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Infrared Observations of Three Unusual Nebulae

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Optical, infrared and radio data are assembled on the three objects M1−67, Sh2-266 and NGC 2346 which previously have been classified as planetary nebulae. It is argued that none of these nebulae is in fact a planetary. M1−67 is almost certainly a ring nebula containing a Population I WN star; Sh2-266 is probably a nebulosity containing an emission-line B star; while the nature of NGC 2346 is presently indeterminate.

INTRODUCTION

During an infrared photometric survey of planetary nebulae (Cohen and Barlow, 1974), the central stars of M1−67, Sh2-266 and NGC 2346 were observed. By comparison with either the energy distributions or the morphology of typical planetaries these three nebulae are anomalous. Optical, infrared and radio data on the objects are assembled and discussed in this paper.

INFRARED OBSERVATIONS

Infrared photometry of the central stars of the three nebulae was secured with the 1.5-metre University of Minnesota/University of California at San Diego Mt Lemmon reflector during the winters of 1972 to 1975. Additional 10-μ photometry of the central star of M1−67 was also obtained with the Kitt Peak 1.3-metre reflector in November, 1974. Several independent sets of multifilter data were acquired for each object using liquid helium cooled bolometers. Sky chopping was used throughout, with 11 arc sec beams separated by 15 arc sec. Near-infrared photometry of NGC 2346 was obtained in April 1975 at Mt Lemmon using an InSb photovoltaic detector (17 arc sec beams, 40 arc sec separation). Table 1 presents the photometry in the form of mean magnitudes with estimated total uncertainties.

DISCUSSION OF THE INDIVIDUAL NEBULAE

a) *M1−67 = PK 50+3°1 = VV 481 = Sh2-80*

Figure 1(d,e) shows two photographs of M1−67 taken in Hα light by Minkowski, with short and long exposures using the Mt Wilson 60-inch reflector. The central star lies within the bright, hexagonal, nebulous patch apparent in the short exposure image. The apparent dimensions of the nebula are a maximum of about 90×75 arc sec in the red.

Merrill (1938) discovered the Wolf–Rayet characteristics of the central star of M1−67. The star (now called Merrill's Star) is the northerly of

TABLE 1

Infrared photometry of the central stars of the nebulae

Nebula	[2.2]	[3.6]	[4.8]	[8.6]	[10]	[10.8]	[11.3]	[12.8]	[18]
M1−67	$+7.69^{m}.09$	$+7.13\pm.13$			$+5.97\pm.25$				$> +0.60$
Sh2-266	$+6.70\pm.05$	$+5.00\pm.05$	$+3.87\pm.10$	$+2.68\pm.11$	$+2.40\pm.10$	$+2.18\pm.11$	$+2.22\pm.10$	$+2.14\pm.15$	$+0.92\pm.25$
NGC 2346	$+8.85\pm.22$	$+7.25\pm.18$			$+4.47\pm.23$				$> +1.80$
Observations obtained with an InSb detector									
		[1.6]	[2.3]	[3.5]					
	NGC 2346†	$+9.84^{m}\pm.04$	$+8.64\pm.02$	$+7.14\pm.03$					

† These near-infrared observations, together with a 1.2-μ magnitude of $+10.7\pm0.2$ obtained by Allen (private communication), are those plotted in Figure 3.

