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BARNARD'S MEROPE NEBULA (IC 349): AN INTERSTELLAR INTERLOPER

JOHN C. BARENTINE
National Optical Astronomy Observatories,[1] P.O. Box 26732, Tucson, AZ 85726-6732; johnb@noao.edu

AND

GILBERT A. ESQUERDO
Planetary Science Institute,[2] 620 North Sixth Avenue, Tucson, AZ 85705; esquerdo@psi.edu
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ABSTRACT

Barnard's Merope Nebula (IC 349) is the optically brightest portion of the diffuse nebulosity that envelops the Pleiades but is not morphologically similar to those nebulae. Knowledge of its true space motion can help clarify whether the object has a kinematic association and possibly a common origin with the Pleiades. Here we report a mean radial velocity result obtained in 1996 from spectra where $\bar{v}_{\rm hel} = -44.4$ km s^{-1} and $\sigma_v = 5.42$ km s^{-1} ($N = 5$). The radial velocity result is presented along with recent values for the object's proper motion, yielding its space motion vector. Galactic space velocity components $(U, V, W) = (50.6 \pm 5.3, -10.3 \pm 6.7, 11.3 \pm 6.4)$ km s^{-1}, referred to the LSR, were calculated for the object. In addition, the region was observed in the near-infrared to determine if a protostellar object is present within the dusty envelope of the nebula; to an equivalent luminosity upper limit of $L = 0.23 \pm 0.05\ L_\odot$, none was observed. These results suggest that IC 349 is kinematically unrelated to the Pleiades and that it does not harbor a protostellar object in its dusty interior.

Key words: ISM: individual (IC 349) — ISM: kinematics and dynamics — open clusters and associations: individual (Pleiades) — techniques: radial velocities

1. INTRODUCTION

Barnard's Merope Nebula (catalog designation IC 349), shown in Figure 1, is among the most enigmatic features of the nebulosity enveloping the Pleiades, significantly differing in morphology from other features observed in and around the cluster. It is this dissimilarity that makes its study important.

The history of the nebula's observation and details of those observations have been collected recently by Herbig (1996). Rather than consisting of the diffuse, tenuous type of nebular material typically associated with the Pleiades, IC 349 is described by Herbig as having an appearance similar to the various cometary nebulae. Arny (1977) was among the first to associate the morphology of the nebula with a possible mechanism to explain its current appearance. He described IC 349 as a clump of dusty nebular material being "blown back" by the radiation pressure of the young Pleiades cluster stars.

To aid in modeling the nebula's motion in the radiative environment of 23 Tauri, Arny attempted to obtain a value for the radial velocity of IC 349 in 1977 with the Kitt Peak National Observatory (KPNO) 2.1 m telescope. His results yielded a value of +5 km s^{-1}, indicating that relative to 23 Tau, IC 349 is virtually at rest. This implies a kinematic association between the nebula and the Pleiades, suggesting that the object may have formed there; this conclusion is, however, at odds with the observation that it does not "fit" morphologically. We hypothesized that IC 349 is a foreign object in the Pleiades on the basis of observational evidence and, as a consequence, expected an observable radial velocity difference between 23 Tau and IC 349. An attempt was made to measure the heliocentric radial velocity of IC 349 by using the Fourier cross-correlation method of Tonry & Davis (1979). This velocity may be compared against velocity fields in the nearby vicinity, including that of the Pleiades cluster itself, to observe any velocity correlation and hence to illuminate IC 349's origin.

Herbig (1996) has advanced two hypotheses regarding the physical nature of IC 349 as a means of explaining the appearance of the nebula. The first concerns the notion that the so-called Nucleus ($\alpha = 3^{\rm h}46^{\rm m}21^{\rm s}.3$, $\delta = +23^\circ56'28''$; J2000.0) of IC 349, identified as the brightest knot of material in the nebula, is a protostellar object embedded in a dusty envelope. To address this issue, we observed the nebula in the near-infrared to detect the signal from any object that might be inside the dusty Nucleus. The other hypothesis regards the nebula as a "high-density condensation belonging to the Tau-Aur clouds"; we compared the space motion of IC 349 with that of several Tau-Aur cloud stars to test this suggested origin.

