself is not large; as noted, it was taken as 0.1 $M_\odot$ for these calculations.

(g) That the motion of the nucleus is nearly enough in the plane of the sky that projected separations are meaningful.

(h) That the dust particles emerge from the nucleus with a significant radial velocity $v_{\rm ej}$. A value of $v_{\rm ej} = 9.0$ km s^{-1} at a distance of $r_0 = 90$ A.U. has been used in these illustrative calculations for silicates of radius $a = 10^{-6}$ cm, because that number reproduces the observed opening angle of the nebular fan. This angle depends on the ratio of $v_{\rm ej}$ to the magnitude of the radiation pressure/drag force, the latter decreasing as particle size increases. Thus any opening angle can be preserved by simultaneously adjusting $v_{\rm ej}$ and a in opposite directions.

The trajectory of the particle was followed in a coordinate system traveling with the nucleus, and in which the nucleus, its velocity vector and 23 Tau lie in the xy plane. The x axis coincides with the velocity vector of the nucleus with respect to 23 Tau, but points in the opposite direction. The star is located at some positive y, defined by the assumption as to the direction of the motion of the nucleus.

The equations of motion are then

$$\ddot{x}=+\frac{GM_*}{d^2}\sin\theta-\frac{GM_{\rm nuc}}{r^2}\frac{x}{r}-\frac{I}{cd^2}\frac{3}{4\rho a}\sin\theta \pm\frac{3n_Hm_H}{4\rho a}(v_x-v_*)^2, \tag{4}$$

$$\ddot{y}=+\frac{GM_*}{d^2}\cos\theta-\frac{GM_{\rm nuc}}{r^2}\frac{y}{r}-\frac{I}{cd^2}\frac{3}{4\rho a}\cos\theta \pm\frac{3n_Hm_H}{4\rho a}v_y^2, \tag{5}$$

$$\ddot{z}=-\frac{GM_*}{d^2}\frac{z}{d}-\frac{GM_{\rm nuc}}{r^2}\frac{z}{r}+\frac{I}{cd^2}\frac{3}{4\rho a}\frac{z}{d}\pm\frac{3n_Hm_H}{4\rho a}v_z^2, \tag{6}$$

where

$$I=\int_{0.05\ \mu{\rm m}}^{10\ \mu{\rm m}} Q_{\rm pr}(\lambda)F_*(\lambda)d\lambda. \tag{7}$$

Here, d is the distance of the particle from 23 Tau, r is its distance from the nucleus, θ is the angle at the nucleus between the positive y axis and the direction to 23 Tau (θ is negative in the second quadrant), ρ is particle density (as above, taken to be 3.0 g cm^{-3}), and v_* is the velocity of the nucleus with respect to 23 Tau and to the ambient medium. It is assumed to be 12 km s^{-1}, following Sec. 4. The particle density in the medium through which the nucleus is moving in n_H.

Given the starting coordinates of a particle which, at distance r_0 from the center of the nucleus, moves radially away at velocity $v_{\rm ej}$, then Eqs. (4), (5), and (6) can be integrated numerically step by step, and the subsequent motion of the grain followed. In the present calculations, a new group of particles of radius $a=10^{-6}$ cm was released at each increment of the motion of the nucleus along the x axis. They were launched from 32 points spread uniformly over the surface of the nucleus, and were followed individually thereafter. Experiment showed that in most cases the shape of the resulting fan did not depend upon details near r_0, for example, whether the nucleus was a disk or a spherical envelope, or whether the particle velocity contained an orbital motion component. Nor did the opening angle depend on the mass assumed for the nucleus, for example if $M_{\rm nuc}$ were taken to be 1.0 instead of 0.1 $M_\odot$.

Two extreme cases can be visualized depending upon the density of the ambient medium: A: if the gas density is low, say $n_H \approx 5$ cm^{-3}, then drag is a minor effect and the motion of the dust leaving the nucleus is controlled largely by the combined effect of $v_{\rm ej}$ and the velocity at which the grain is driven by radiation pressure. In this case, the third term in Eqs. (2)–(4) predominates. At the other extreme is B:n_H is large, >100 cm^{-3}, in which case the major force on the dust is the drag resulting from the motion of the nucleus through the ambient medium; the 4th term predominates.