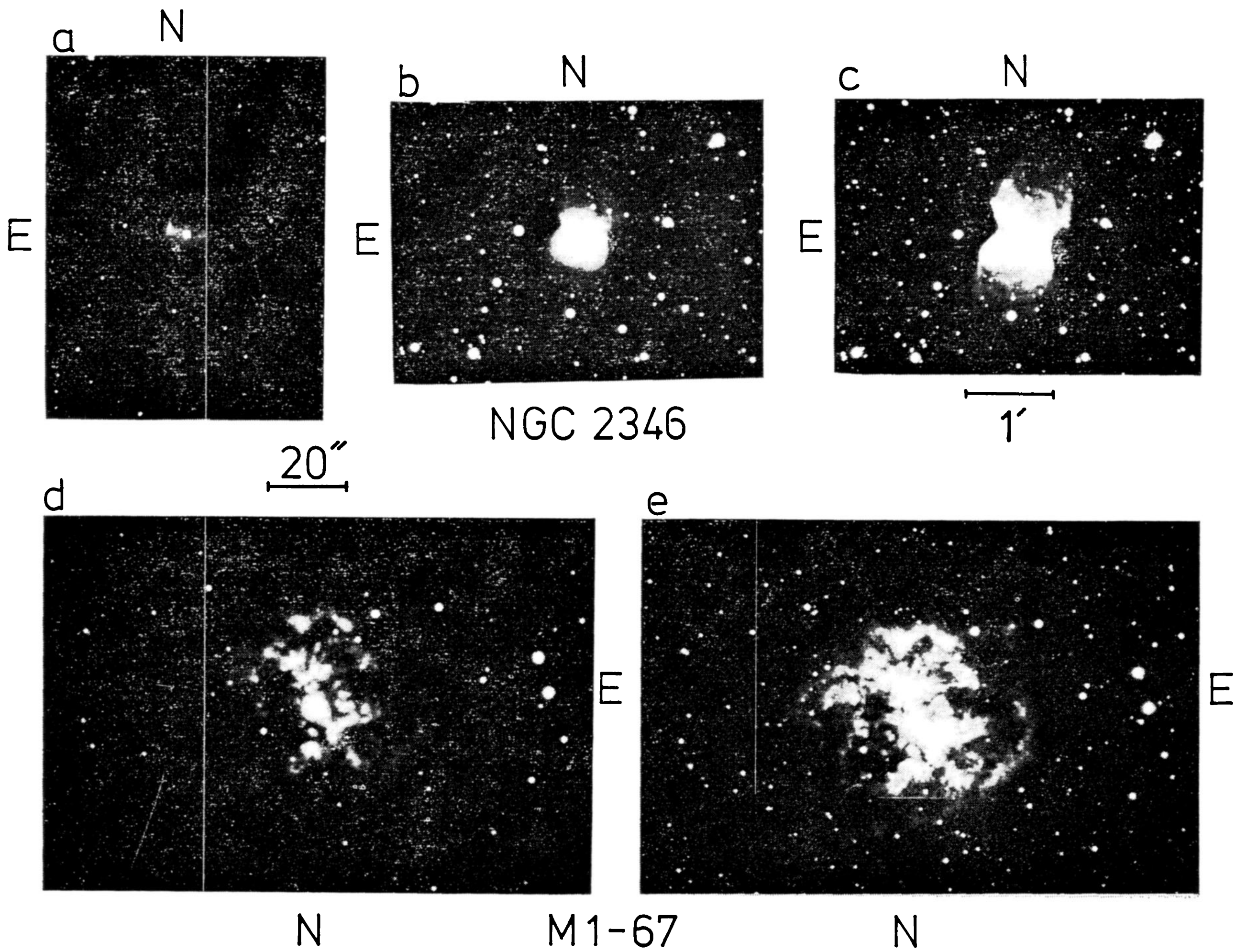

FIGURE 1 Minkowski's photographs of NGC 2346: (a) short exposure in Hα; (b) in the [O III] lines λλ 61959, 5007; (c) long exposure in Hα; and of M1 − 67: (d) short exposure in Hα and (e) long exposure in Hα.

a pair of almost equally bright stars separated by 2 arc min. The spectrum of Merrill's Star has been classified as WN8 by Bertola (1964) and by Smith and Aller (1969).

Shao and Liller (1974) have obtained UBV photometry of Merrill's Star and find $V = 11.08$, B–V = +1.07, U–B = −0.09. We have used this data to deredden the optical and infrared spectral points. Pyper (1966) has considered the effect of emission lines on the colour indices of Wolf–Rayet stars and has estimated corrections Δ(B–V) and Δ(U–B) of +0.04 and −0.04 respectively for WN8 stars, where the perturbation arises almost entirely in the B-band. We therefore obtain a corrected B–V colour index of (B–V)* = 1.11. The adoption of an intrinsic B–V colour index for the continuum of Wolf–Rayet stars of $(B{-}V)_0 = -0.24$ from the work of Smith and Kuhi (1970) leads to a colour excess $E(B{-}V)^* = 1.35$, which in turn gives a visual extinction $A_V = 4.05$ for $A_V = 3E(B{-}V)$. The extinction at other wavelengths has been calculated using $A_U/A_V = 1.58$, $A_B/A_V = 1.33$, $A_J/A_V = 0.22$, $A_H/A_V = 0.14$, $A_{2.2}/A_V = 0.10$, $A_{3.5}/A_V = 0.03$, and $A_{10}/A_V = 0.0$, derived from van de Hulst's curve number 15. We have incorporated the J(1.2μ) and H(1.6μ) data of Allen (1974) with our photometry, since there is good agreement between his data and ours at 2.2 and 3.5μ. The dereddened spectrum of Merrill's Star is plotted in Figure 2. The presence of circumstellar free–free emission can be recognized longward of 1.6μ, by subtracting the extrapolated Rayleigh–Jeans curve of the hot star from the infrared energy distribution (*cf.* Cohen *et al.*, 1975).