2. OBSERVATIONS AND REDUCTIONS

2.1. *High-Resolution Spectroscopy*

We obtained optical wavelength spectra on the position of the brightest portion of IC 349 during 1996 January 26–29 at the KPNO Coudé Feed telescope. A combination of camera 5 and grating B was employed to produce images with the F3KB CCD detector at a resolving power of $R \simeq 27{,}000$. The wavelength band covered by the observations was centered at 3917.3 Å and was approximately 500 Å wide. For both the object and the comparison spectra, a 300 μm–wide slit was used to achieve optimal image densities. Object spectra were imaged with the large set of openings on decker No. 2 at a setting of 6, yielding a slit length of $15''.0$ as projected on the sky. Comparison spectra for wavelength calibration were taken of a ThAr source before and after each object spectrum integration. No sign of the nebula was seen in the TV camera normally

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[2] A division of the San Juan Capistrano Research Institute.

FIG. 1.—IC 349 in a 45 minute exposure taken at the KPNO 4 m telescope on 1973 November 2. North is at top and east at left; the image is approximately 155″ tall by 120″ wide. Merope (23 Tau) is shown at top and IC 349 at bottom left. The spectrograph slit used in obtaining optical spectra was positioned on the bright knot of nebulosity closest to 23 Tau.

used for guiding, and as a result, direct guiding on the nebula was impossible. Offset guiding, involving the repositioning of the slit every 10 minutes during the integrations, was used instead to maintain the slit's position on the coordinates of the Nucleus by compensating for field rotation.

Five integrations, each of 3600 s duration, were taken; each integration was reduced separately with an individual comparison spectrum for wavelength calibration. In addition, high (> 300) signal-to-noise ratio comparison spectra of 23 Tau were obtained on the first and second nights. A spectrum consisting of the five integrations averaged with the IRAF routine IMCOMBINE is shown along with the 23 Tau comparison spectrum in Figure 2. Radiation events recorded on the chip during the integrations were manually removed in the SPLOT routine by altering pixel values to the continuum level in the regions affected by the events. To aid in discerning the true light of the Nucleus from the scattered light of 23 Tau, the spectra were extracted in the long-slit fashion.

The IRAF routine FXCOR was used to carry out Fourier cross-correlations of the processed spectra. We used 23 Tau as the radial velocity standard for the calculation of the nebula's heliocentric radial velocity. Each of the five individual object spectra was cross-correlated with the comparison spectrum; for the " template " velocity in FXCOR, a value of $+5.5 \pm 2.2$ km s^{-1} (Morse, Mathieu, & Levine 1991, p. 1506) for 23 Tau was used. The results of these five calculations are given in Table 1.

TABLE 1

RADIAL VELOCITY RESULTS

Integration Start (1996 Jan UT)	R.V. (km s^{-1})
26.122	-39.8 ± 0.5
26.173	-39.9 ± 0.6
26.232	-51.0 ± 0.5
26.275	-40.1 ± 0.9
27.132	-51.0 ± 1.0
Mean	-44.4
σ	5.42

NOTES.—Results from Fourier cross-correlation of spectra of the " Nucleus " of IC 349 and 23 Tau along with the mean and standard deviation of the velocities. Start times for each integration are given in UT decimal days in 1996 January; uncertainties in the individual radial velocities are those computed by FXCOR, which are probably underestimates of the actual uncertainties.

In addition to observations of IC 349 and 23 Tau, spectra were obtained of several bright Pleiades member stars, as well as nonmember stars of similar spectral type, as a check of the accuracy of the measurement process. The radial velocities of these stars were determined in the same fashion as for the Nucleus, using the same template spectra of 23 Tau; these values are shown in Table 2 along with reference velocities from other observers.