In case A the fan axis would be directed toward 23 Tau, in B it would lie along the velocity vector of the nucleus. The direct images show that the fan axis points very nearly at 23 Tau, but according to Sec. 4, the nucleus is moving in approximately the same direction (Fig. 4). Since sufficiently precise proper motion information is lacking, one cannot now choose between the two possibilities.

Figure 5 shows the evolution of IC 349 as modelled by this procedure, Fig. 4 being taken into account. The projection is on the xy plane, which is the plane of the sky, and is viewed from the direction of positive z. The diagram in the upper left shows the path of the nucleus, moving leftwards along the x axis toward the origin, where the nucleus is assumed to be located at the present time, 3400 A.U. from 23 Tau. The angle between the velocity vector and the direction toward 23 Tau at the origin is taken as 5°. The three other panels show the predicted shape of the IC 349 fan at the present time if dust ejection began 3000 years ago (C), 2000 years (B), or 1000 years before the present. (The slight curvature of the motion of the nucleus with respect to the x axis is not shown in the diagram.)

The size of the individual points in these plots is greatest for those particles released when the nucleus was nearest 23 Tau, and smallest at the start of ejection. They have no other quantitative significance.

If there had been no information on the direction of motion of IC 349 with respect to 23 Tau (Fig. 4), one might have considered the possibility that it is moving not in the general direction of that star, but even at a large angle to it. As an illustration of the consequence, a similar calculation was carried out for the specific example of the nucleus approaching the cluster not toward P.A. 325° but toward P.A. 95°, which is the direction envisaged by White & Bally (1993). In that case, the nucleus must have passed the point of minimum angular separation from 23 Tau several hundred years ago, as shown in the sketch in the upper left panel of Fig. 6. The other panels show the predicted structure of IC 349 if ejection of dust had begun 1000, 2000, or 3000 years before the present. In all cases, the fan would have been curved, convex to the direction of motion, as is seen in the dust tails of comets passing near the Sun. Of course, this assumes that radiation pressure is the dominant force acting upon the dust. If drag by intercluster gas were dominant, the fan would not be curved but then the fan axis would lie along the velocity vector, not toward 23 Tau as is observed. Since no curvature in the plane of the sky is observed, the direction of motion toward 325° (Figs. 4 and 5) must be nearer the truth than that it moves toward 95° (Fig. 6).

Of course, that same curvature presumably is present in the three-dimensional fans of Fig. 5, but because there the velocity vector is so nearly directed toward 23 Tau, the curvature is in the line of sight and so is not seen in projection, although it does have the effect of limiting the apparent extension of the fan.