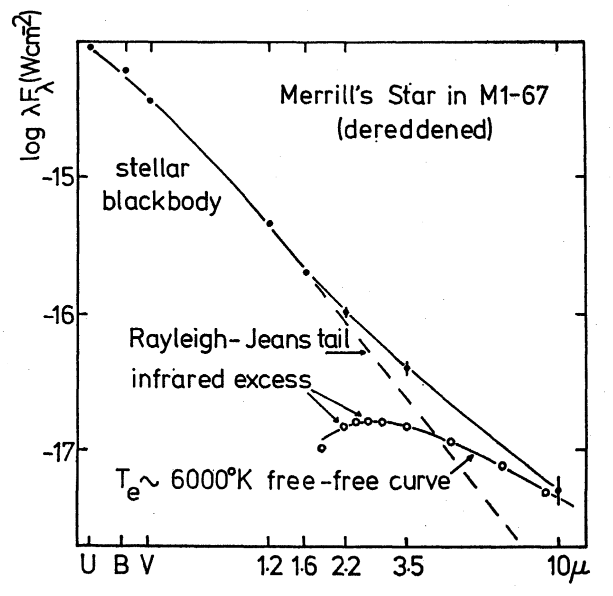

FIGURE 2 The dereddened energy distribution of Merrill's Star in M1−67, showing the free–free excess of infrared radiation over the stellar Rayleigh-Jeans tail.

M1−67 included in Perek and Kohoutek's (1967) Catalogue of Galactic Planetary Nebulae, but there are several reasons for believing that it does not in fact belong there. These reasons are enumerated below.

1) Morphologically, the structure of M1−67 is complex, consisting of filaments and many small knots of nebulosity. This has caused Khromov and Kohoutek (1968) to include it amongst "objects which probably do not belong morphologically to the class of planetary nebulae". Although of smaller apparent diameter, M1−67 should be compared instead to NGC 6888 and NGC 2359, objects which it resembles in structure. These latter two nebulae are members of a class of objects called "ring nebulae", each of which contains a population I WN star. The structure of this type of nebula is attributed to a continual process of mass loss from the exciting Wolf–Rayet star, which sweeps the surrounding interstellar gas into an ellipsoidal shell, the mass loss by the WN star contributing only a fraction of the total nebular mass (Johnson and Hogg, 1965).

2) A red spectrum of Merrill's Star, taken at the coudé focus of the 3-metre reflector at Lick Observatory, shows Hα and the adjacent [N II] lines to consist of sharp, narrow nebular components superposed on the much broader stellar features, and to this extent at least M1−67 shows a nebular spectrum similar to that of a planetary. On the other hand [O III] was not found by Bertola (1964) and we concur with his conclusion that [N II]λ6583 is anomalously strong for a planetary, the [N II] line ratio instead being close to the canonical value for H II regions.

3) Standard models of planetary nebulae (*e.g.* Higgs, 1971) give a distance of about 800 pc for M1−67. This would imply a linear diameter of 0.4 pc, unusually large for a planetary nebula. More importantly, the exciting star undergoes four magnitudes of visual extinction, an excessive amount if it were only at a distance of 800 pc. If instead the star is a Population I WN8 star, with an absolute magnitude $M_V = -6.2$ (Smith, 1973), then a distance of 4.33 Kpc is derived, entirely consistent with the observed extinction. This distance implies linear dimensions of 1.9 × 1.6 pc.

4) If M1−67 were a planetary nebula it would

be the sole example of a planetary with a WN nucleus. Planetary nuclei with WC and WC-related spectra are common on the other hand (Smith and Aller, 1969), and there are theoretical reasons for expecting the nuclei of evolved planetary nebulae to be carbon rich rather than nitrogen rich (Wood and Faulkner, 1973). Smith and Aller (1971) have compared the spectrum of a Population I WC9 star with that of a WC9 planetary nucleus and have found the emission lines of the latter to be systematically narrower than those of the former. However, the emission lines in Merrill's Star are very comparable in width with those in the Population I WN8 star AS374.