TABLE 2

STELLAR RADIAL VELOCITIES

HD	$v_{\rm hel}$	σ_v	N	Ref. v	Ref. σ_v	N
23302	+4.4	0.1	2	+8.9[a]	0.1	2
				+10.9v[b]	2.3	8
				−0.3[c]	11.0	14
23338	+4.4	0.1	1	+12.5v[a]	3.7	7
				+4.2[b]	2.1	12
				+5.9v[c]	8.2	12
23408	+4.4	0.3	2	+7.6[a]	0.4	2
				+8.3[b]	3.4	8
				+7.3[c]	9.9	11
23630	+4.5	0.3	1	+7.9[a]	2.4	7
				+8.9[b]	4.4	10
				+0.9[c]	5.3	11
23850	+4.6	0.5	1	+16.4[a]	3	1
				+7.5[b]	3.7	12
				−0.4[c]	10.7	13
23862	+4.6	0.4	1	−4.2[a]	3	1
				+6.9[b]	0.7	3
				−2.5[c]	7.6	9
47105	−15.4	0.9	1	−12.5[d]	0.9	35
73262	+22.5	0.9	1	+11[d]	5.8	44
74198	+32.0	1.2	1	+28.7[d]	4.6	20
79469	−16.5	0.8	1	−8[d]	12.2	16
80081	+11.6	1.5	1	+1.6[d]	1.9	23
87901	+10.5	0.5	1	+3.5[d]	2.6	32

NOTES.—Radial velocity data for observed bright Pleiades member stars and noncluster reference stars. Radial velocities are those computed via FXCOR; uncertainties in the velocity are those determined by FXCOR and are likely underestimates. Mean reference velocities and uncertainties are given along with the number of observations used in determining the means. Velocities and their uncertainties in all cases are given in km s^{-1}.

[a] Liu et al. 1991.

[b] Pearce & Hill 1975.

[c] Abt et al. 1965.

[d] Wilson 1953.

2.2. *Near-Infrared Imagery*

To check the validity of the protostellar object hypothesis, observations were made with the Diffraction Limited Infrared Imager (DLIRIM) on the KPNO 4 m telescope operating at Cassegrain focus on 1996 April 1. DLIRIM takes a series of short integrations on both the object and the sky to account for background variations, and consequently each frame in the series is background limited. A series of images was made in the unguided mode in the *L*′

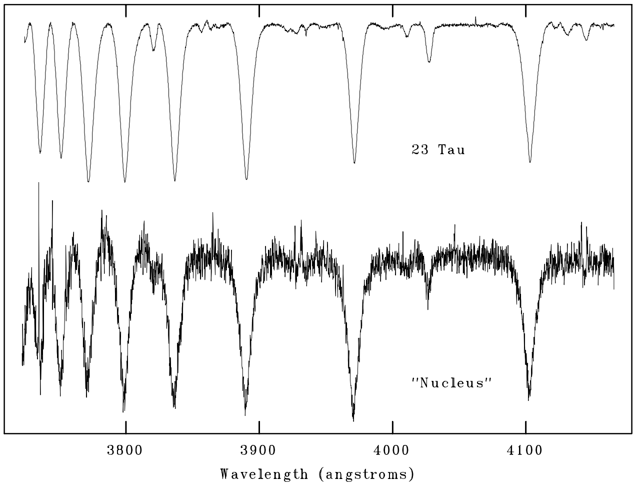

FIG. 2.—Spectrum of 23 Tau (*top*) and the combined spectrum of the position of the " Nucleus " of IC 349 (*bottom*). The continua in both spectra have been set to arbitrary values for display purposes.

(3.8 μm) wavelength band; during this time the telescope was positioned on the location of the Nucleus. The total integration time on the position was 0.2 s.