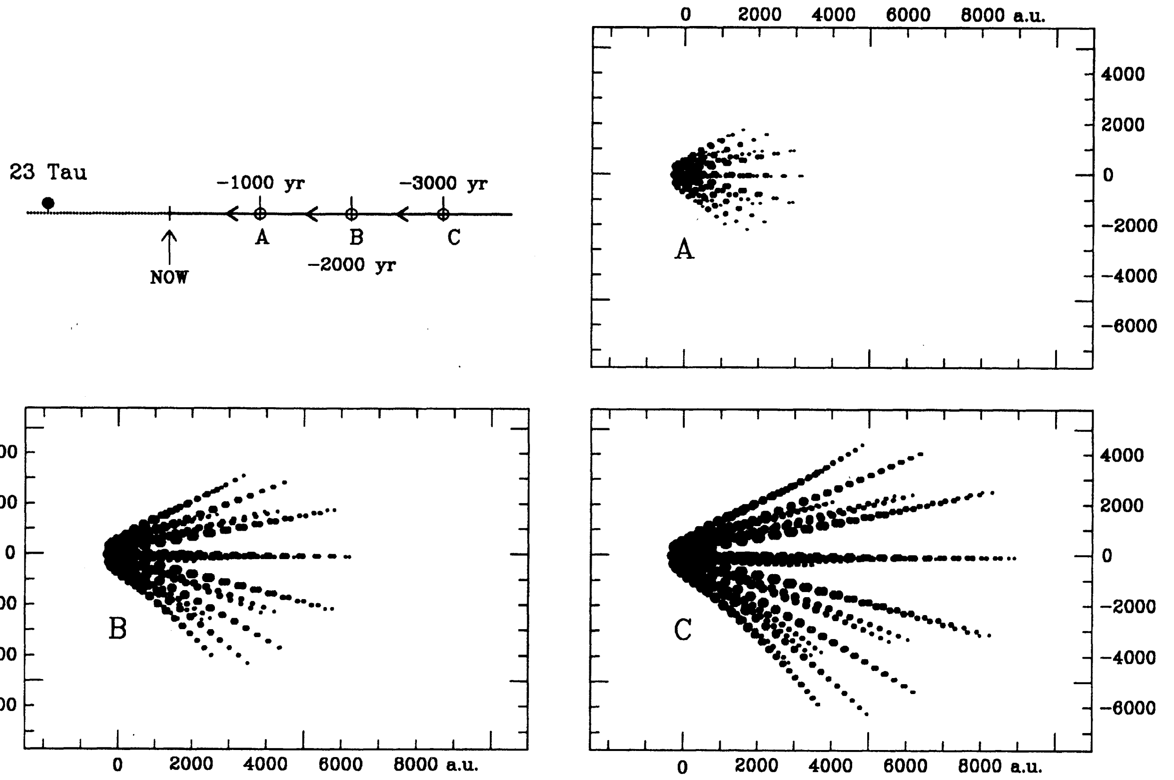

FIG. 5. Three snapshots of the development of the dust fan of IC 349 as it moves along the vector of Fig. 4 toward its present position, as calculated by the procedure of Sec. 6. The diagram on the upper left shows the three starting positions: 1000, 2000, and 3000 years before the present. The significance of the dot sizes is explained in the text.

Such calculations do reproduce the general outline of the IC 349 fan, at least near the apex, but the match leaves something to be desired. The arc and filaments within the fan are not explained at all, although one can imagine complications that could be added to the model that might account for such structures, such as rotation of the nucleus, or intermittent or nonisotropic ejection, or time variation of v_{ej}. But the time for elaborating this simple model will come when better information on the input parameters—radial velocity, proper motion, expansion velocity—becomes available.

7. MASS LOSS

The outer edge of IC 349 on the present images is about 2200 A.U. from the nucleus. The modeling of Sec. 6 gives the time t_a required for a silicate grain of radius a to be swept out to that distance. For $a=10^{-6}$ cm, t_a is about 900 years, so all such material now in the nebula has been ejected during that time. The models say nothing about the amount of dust involved, but under simplifying assumptions that quantity can be estimated from the surface brightness of the fan. Thereby one obtains a value of $\langle \dot{M}_a \rangle$, the average *dust* mass-loss rate over the last t_a years. The procedure is as follows.

All the V-band luminosity of the fan is assumed to be single-scattered radiation of 23 Tau. The angle θ and the projected separation of a particle from 23 Tau were defined in Sec. 6. The scattering angle at the particle is $\alpha=\theta+\pi/2$, so if F_* is the V-band flux emitted by 23 Tau, the flux scattered by the particle in the direction α toward the Sun is, per unit solid angle,

$$\frac{F_*}{4\pi d^2}\sin^2\alpha\,\pi a^2 Q_{\rm sca} f(a,\alpha), \tag{8}$$

where $f(a,\alpha)$ contains the directional dependence of the scattering. In this case, the Henyey–Greenstein function was used:

$$f(a,\alpha)=\frac{1-g^2}{4\pi}\,\frac{1}{(1+g^2-2g\cos\alpha)^{3/2}}, \tag{9}$$

where $g=\langle\cos\alpha\rangle$ and follows from Mie theory, given particle radius and optical constants. Let N be the total number of scatterers in a given cm^2 column of the nebula, so that if $v_{\rm neb}$ is the surface brightness of the nebula not in magnitudes arcsec^{-2} at the Sun but in magnitudes cm^{-2} at the source,

$$N=\frac{d^2}{\pi a^2\sin^2\alpha\, Q_{\rm sca} f}\,2.512^{V_*-v_{\rm neb}}. \tag{10}$$

