M2-9: A PLANETARY NEBULA WITH AN ERUPTIVE NUCLEUS?

Bruce Balick[a]
Astronomy Department, FM-20, University of Washington, Seattle, Washington 98195
and
Sterrewacht Leiden, Leiden University, 2300 RA Leiden, the Netherlands
Received 2 September 1988; revised 2 November 1988

ABSTRACT

M2-9 is a striking bipolar, or butterfly, planetary nebula (PN) whose nuclear spectrum is uncharacteristic of PN nuclei. Narrow lines ranging in ionization from O I, Fe II, [Fe II], and Si II through [O III] are observed in the stellar spectrum. The Hα emission line has wings extending nearly 11 000 km s^{-1} at the base, and there is a deep self-absorption feature near the Hα line peak at the same velocity as nebular gas observed in one of the two bipolar lobes. The spectrum of M2-9's nucleus is more similar to the slow nova RR Tel, some symbiotic stars, and Seyfert (type 1.9) galactic nuclei than the central stars of most other PNs. Although its morphology, size, and nebular spectrum share many similarities with other PNs, M2-9 may not share a common evolutionary history with that class of objects.

I. INTRODUCTION

M2-9 (PK 10 + 18°2) has been identified with a class of objects "which bear characteristics thought to be indicative of very young planetary nebulae" such as CRL 618, M1-91, M1-92 (Schmidt and Cohen 1981) or protoplanetary nebulae (Walsh 1981). The nebula appears as a very symmetric "butterfly" planetary nebula (PN) with narrow, open lobes extending about 20″ north and south of the bright centrally located nucleus (e.g., Balick 1987). A dense disk of luminous dust of radius $\approx 7''$ surrounds the central nucleus and shares the same symmetry axis as the nebula (Aspin *et al.* 1988). The identification of M2-9 with PNs is based primarily on its compact size, its highly symmetric bipolar shape, and the other usual morphological and spectroscopic grounds. Yet there are some exceedingly peculiar characteristics of M2-9 that indicate that although M2-9 fits the morphological classification criteria for PNs, its history may have little in common with them.

M2-9 exhibits some important differences from many PNs. For one, there are spatially unresolved knots between 2″ and 10″ from the central star in the lobes of the nebula which vary on short timescales (van den Bergh 1974) and have very large proper motions (as high as 5″ in 25 yr) associated with them (Kohoutek and Surdej 1980). For another, whereas all butterfly-shaped PNs appear to have excited molecular hydrogen in disks surrounding the central star, M2-9 is not yet detectable in H_2 (Balick, Gatley, and Zuckerman 1989). Most of all, the nucleus of M2-9 is spectroscopically unique among PNs. The central star is designated as a B IV by Calvet and Cohen (1978) and as a late O star by Swings and Andrillat (1979). Allen and Swings (1972), Ciatti and Mammano (1975), Calvet and Cohen (1978), Swings and Andrillat (1979), Schmidt and Cohen (1981), and Feibelman (1984) noted the presence of circumstellar lines of very low to high ionization, e.g., permitted and forbidden lines of O I, Fe II and III, and high-ionization lines such as [O III], [Ne III], and N V. Swings and Andrillat (1979) and Walsh (1981) noted that the nuclear Hα line is exceptionally broad: $\approx$400 km s^{-1}. (Data presented later show that the line is actually much wider.) An unresolved ($\leqslant 0.1''$) thermal radio source, which is optically thick at λ 1.3 cm, is coincident with the nucleus (Bignell 1983).

In this paper, attention is drawn to the "nucleus": the central star, a dense spatial unresolved circumstellar envelope, and nebulosity within about 1″ of the star. Regions outside the nucleus are denoted as the "nebula," whose structure, kinematics, and evolution are the subject of a companion paper (Icke *et al.* 1989). This unusual nucleus and the striking bipolar nebula that surrounds it present an easily studied system that is certain to enhance our understanding of active, mass-loss-driven systems such as protostellar objects and, perhaps, some active galactic nuclei.

Hereafter, we abbreviate north, east, south, and west as N, E, S, and W, respectively. [O I], [N II], and [O III] are used to designate the emission lines [O I] λ 6300 Å, [N II] λ 6583 Å, and [O III] λ 5007 Å, respectively, unless noted otherwise below.