3. DISCUSSION OF RESULTS

3.1. *The Radial Velocity Measurement*

The cross-correlation functions (CCFs) yielded a mean value for the radial velocity of $\bar{v}_{\rm hel} = -44.4$ km s^{-1}, with $\sigma_v = 5.42$ km s^{-1}. The magnitude of the velocity obtained is significantly higher than either the systemic velocity of the cluster ($V_{\rm hel} + 6.0 \pm 0.5$ km s^{-1}; Liu, Janes, & Bania 1991) or that of 23 Tau. However, it is noted that the heliocentric radial velocity measured from Earth contains as components not only the true radial motion of the Nucleus, but also a contribution from the relative radial velocity between IC 349 and 23 Tau and, possibly, one caused by the expansion of ejected dust from the surface of the Nucleus. This concern is addressed further in § 3.2.

The role played by scattered light in these observations was a principal concern. To determine the effect of this contribution, a 3600 s integration was made at a position 23''.8 north and 6''.2 west of 23 Tau: the same angular distance and a position angle of 180° away from the location of the Nucleus with respect to 23 Tau. This spectrum yielded a velocity of -7.1 ± 1.7 km s^{-1} when cross-correlated with the spectrum of 23 Tau, clearly suggesting the observation of scattered light from the surrounding nebulosity rather than from within the instrument. In addition, this offset-position observation was of lower flux than the "on target" measurement, further supporting the argument that instrumentally scattered light from 23 Tau was not a factor in these observations.

The reliability of the velocities determined by FXCOR was tested by fitting Gaussian profiles to the broad hydrogen lines in the offset-position spectrum with SPLOT, manually calculating their velocity shifts and then applying heliocentric corrections to the resulting values. In this manner we found a mean radial velocity of -9 km s^{-1} and a σ of 6 km s^{-1} with $N = 4$; individual velocities had errors, derived from line center rms errors in SPLOT, of approximately 5 km s^{-1}. This result agrees reasonably with the FXCOR value.

3.2. *Uncertainty in the Velocity Measurement*

The cited errors of the individual radial velocities are uncertainties in the width and position of the CCF peak. As a result, they do not reflect any velocity contribution other than the radial component of the nebula's space velocity. In addition, fluctuations of measurement because of the finite precision of the measuring instrumentation are present, represented statistically by the sample variance s^2. The value of the sample standard deviation for these velocities is $s = 6.06$ km s^{-1}, and each of the individual velocity measurements falls within an interval of 2s. Thus, we deduce that all of the velocity values are valid within the instrumentational error limit.

The angle between IC 349 and the plane of the sky passing through 23 Tau is unknown; as a result, it is impossible to know the relative radial velocity between the two objects. Since the Nucleus is seen entirely in light reflected from 23 Tau, any radial velocity component between the two objects will be added to that of the actual radial velocity between Earth and the Nucleus. Herbig's (1996) analysis indicates that the nebula must be moving almost directly toward the star to produce the observed shape of the dust fan. Given his value for the current distance of the nebula from 23 Tau and his estimate of the amount of time until the nebula's position corresponds with that of the star, the velocity between the two objects is approximately 8 km s^{-1} in approach. This results in a correction to our radial velocity insufficient to affect our conclusion regarding the kinematic independence of these objects.

At least a small amount of the measured radial velocity can be attributed to the presumed ejection of dust from the Nucleus and cannot be discerned from other velocity components in the optical regime. As suggested by Herbig (1996), the dominant method of dust particle ejection from the Nucleus, which accounts for the presence of the "fan" in optical images of IC 349, appears to be sublimation of CO ices from the surfaces of dust grains. To account for the shape of the dust fan, an ejection velocity $v_{\rm ej}$ of 5 to 10 km s^{-1} is necessary; further studies, perhaps involving CO spectroscopy, might allow direct measurement of this velocity. The presumed value of the ejection velocity does not significantly affect the space motion conclusions reported here.