If the column is not optically thin, however, this expression becomes

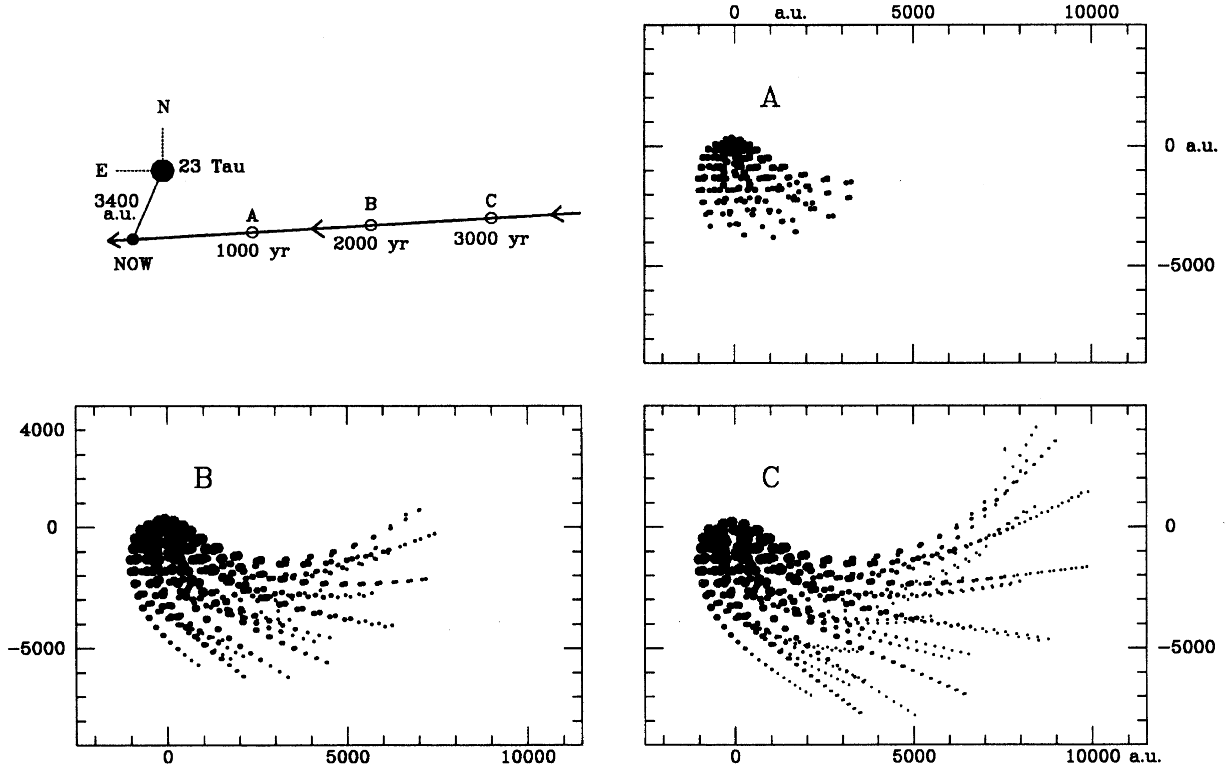

FIG. 6. Three snapshots of the development of the dust fan of IC 349, as in Fig. 5, but now the motion of the nucleus toward its present position is assumed to be in the direction of P.A. 95°, instead of toward 325°. Since radiation pressure is always directed away from the star, the axis of the fan turns as the nucleus moves along its trajectory. Such curvature is not observed for IC 349.

$$N = -\frac{1}{c_3}\log_e\left(1-\frac{1}{c_2}2.512^{V_*-v_{\rm neb}}\right), \tag{11}$$

where $c_2=\gamma f\sin^2\alpha/d^2$, and $c_3=\pi a^2 Q_{\rm sca}/\gamma$, the particle albedo being γ.

The surface brightness across the V and B images of the IC 349 fan was measured for about 300 small areas, each 3×3 pixels square, or 0.″63 on a side, covering essentially all the fan except for the immediate area of the nucleus. Conventional V, $B-V$ values were extracted for each of the elements of this array by the photometric procedures of Sec. 3, and converted to dust column densities as above. The particle column densities for each 3×3 pixel area are then $(0.63\times135\times1.496\times10^{13})^2N$.

The results, summed over the entire fan, are shown as N_a in Table 5 for $a=3.0\times10^{-6}$ and 3.0×10^{-5} cm, and $\theta=0°$. The third column gives $M_a=N_a 4\pi a^3\rho/3$, the dust mass if all the light of the nebula is scattered by silicate grains of that single size. The fourth column contains t_a in years, from the modeling of Sec. 6, the time required for a substantial fraction of the ejected dust to have been driven out to about 2200 A.U. in the fan. From these follow the average silicate mass-loss rate $\dot{M}_a$, in column 5.