5) If detected at 10μ, the nuclei of planetary nebulae always show an excess attributable to dust emission (Cohen and Barlow, 1974). There is no evidence for dust emission from Merrill's Star, the spectrum out to 10μ instead being attributable to circumstellar free–free emission. The spectrum is essentially identical to those of Population I WN stars, in particular the Population I WN8 star AS374 (Cohen *et al.*, 1975).

In view of the above evidence, the interpretation in the remainder of this section will be in terms of M1 – 67 as a ring nebula, containing a Population I WN8 star, at a distance of 4.33 Kpc.

The compilation of radio data by Higgs (1971) indicates a thermal radio spectrum for M1 – 67. The radio data may therefore be used in conjunction with the visual data for Merrill's Star to derive an effective temperature for the star, using the modified Zanstra method of Morton (1969, 1970). For a single star exciting a nebula, Morton finds the ratio of Lyman continuum photons to the stellar flux in the visual magnitude band to be given by

$$N_L/\pi F_V = 3.46\times 10^{30} f_\nu [1+0.13 \log(T^{3/2}/\nu)]^{-1} \times 10^{0.4(V-A_V)} \text{ photons erg}^{-1},$$

where f_ν is the observed radio flux in ergs cm^{-2} s^{-1} Hz^{-1} at a frequency ν and T is the *nebular* electron temperature. The derived value of $N_L/\pi F_V$ can then be compared to stellar atmosphere models to give an effective temperature (Morton, 1969). The method is independant of an assumed distance and is fairly insensitive to small errors in the extinction and radio flux estimates. We assume here an electron temperature $T = 10^4$ K for M1 – 67 and take a 10 GHz flux of 0.213 Jy from Higgs (1971). An effective temperature $T_{eff} = 26{,}000$ K is derived, in good agreement with the effective temperature of 25,000 K derived by Morton (1970) for the WN8 star HD96548. An effective temperature of 26,000 K corresponds to a bolometric correction of -2.6, so that the bolometric magnitude of Merrill's star is equal to -8.8.

Using the free–free flux at 10μ, which can be derived from Figure 3, the mass loss rate for Merrill's Star can be obtained using the method of Wright and Barlow (1975). The derivation of the mass loss rate for this star is discussed in detail by Barlow *et al.* (1975). An expansion velocity of 650 km/sec for the mass outflow was assumed, in the line with the observed blueward shifts of the absorption components of the He I emission lines at λ4471 (Merrill, 1938) and at λ5876 (our spectrum). A mass loss rate of $\dot{M} = 8.7 \pm 2\times 10^{-5}$ $M_\odot$/yr is obtained, where the estimated errors arise chiefly from uncertainties in the He II to He III ratio in the atmospheres of WN8 stars. This mass loss rate lies within the range found for other Population I WN stars by Barlow *et al.* (1975).

Although the density distribution in M1 – 67 can be seen to be highly non-uniform, the uniform H II region model of Mezger and Henderson (1967) may be used in order to get an indication of the mean electron density and the total ionized mass of the nebula. We take their uniform spherical mass distribution case, with a mean diameter of 1.38 arc min for M1 – 67, corresponding to a Gaussian HPW, $\theta_G = 0.94$ arc min. Equations A.13 and A.14 of Mezger and Henderson then give $\bar{N}_e = 134$ cm^{-3} and $M = 9M_\odot$, respectively, for a nebular distance of 4.33 Kpc, an electron temperature of 10^4 K, and a 10 GHz flux of 0.213 Jy. The derived electron density and mass lie within the range found for other ring nebulae by Smith and Batchelor (1970).

Knowing the mass and radius of the nebula, along with the mass loss rate and mass outflow velocity from the WN8 star, the approximate age of M1 – 67 can be estimated using the model of Johnson and Hogg (1965). An age of $\sim 1.4\times 10^4$ years is derived. The model also predicts a nebular expansion velocity of ~ 65 km/sec. The errors involved in these estimates arise chiefly from uncertainties in the total nebular mass, due the non-uniform structure. For an age of 1.4×10^4 years, the WN8 star would have contributed about one eighth the total nebular mass. Table 2 collects together theses physical parameters of M1 – 67.