II. OBSERVATIONS AND RESULTS

a) Moderate-Dispersion Observations

The observations were performed using the "gold" spectrograph and TI5 CCD camera (Seitzer *et al.* 1988) on the 2.1 m telescope of Kitt Peak National Observatory (KPNO) on the night of 26 April 1988. The slit was open to 1″, the seeing was 1.″5, and the atmospheric transparency was excellent. Approximately 45% of the light of a star is passed through the slit, and the same slit was used for observations of M2-9 and a flux-calibration standard. A grating with 300 lines per mm gives 1976 Å spectral coverage at 2.5 Å per pixel, and an unresolved spectral line has a FWHM of 5 Å.

Data were calibrated using standard techniques and software. Three 60 s integrations were averaged to form the final spectrum of the central star of M2-9 shown in Figs. 1(a) and 1(b). The relative (absolute) line fluxes are accurate to about 5% (25%). The nebular spectra shown in Fig. 1(b) were obtained at the same time and in the same manner as the stellar spectrum.

b) High-Dispersion Observations

The long-slit echelle spectrograph was used with the TI2 CCD camera on the 4 m Mayall telescope of NOAO on 30 December 1986. The slit length is larger than the nebular dimensions. Details of the data calibration are described in Balick *et al.* (1987). The slit width and the seeing were 1″ (3

[a] Guest Observer, Kitt Peak National Observatory (KPNO), which is operated by the National Optical Astronomy Observatories (NOAO). NOAO is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

 0004-6256/89/020476-05$00.90

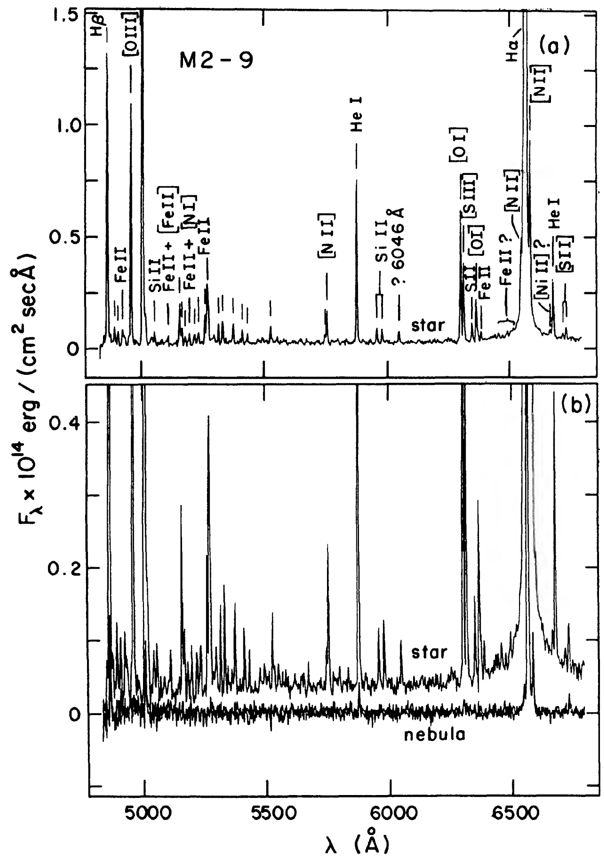

FIG. 1. Moderate-dispersion spectrum of the nucleus of M2-9 between 4830 and 6800 Å (see the text). Lines in the upper panel with short ticks above them and without any other identification are [Fe II] emission features. The traces labeled "star" are the sum of five CCD rows in which emission from the central star is observed. Nearby nebular emission is very faint (the lower trace marked "nebula" shows two overplotted nebular spectra obtained at points 3″S and 3″N of the nucleus), and has not been subtracted.

pixels). Only one echelle order was projected on the chip. The spectrum covers the spectral region 6545 to 6585 Å with a spectral resolution (after 2 pixel smoothing) of $\approx$0.2 Å. No correction for sensitivity variations as a function of wavelength or position along the slit is necessary, and none has been applied. The stellar spectrum is not precisely perpendicular (by 2°) to the slit, owing to the internal optics of the echelle. Relative fluxes are accurate to 5%. No attempt at an absolute flux calibration has been made.