The amount of gas which accompanies this dust is unknown. If one were prepared to assume that the ejected material contained all the elements in their normal cosmic proportions, but that all the Si was bound up in the $Mg_{1.1}Fe_{0.9}SiO_4$ grains (Draine & Lee 1984), then the ratio total mass: silicate grains is about 2400:1. The last column of Table 5 gives the $\dot{M}_a$'s multiplied by that factor.

Formally, this ratio is consistent with the assumptions as to grain size and composition that were made to make the calculations, but it cannot be justified on physical grounds. Grains of other sizes and compositions surely contribute to the surface brightness of the fan. Nor does one know if the surface layers of the nucleus contain all the elements in their cosmic proportions.

At the other extreme would be the supposition that the surface brightness of the nucleus is produced by the kind of grains responsible for conventional interstellar extinction in the visual, and that they all have the average $a=2.0\times10^{-5}$ cm. The optics of reflection nebulae suggest that both γ and g are about 0.7, so that if $Q_{\rm sca}=1.0$ and the grains are largely ice, with $\rho=1.0$ g cm^{-3}, then the numbers in the last row of Table 5 follow. If these grains contain *all* the condensible heavy elements in the gas, then the mass ratio of gas: grains would be about 60:1. The last column of Table 5 shows $\dot{M}_a$ scaled up by that factor.

All these guesses for $\dot{M}$ are surprisingly high, although they are comparable with mass-loss rates found for pre-main-sequence stars. But it would be prudent not to take them too seriously. Mass-loss rates, and the total mass lost by the nucleus during its passage near 23 Tau, and hence to what

TABLE 5. The mass of dust in the IC 349 fan.

a (cm)	log N_a	M_a ($M_\odot$)	t_a (yr)	$\dot{M}_a$ ($M_\odot$/yr)	gas/dust	$\dot{M}_{\rm tot}$ ($M_\odot$/yr)
3.0(−6)	44.257	3.083(−5)	1000.	3.083(−8)	2400	7.40(−5)
3.0(−5)	39.991	1.671(−6)	1200.	1.392(−9)	2400	3.34(−6)
2.0(−5)	40.948	1.495(−6)	1000.	1.495(−9)	60	8.97(−5)

degree it will survive that passage, await spectroscopy of the gaseous component of IC 349.

In all the foregoing, the nucleus has been regarded as if a surface exists; i.e., that it is optically thick. This assumption can be tested as follows. If all the silicate particles ejected are of radius a, and the total number in the fan is N_a (Table 5), and if all have been ejected at velocity $v_{\rm ej}$ over a time interval t_a, then the average particle density just above the "surface" is $n_a = N_a/4\pi r_0^2 t_a v_{\rm ej}$. If the opacity of the nucleus is due entirely to such particles, and particle density is uniform throughout the interior, then the optical thickness through a diameter is $\tau = 2r_0 n_a Q_{\rm ext}\pi a^2$. For the case of $a = 3.0\times10^{-6}$ cm, $\tau = 0.52$. The result is essentially the same if $a = 3.0\times10^{-5}$ cm. Clearly these are lower limits on τ: the density surely increases inward, and particles of other sizes contribute to the opacity. But the calculation does show that the concept of an opaque nucleus at optical wavelengths is consistent with the other parameters obtained here.

8. DISCUSSION AND CONCLUSIONS

With the information now on hand, one can only speculate on the true nature of the nucleus of IC 349. In the optical, it is not self-luminous: it is seen only in scattered light from 23 Tau. Infrared imaging may reveal whether or not there is a star inside. Until that can be established, two possibilities present themselves:

(a) There is a pre-main-sequence star deep inside, and what we see is the periphery of its circumstellar envelope (or disk) being dissipated.

(b) Or, it is a high-density condensation belonging to the Tau-Aur clouds, and it is the surface layers that are being swept away.

If (b) were the case, one could account for the rarity of objects like IC 349 by the fact that the duration of such a phenomenon would be short if the illuminating star were at rest with respect to the surrounding nebulosity. That is usually the case where the star was formed nearby, in that same cloud. This would be the conventional situation, and especially so for stars of higher mass having short main-sequence lifetimes. The situation at the Pleiades is quite different, since there the association of cluster and cloud is a transient one, and so one ought not to be surprised if unusual phenomena of relatively short duration might be observable.