An unusual feature peculiar to M1 – 67 is the very large radial velocity of ~ 200 km/sec associated

TABLE 2
Parameters of M1 – 67

Star		Nebula	
Spectral type	WN8	Dimensions (pc)	1.9 × 1.6
M_V	– 6.2	$\bar{N}_e$(cm^{-3})	130
A_V	4.05	$M(M_\odot)$	9
D(Kpc)	4.33	Age (yr)	~1.4 × 10^4
T_{eff}(K)	26,000		
M_{Bol}	– 8.8		
$\dot{M}(M_\odot/yr)$	8.7 × 10^{-5}		

with both the star (Merrill, 1938; Bertola, 1964) and the nebula (Minkowski: see Perek and Kohoutek (1967); our spectrum yields a nebular radial velocity of 195 km/sec). The kinematics of M1 – 67 were therefore investigated by Perek (1956), who concluded that it must have either a very eccentric or a hyperbolic galactic orbit. One possible interpretation could be that Merrill's Star has been ejected with a high velocity following the catastrophic disruption of a binary or multiple stellar system. In this connection it is interesting to note that M1 – 67 lies 1°2 away from the recently discovered binary pulsar PSR 1913 + 16 (Hulse and Taylor, 1975). However, although the slight elongation of M1 – 67 is in the direction of the line joining the nebula to the pulsar, the exciting star is not notably off-centre. If the nebula and pulsar were at a common distance of 4.33 Kpc the projected separation would be 93 pc, which would imply a projected velocity of ~300 km/sec in the plane of the sky for M1 – 67, if the nebula and pulsar had equal and opposite velocities. Even allowing for the height of 250 pc above the plane, the star might still be expected to be off-centre, so that we must conclude at present that the proximity of nebula and pulsar is in all likelihood a chance coincidence.

b) *Sh2 – 266 = PK 195 – 0°1 = VV 42*

This is a very red, almost elliptical, nebulosity, some 2 arc min along the major axis. It consists of an irregular outer ring and a central patch of nebulosity about the exciting star, MWC 137. The overall structure is somewhat reminiscent of NGC 6888. In the blue, only a trace of nebulosity is seen near MWC 137. Sh-2266 is included in the catalogue of Perek and Kohoutek (1967), yet MWC 137 is also included in the catalogue of stars of the Orion population (Herbig and Rao, 1972), albeit with a cautionary note that it may not be a member of this class. Doubts about its classification as a planetary nebula have been expressed by Khromov and Kohoutek (1968) and by Frogel *et al.* (1972).

There is good agreement between our photometry of MWC 137 and that obtained by Allen (1973) in the near-infrared, and by Frogel *et al.* (1972) who included a broad 10-μ measurement. Figure 3 shows the observed energy distribution of

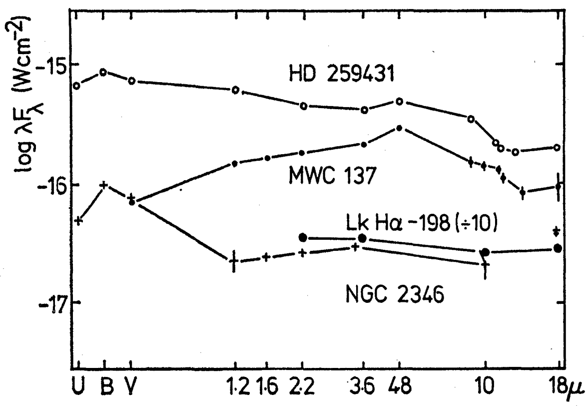

FIGURE 3 The observed energy distributions of the central stars of Sh 2-266 (MWC 137) and NGC 2346 compared, respectively, with those of the nebulous emission-line B star HD 259431 and the nebulous star Lk Hα–198.