3.3. *Near-Infrared Observations*

Our near-infrared imagery yielded no detection of any object at the position of the Nucleus. As a result, we can offer only an upper limit for the luminosity of a hypothetical object based on an apparent magnitude defined by the noise level of the detector. A value for the observed flux from the position of the Nucleus was obtained through aperture photometry of the object image and an image of the photometric standard star HD 129655 using a circular aperture 10 pixels in radius in the IRAF task APPHOT. Using a flux calibration value of 200 μJy for an $m_{L'} = +15.2$ object (IRTF 1986, p. 21), we computed an upper limit for the observed flux from the Nucleus as defined by the noise level. Given the *Hipparcos* value (ESA 1997) for the distance to 23 Tau ($\simeq$110 pc), we determined an upper limit of $m_{L'} = +11.5$ at the 3 σ noise level. This apparent value corresponds to an absolute limiting magnitude of $M_{L'} = +6.3$. This information allowed for the calculation of the irradiance of the Nucleus over all wavelengths at the distance of Earth (6×10^{-13} W m^{-2}) and, hence, an upper limit for the luminosity of an object at the position of the Nucleus.

4. ANALYSIS

4.1. *Space Motion of IC 349*

Our value for the radial velocity of IC 349 represents a significant departure from Arny's value. Arny likely failed to measure the true light from the nebula, and his method was prone to measurement of scattered light from 23 Tau, resulting in the similarity in velocities. Furthermore, Arny's measurement involved the fitting of a velocity-shifted reference line to the Hζ line in his spectrum, which yielded less precise results than the method used here.

Even within the limits of error, our value suggests a strong kinematic *disassociation* with the Pleiades cluster members. The radial velocity dispersion of the Pleiades is $\sim$1 km s^{-1} about the mean (Liu et al. 1991), which rules out IC 349's membership in the cluster. IC 349 is an interloper in the Pleiades and does not appear to have formed there originally. Furthermore, it is apparently unrelated to the interaction of the cluster and the interstellar medium, as proposed by White & Bally (1993), since it does not share the velocity of that component of the interaction. Given our value for the radial velocity, the characteristic time of the nebula to cross the Pleiades is of order 10^5 yr, assuming a cluster width of 5 pc.

Recent proper-motion studies of IC 349, when combined with our radial velocity, have allowed determination of an approximate space motion vector. Preliminary results, measured by B. Jones (1997, private communication) on a 13 yr baseline with the Lick Observatory 3 m telescope, suggest proper-motion values of $\mu_\alpha = -1\farcs52 \pm 0\farcs87$ per century and $\mu_\delta = 1\farcs54 \pm 1\farcs52$ per century relative to the motion of the Pleiades. These values, along with our radial velocity, were used to calculate the Galactic space velocity components of IC 349, $(U, V, W) = (50.6 \pm 5.3, -10.3 \pm 6.7, 11.3 \pm 6.4)$ km s^{-1}. Figure 3 shows the projection of the space motion vectors of IC 349, several Pleiades member stars (HD 23302, 23338, 23408, 23630, 23850, 23862), and several T Tauri stars in the Tau-Aur clouds (T Tau, GI Tau, SU Aur, RY Tau) into the U-V velocity plane. The T Tauri stars chosen for inclusion in the figure were those with the least uncertain published radial velocity values. Parallax, proper-motion, and radial velocity data for the U, V, W calculations were taken from Herbig (1977) and the *Hipparcos* Catalogue (ESA 1997) with the exception of the Pleiades radial velocities, where our values from Table 2 were used. Clearly, the nebula's space motion does not correspond with the two velocity groups in the figure, indicating an origin outside of both systems.

4.2. *Viability of IC 349 as a Protostellar Environment*

Our data yield a value of $L = 0.23 \pm 0.05\ L_\odot$ as an upper limit for the luminosity of an object at the distance of IC 349. At this luminosity, any object ostensibly embedded in the Nucleus is not likely to be protostellar. The extant dust envelope around the Nucleus and our nondetection in the near-infrared indicate that nuclear ignition has not taken place; thus, we consider only the evolution of stars that have not begun deuterium burning in this analysis. Based on the detailed evolutionary tracks of very low mass stars by D'Antona & Mazzitelli (1985, 1994), the locus of the D-burning line at our computed luminosity value corresponds to an upper mass limit of $M = 0.15\ M_\odot$ for a protostellar object. This mass limit is similar to the $0.1\ M_\odot$ value used by Herbig (1996) in his simulation of the evolution of the nebula's dust fan in time, which reproduces well the shape of the fan. The absence of emission lines characteristic of pre–main-sequence stars in the spectrum of IC 349 suggests the lack of a protostar regardless of mass. We conclude from these observations that there is not a protostellar object embedded in IC 349. Rather, it appears that the nebula is merely a large clump of dust that lacked a sufficient amount of gas to undergo star formation. Its space motion does not correspond to that of the T Tauri stars in the Tau-Aur clouds, which have been found to be strongly linked kinematically to the clouds by Herbig (1977). Thus, we have dismissed a protostellar origin in these clouds on the basis of the space motion discrepancy.