Whether (a) or (b) is nearer the truth, one naturally wonders if objects like IC 349 can be found elsewhere. There is a heavy bias favoring the Pleiades because of its nearness, and because of the special circumstance of its association with the molecular cloud. The situation at the Orion Nebula is quite different, because that region is dominated by the ionizing radiation field and winds from the Trapezium OB stars. At that distance, the nucleus of IC 349 would have V about 17.5, and a FWHM of about 0.″4. A number of such "fuzzy stars" have been known in the Orion Nebula for many years. They are detectable on direct images obtained in near-infrared passbands chosen to avoid the stronger emission lines of the H II region. More recently, many such objects have been detected near the Trapezium by direct imaging with the *HST* (Prosser *et al.* 1994; Stauffer *et al.* 1994; O'Dell *et al.* 1993; O'Dell & Wen 1994), and by infrared imaging from the ground (McCaughrean & Stauffer 1994; Hayward *et al.* 1994; McCullough *et al.* 1995). Since point sources are detectable in most of these "compact objects," the general opinion seems to be that they are circumstellar envelopes around low-luminosity stars that are ionized and shaped by the radiation and winds from the Trapezium stars. The most massive component of the Trapezium has a main sequence lifetime of about 5×10^6 yr, so one would have to account for the survival, or regeneration, of such objects on such a time scale. Clearly, the encounter of the nucleus of IC 349 with 23 Tau is of much shorter duration, and involves a dust shroud of much greater optical thickness.

As noted above, the phenomenon postulated to be taking place at IC 349 is analogous to that observed in comets near the Sun, where the nucleus is warmed sufficiently that frozen volatiles such as CO evaporate, and in escaping carry dust with them. The cometary values of $v_{\rm ej}$ are expected to be near the thermal velocity of the escaping gas, which for H_2O and CO at $T = 300$ K is about 0.6 km s^{-1}. Actual determinations from the shapes of infrared and radio-frequency lines have given values of 1–2 km s^{-1} for comets at $r \approx 1$ A.U. from the Sun (Combi 1989; Bockelée-Morvan *et al.* 1990; Larson *et al.* 1991); i.e., somewhat higher than expected. The calculations which generated Figs. 5 and 6 and which reproduce the observed opening angle of the fan of IC 349 necessarily assume that $v_{\rm ej} = 9$ km s^{-1}. This is very much larger than the thermal velocity of volatiles at about $T = 100$ K (0.3–0.4 km s^{-1}), the temperature calculated in Sec. 5. Very obviously, the cometary analogy breaks down here.

If a much smaller $v_{\rm ej}$ were preferred, it is true that the opening angle of the resulting fan could be preserved by increasing the particle size. For example, if $a = 10^{-5}$ instead of 10^{-6} cm, the shape of the fan would be about the same if $v_{\rm ej}$ were then taken as 6 km s^{-1} instead of 9 km s^{-1}. However, this is a very artificial solution, requiring a carefully contrived particle population. Nevertheless, it seems unavoidable that dust is being ejected from the nucleus as the result of some internal activity, not because of the heating of the surface by 23 Tau. One may see in this fact some support for possibility a, above.

It is important that an effort be made to measure the value of $v_{\rm ej}$ directly, as would be possible if CO emission were detectable from IC 349. This will be a nontrivial observation, because ^{12}CO maps of the area, very kindly made available by John Bally, show no sign of IC 349. Such an observation would not only provide $v_{\rm ej}$ from the line profile, but would give the radial velocity of IC 349 as well.

Submillimeter observations are also recommended. Zuckerman & Becklin (1993) have reported a measurement of 23 Tau at 800 μm, but with a beam size FWHP of only about 18″, so that there could have been in that signal only a minor contribution from IC 349.

If a direct determination of the proper motion of the nucleus also became available—to replace the indirect estimate from *T* Tauri stars that was used here—then this entire exercise could be repeated on a firmer basis.

It goes without saying that better observations of IC 349 at almost every frequency and angular resolution, including infrared imaging, improved spectroscopy, and polarization studies, would be of great interest.