Contour representations of two echelle spectra in which the slit passes through the central star along the lobes (P.A. 0°) and across them (P.A. 90°) are shown in Fig. 2. (The nebular spectrum more than 1″ from the nucleus is shown for reference only.) A trace along the nuclear spectrum is shown in Fig. 3. An apparent Hα absorption feature is clearly visible just to the short-wavelength side of the profile peak in both figures. Above and below the Hα nuclear spectrum in the upper panel of Fig. 2, both a narrow line (arising from the nebula and the knots therein) and a very broad line are observed. The broad line is almost certainly the result of the scattered nuclear Hα photons by dust near the nucleus (Aspin and McLean 1984). Nebular and nuclear [N II] lines of λ 6548 and 6583 Å appear near the left and right edges, respectively, of the spectra in Figs. 2 and 3.

c) Gaussian Fits

Gaussians have been fitted to the circumstellar spectrum of Fig. 3. The fitted widths and amplitudes of the widest lines are certainly affected by the limited spectral coverage of these data. The results are compiled in Table I.

The velocity of the stellar Hα absorption line is essentially the same as the velocity of the southern nebular lobe (-11 km s^{-1}). For comparison, the width of the fitted nuclear absorption line is 37 km s^{-1}, while that of the nebular lobes is 30 km s^{-1}. (However, the Hα absorption line seen near the peak of the emission profile has a broad minimum, suggesting that the absorption line is saturated. If the absorption line were unsaturated its FWHM would be less than the fitted value.)

The nuclear [N II] lines are well characterized by a bright central Gaussian at rest (with respect to the systemic nebular velocity) plus two weaker "satellite" lines at about $\pm$ 52 km s^{-1}. None of these lines match in velocity or width with [N II] lines seen in the bipolar lobes. Moreover, the surface brightness of the nuclear [N II] lines falls nearly to zero between the star and the lobes. This and the disparate nuclear and nebular [N II] velocities argue that (1) the nuclear and nebular [N II] lines arise in distinct systems, and (2) the bright [N II] emission seen towards the nucleus is aptly described as "circumstellar." The second conclusion is also supported by the very large ratio of [N II] λ 5755 to λ 6583 Å intensities observed towards the nucleus, as noted later.

Interestingly, the circumstellar [N II] lines are spatially unresolved when the slit is oriented E–W (perpendicular to the lobes). Yet with the slit along the lobes, the two satellite [N II] lines are offset about $\pm$ 2 pixels (0.7″) from the central star. Thus the satellite lines probably arise along the nebular symmetry axis, and are unlikely to be directly associated with the putative E–W disk observed at 2 μm surrounding the star by Aspin *et al.* (1988).

III. DISCUSSION AND CONCLUSIONS

a) Nuclear Characteristics

Here we explore the luminosity, temperature, and other characteristics that might help to relate the nucleus to other stars about which more is known. To summarize, the exceptional characteristics of the nucleus of M2-9 are its wide Hα profile (which is seemingly self-absorbed near the peak) and the appearance of forbidden lines of ionic species from O^0 and Fe^+ through O^{++}. The Hα linewidth of about 11 000 km s^{-1} is unprecedented for galactic objects other than SNRs and SS 433. Lines from the nucleus are spatially unresolved, with the minor exception of the two satellite [N II] lines. There are no signs of photospheric lines, coronal lines such as [Fe VII] λ 6087 Å or He II λ 4686 or 5412 Å, or W–R-like features. The nuclear spectrum of M2-9 suggests that the observed emission is dominated by a circumstellar envelope.

Further support for the last assertion derives from the [N II] lines. The moderate-dispersion data obtained with a 1″ slit width show that the [N II] λ 5755 Å to [N II] λ 6583 Å intensity ratio is $\approx$0.25, a value which implies that the near-nuclear gas is characterized by an electron density of $\approx 10^{5.7}$ cm^{-3} if the electron temperature is 10^4 K (Calvet and Peimbert 1983; Feibelman 1984). (Note also that the [S II] λ 6717 Å to [S II] λ 6731 Å ratio is in its high-density limit of about 1.4, consistent with a density exceeding $\approx 10^4$ cm^{-3}.) This high density and the slightly spatially extended satellite [N II] lines (Fig. 2) argue that at least some of the near stellar gas arises from a relatively dense, low-ionization,