MWC 137, including the magnitudes at V (Herbig and Rao, 1972), J and H (Frogel *et al.*, 1972). It does not possess the steeply rising flux curve typical of the emission-line nuclei of planetary nebulae (*cf.* Cohen and Barlow, 1974). MWC 137 is compared in Figure 3 with the energy distribution (UBVJ from Strom *et al.*, 1972; infrared multifilter data from Cohen, 1973) of HD 259431 (MWC 147), the B5e star embedded in the amorphous nebulosity NGC 2247. The two flux distributions are strikingly similar and have slopes in the 10-μ region somewhat suggestive of optically thin free–free emission, although the points lie above this slope. Neither curve shows any feature near 10μ that might be attributable to the signature of some specific type of dust grain, but this does not preclude thermal emission by dust as the origin of the radiation. That the infrared flux does not arise from the nebula has been demonstrated by Frogel *et al.* (1972), from the aperture independence of the near-infrared flux, and from an estimate that the extrapolated nebular radio flux falls far short of the observed infrared flux. From Higgs' (1971) compilation the radio spectrum appears to be thermal, although interferometer observations

(Purton, 1974) indicate that the region around MWC 137 is confused.

Adopting Higgs' (1971) distance of ~900 pc yields a nebular diameter close to 0.4 pc, once again somewhat large for a planetary. It seems highly probable that MWC 137 is a nebulous emission-line B star, rather than the nucleus of a planetary nebula.

c) *NGC 2346 = PK 215+3°1*

This is a remarkably under-observed nebula, some 2×1 arc min in size, containing an eleventh magnitude star which has been classified as A-type (Aller, 1968). Figure 1(a,b,c) presents three photographs of NGC 2346 taken by Minkowski with the Mt Wilson 60-inch telescope, comprising short (a) and long (c) Hα exposures and an exposure (b) in the $\lambda\lambda$4959, 5007 lines of [O III]. In the long exposure Hα photograph the structure is biconical, very like the cometary nebula about the star Lk Hα−208 (*cf.* Herbig (1960), Figure 8), an aspect shown by the [O III] plate also. However, a short exposure in Hα reveals a complex inner structure. This inner nebulosity appears as an elliptical patch of highly non-uniform brightness, terminated to the east by a bright nebulous knot, and shows several tiny condensations. The bright knot may indicate the presence of dense opaque material which obstructs the light from the central star, producing the remarkably sharp triangular edge to the nebula on the east.

The infrared energy distribution is exceptionally flat (Figure 3), totally unlike that of typical planetaries, and is compared with that of Lk Hα−198 (Cohen, 1974a), at the same wavelengths, which is a star also associated with a cometary nebula. The energy distribution cannot be fitted by free–free emission. Very flat λF_λ curves are representative of a wide variety of young stars, particularly those in cometary nebulae (Cohen, 1973, 1974b).

The compilation of radio data by Higgs (1971) indicates a thermal spectrum for NGC 2346, although Terzian *et al.* (1974) report that there is another small source nearby which confuses radio flux measurements of this nebula.

In view of the problems associated with explaining the excitation of NGC 2346 by B9−AO star, Kohoutek and Senkbeil (1973) have attempted to fit UBV photometry (shown in Figure 3) of the nucleus of NGC 2346 by arguing that it is a binary, whose as yet unseen component is the true exciting star of the nebula. They draw an analogy with the A star and O subdwarf system within NGC 1514. However, the existence of an O type companion in NGC 2346 cannot be demonstrated without a spectrum, and, in contrast to the nucleus of NGC 2346, the composite nucleus of NGC 1514 shows nothing unexpected at 2.2 or 3.6μ, with only an upper limit at 10μ (Cohen and Barlow, 1974). For a star with a spectral type close to B9 and V = 11.12, (B–V) = 0.20 (Kohoutek and Senkbeil, 1973), we obtain $A_V \approx 0.8$ and $V_0 = 10.3$. Consequently, we predict [2.2] ≈ 10.4 and [3.6] ≈ 10.3, so that the central star of NGC 2346 has an appreciable near-infrared excess, which increases to larger wavelengths.

It may therefore be possible that NGC 2346 is a biconical cometary nebula about a young star, rather than a planetary nebula, although it is not yet possible to interpret the details of its inner nebular structure. On the other hand, Chopinet and Lortet–Zuckermann (1975) report the detection of He II in the spectrum of the nebula, in which case it might be difficult to maintain the cometary nebula interpretation. If NGC 2346 is in fact a high-excitation object it might be possible to draw an analogy between its morphology and that of the very high-excitation objects NGC 6537, M2−9 and NGC 6302, although the infrared energy distributions differ. In particular there is a strong structural resemblance to the peculiar nebula NGC 6302, photographs of which may be found in Minkowski and Johnson (1967).

It is concluded that the status of NGC 2346 is at present indeterminate.

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