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REFERENCES

Andersen, J. 1991, A&A Rev., 3, 91
Arny, T. 1977, ApJ, 217, 83
Barnard, E. E. 1891a, Astron. Nach., 126, 293
Barnard, E. E. 1891b, Astron. Nach., 127, 135
Barnard, E. E. 1895, Astron. Nach., 139, 41
Bockelée-Morvan, D., Crovisier, J., & Gérard, E. 1990, A&A, 238, 382
Breger, M. 1976, ApJS, 32, 7
Breger, M. 1987, ApJ, 319, 754
Burnham, S. W. 1892, Astron. Nach., 129, 17
Combi, M. R. 1989, Icarus, 81, 41
Draine, B. T. 1985, ApJS, 57, 587
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Fukui, Y., & Mizuno, A. 1991, in Fragmentation of Molecular Clouds and Star Formation, IAU Symposium No. 147, edited by E. Falgarone, F. Boulanger, and G. Duvert (Kluwer, Dordrecht), p. 275
Gehrz, R. D., Hackwell, J. A., & Jones, T. W. 1974, ApJ, 191, 675
Gordon, K. J., & Arny, T. T. 1984, AJ, 89, 672
Hanuschik, R. W., Kozok, J. R., & Kaiser, D. 1988, A&A, 189, 147
Hayward, T. L., Houck, J. R., & Miles, J. W. 1994, ApJ, 433, 157
Johnson, H. M. 1960, PASP, 72, 10
Jones, B. F. 1973, A&AS, 9, 313
Jones, B. F., & Herbig, G. H. 1979, AJ, 84, 1872
Keeler, J. E. 1898, PASP, 10, 245
Kurucz, R. L. 1979, ApJS, 40, 1
Landolt, A. U. 1991, AJ, 104, 340
Larson, H. P., Hu, H.-Y., Hsieh, K. C., Weaver, H. A., & Mumma, M. J. 1991, Icarus, 91, 251
Liu, T., Janes, K. A., & Bania, T. M. 1991, ApJ, 377, 141
McCaughrean, M. J., & Stauffer, J. R. 1994, AJ, 108, 1382
McCullough, P. B., Fugate, R. Q., Christou, J. C., Ellerbroek, B. L., Higgins, C. H., Spinhirne, J. M., Cleis, R. A., & Moroney, J. F. 1995, ApJ, 438, 394
McNamara, B. J. 1987, ApJ, 312, 778
Morse, J. A., Mathieu, R. D., & Levine, S. E. 1991, AJ, 101, 1495
O'Connell, R. W. 1973, AJ, 78, 1074
O'Dell, C. R. 1965, ApJ, 142, 604
O'Dell, C. R., Wen, Z., & Hu, X. 1993, ApJ, 410, 696
O'Dell, C. R., & Wen, Z. 1994, ApJ, 436, 194
Olano, C. A., & Pöppel, W. G. L. 1987, A&A, 179, 202
Pritchard, C. 1891, Astron. Nach., 126, 397
Prosser, C. F., Stauffer, J. R., Hartmann, L., Soderblom, D. R., Jones, B. F., Werner, M. F., & McCaughrean, M. J. 1994, ApJ, 421, 517
Rickman, H. 1992, in Interrelations between Physics and Dynamics for Minor Bodies in the Solar System, edited by D. Benest and C. Froeschlé (Editions Frontières, Gif-sur-Yvette)
Rosvick, J. M., Mermilliod, J.-C., & Mayor, M. 1992, A&A, 255, 130
Slettebak, A. 1982, ApJS, 50, 55
Slettebak, A., Collins, G. W., & Truax, R. 1992, ApJS, 81, 335
Stauffer, J. R., Prosser, C. F., Hartmann, L., & McCaughrean, M. J. 1994, AJ, 108, 1375
Trumpler, R. 1922, PASP, 34, 165
Ungerechts, H., & Thaddeus, P. 1987, ApJS, 63, 645
White, R. E. 1984, ApJ, 284, 695
White, R. E., & Bally, J. 1993, ApJ, 409, 234
Witt, A. N. 1977, PASP, 89, 750
Wu, C.-C., *et al.* 1983, The *IUE* Ultraviolet Spectral Atlas, *IUE*/NASA Newsletter No. 22
Zuckerman, B., & Becklin, E. E. 1993, ApJ, 414, 793