Our conclusion is not reconciled with Herbig's (1996) contention that dust ejection from the Nucleus is the result of internal activity rather than photoelectric heating by 23 Tau. It is not yet apparent at this time what the mechanism of heating is that drives dust production in the Nucleus. However, the ejection pattern of dust from the Nucleus is neither spherically symmetric nor indicative of a bipolar flow, suggesting an external source of energy driving the dust ejection.

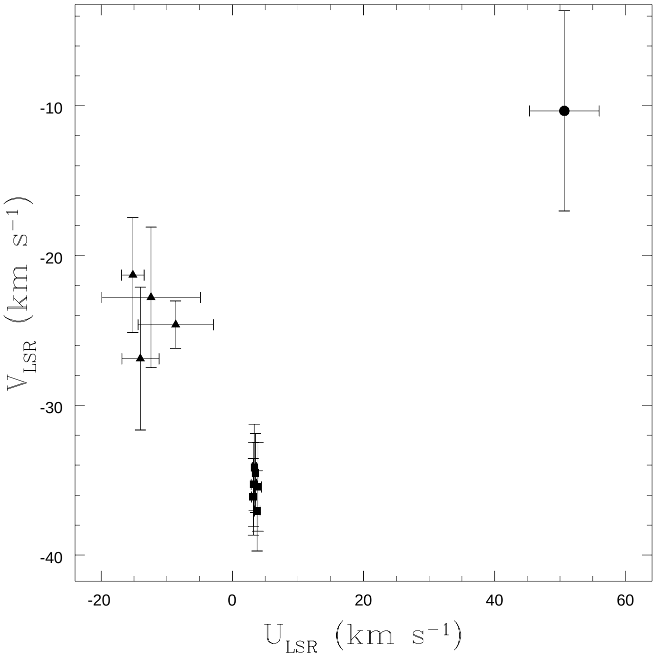

FIG. 3.—Galactic coordinate space velocity (U, V) plot of three kinematic associations. The "Nucleus" of IC 349 is represented with a circle, bright Pleiades member stars with squares, and a selection of T Tauri stars in the Tau-Aur clouds with triangles. U, V velocities were calculated as described in the text; error bars are σ_U and σ_V, as defined by Upgren (1978).

5. CONCLUSION

We have presented a new determination of the heliocentric radial velocity of IC 349 obtained via spectral observations in the optical regime, yielding a mean value of $\bar{v}_{\rm hel} = -44.4$ km s^{-1} and a standard deviation of $\sigma_v = 5.42$ km s^{-1}, not adjusted for the relative radial velocity between IC 349 and the illuminating star 23 Tau. This value differs significantly from the radial velocities of other objects in the region of the Pleiades. Recent proper-motion results allowed calculation of the U, V, W components of the space motion of IC 349 as referred to the LSR; these values suggest an origin in neither the Pleiades nor the Tau-Aur clouds. Near-infrared imagery of the nebula has ruled out the presence of a protostellar object of $L \geq 0.23 \pm 0.05\ L_\odot$ embedded in the Nucleus, indicating that star formation is not likely taking place inside IC 349; qualitative observations of the nebula's dust envelope and its composition support this result.

Further observations of this object are encouraged, including a program of faint infrared observations and radio measurements of the velocity field to determine the rate of mass loss in the nebula and the velocity at which dust is ejected. In addition, submillimeter spectral observations could provide information on the composition of the object and abundances of elements within it.

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