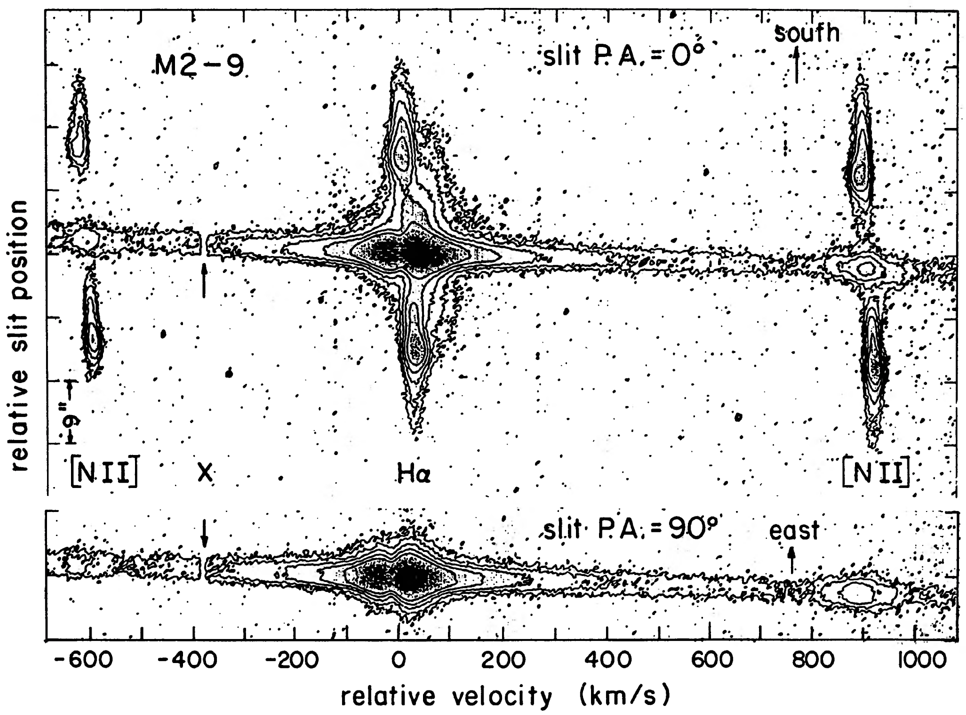

FIG. 2. High-dispersion spectrum of the nucleus of M2-9 between ≈ 6545 and ≈ 6585 Å (see the text for details). The spectral resolution is $\lambda/\Delta\lambda \approx 33\,000$. A linear range of grey scales is used to show intensity values between 0 and 16 000 in arbitrary intensity units. Contours are used to show the lower intensities at values of 25, 50, 100, 200, and 400 intensity units. A bad CCD column is marked with an "X."

high-velocity zone seen in projection within ≈ 1000 AU of the nucleus of M2-9.

Calvet and Cohen (1978) place the star at or just below the cool end of the Harmon–Seaton sequence for PN nuclei. They estimate the stellar temperature as $\approx 35\,000$ K from the nebular ionization fractions, and they find the nuclear luminosity to be $\geqslant 844$ $(D/\mathrm{kpc})^2$ $L_\odot$, where M2-9 is assumed to be at a distance D of 1 kpc (Calvet and Peimbert 1983). However, the complex nuclear spectrum and the highly uncertain distance serve as warnings that the position of the star in the proto-PN region of the H–R diagram might be no more than coincidental.

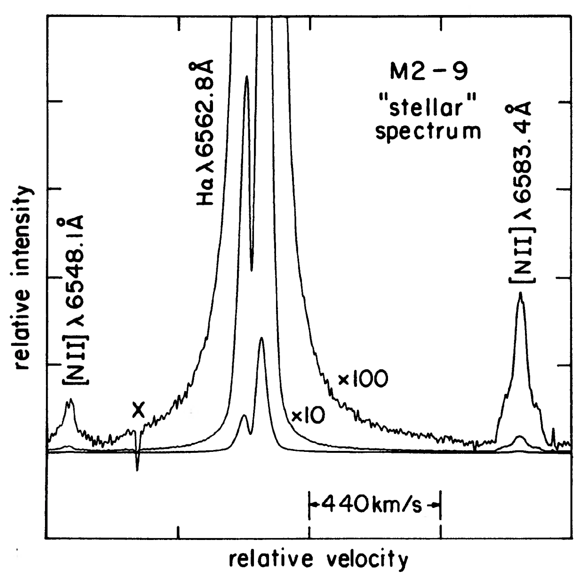

FIG. 3. Trace of the "stellar" spectrum in the upper panel of Fig. 2. An "X" marks a bad CCD column.

b) Similar Objects

M2-9 is one of a small but growing class of compact, symmetric nebulae with very unusual nuclear spectra. Other, possibly related objects deserve mention.