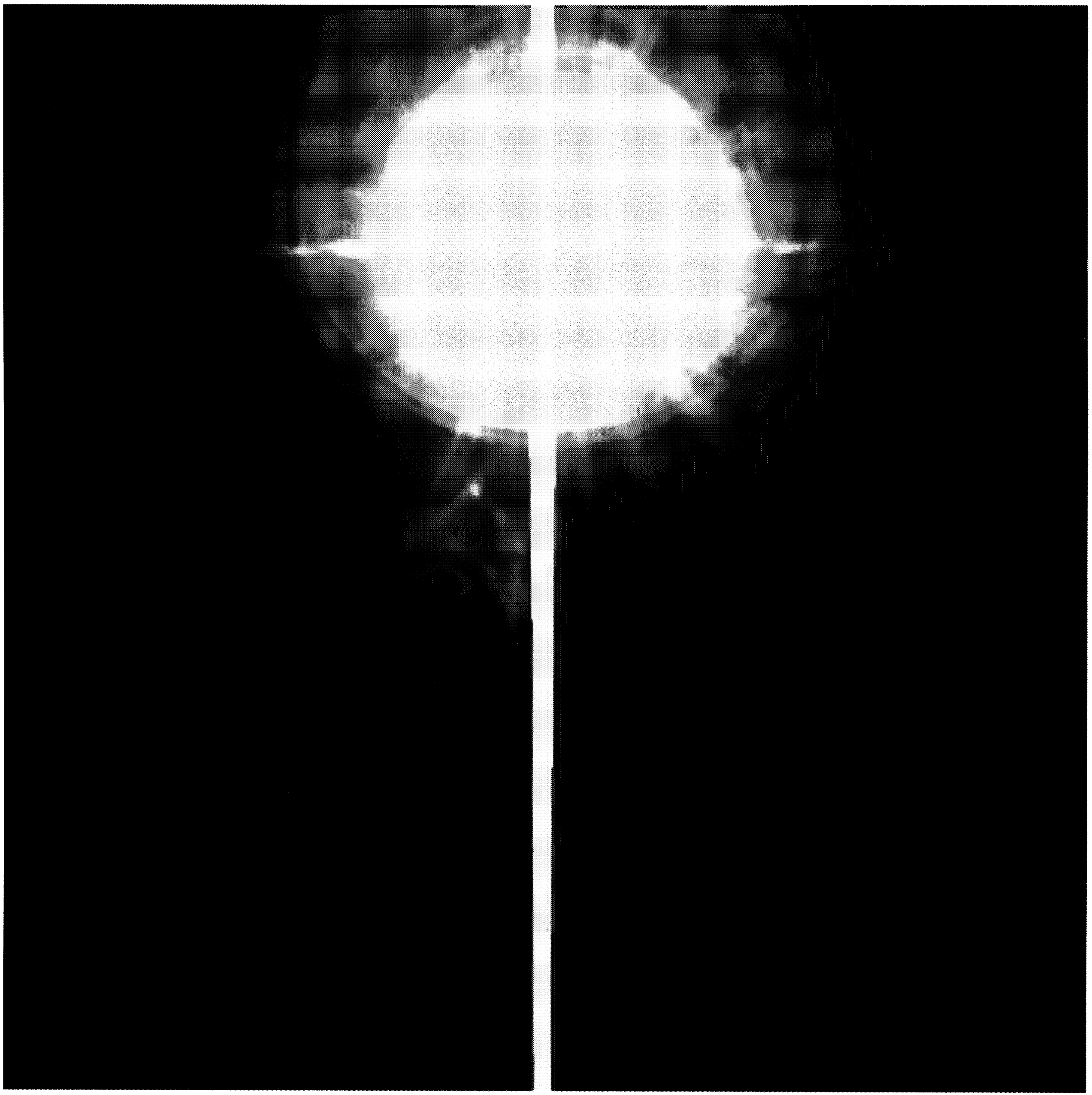

FIG. 1. IC 349 and 23 Tauri. This is a false-color image produced by combining the *B*, *V*, and *R* frames in proportions to reproduce approximately the colors of the field stars. The area shown is about 110″ on a side. In this and the following figures north is at the top and east to the left. The bright vertical bar through the image of 23 Tau is a CCD artifact.

G. H. Herbig (see page 1242)