The identified lines in the spectrum of the nucleus of M2-9 are strikingly similar to those of η Car, the active young star, and RR Tel, the slow nova in its "E" phase (e.g., Thackery 1977 and references therein). The latter are stars whose lines originate in dense, rapidly cooling envelope material perhaps only recently ejected. However, neither η Car nor RR Tel have wide Hα lines.

Wide Hα profiles with narrow absorption "notches" and [Fe II] emission lines are common in symbiotics (Garcia 1986; Oliverson and Anderson 1982; see also Feibelman 1984). Also like some symbiotics, the spectral characteristics of the nucleus of M2-9 are highly characteristic of type 1.9 nuclei of Seyfert galaxies (see Penston 1988 for a discussion). However, aside from emission lines, the nuclear spectrum of M2-9 is featureless. Hence there is no direct spectral evidence of a companion with a loosely bound atmosphere.

MZ-3 is a compact southern bipolar which shares many morphological similarities with M2-9. The nebular and nu-

TABLE I. Gaussian-fitting parameters for stellar line profile of M2-9.

Line	Velocity[a] (km s^{-1})	Rel. flux[b] (arb. units)	Width (km s^{-1})
Hα	-8.5 ± 0.1	-1[c]	37.4 ± 0.5
	$+1.4 \pm 0.1$	$1.74 \pm 1\%$	58.6 ± 0.3
	$+1.6 \pm 0.3$	$0.48 \pm 3\%$	112.8 ± 1.4
	$+12.4 \pm 3.4$	$0.13 \pm 14\%$	341 ± 14
[N II]	-1.8 ± 0.1	$0.0017 \pm 1\%$	44.4 ± 0.5
	-54.0 ± 0.7	$0.0028 \pm 5\%$	31.9 ± 1.0
	$+51.0 \pm 0.7$	$0.0026 \pm 6\%$	36.1 ± 1.4

[a] Relative to the average systemic velocity of the nebular lobes.
[b] Proportional to the product of line amplitude and width.
[c] Adopted as the standard, or unit, flux.

clear kinematics have been studied by López and Meaburn (1983) and Meaburn and Walsh (1985), who find a pattern of nebular motions spanning nearly 200 km s^{-1} extending at least 20″ from the core into the nebula. (The nebular emission lines show satellite kinematic features similar to those in M2-9.) The central star is obscured from direct view by a dust lane, although there is a bright starlike core much like that seen in M2-9. At the core, the Hα line exhibits wings extending 54 Å ($\pm$1230 km s^{-1}) at the base. Lines of [Fe II], [Fe III], and He I are found near the nucleus. The density exceeds $\approx 10^5$ cm^{-3}. The nucleus of MZ-3 is relatively cool and is found in the same region of the H–R diagram as M2-9 (Calvet and Cohen 1978).

CRL 618 is a compact bipolar believed to be a young PN (Westbrook *et al.* 1975). No central star is visible; however, a deep absorption lane separates the lobes in the presumed direction of the nucleus. The spectrum of the brighter lobe by Schmidt and Cohen (1981) reveals a spectrum with many similarities to that of M2-9, including lines of [Fe II]. The high degree of polarization suggests that the spectrum of the lobe contains a strong contribution from scattered starlight. Unlike M2-9, the Hα line profile of CRL 618 published by Schmidt and Cohen does not appear broadened.

G70.7 + 1.2 (M3-60) was recently investigated by Muizon *et al.* (1988) and Becker and Fesen (1988). A red star that is seen through an apparent dust lane near the center of the nebula has a spectrum very similar to that of M2-9, with even stronger lines of low ionization ([O I], [Fe II], etc.) relative to Hα. The stellar Hα profile is broad and seemingly self-absorbed near the peak of the line. Unlike M2-9, no lines in [O III] or He I are detected in M3-60. The nebula is egg shaped and has an inner shell whose radio spectrum is nonthermal.

AG Car, a bright, highly variable Ofpe/WN7 star, is surrounded by a bright elliptical ring of nebulosity similar in morphology to M3-60. The profile shapes of the circumstellar Hα and [N II] lines (Stahl 1986) are extremely similar in shape to the corresponding lines of M2-9 shown in Fig. 3. Stahl finds a higher ratio of [N II] λ 5755 Å to [N II] λ 6583 Å in AG Car than found in M2-9, implying higher circumstellar densities in the former. AG Car, like other stars of the same general type, has a spectrum rich in lines of Fe II and other permitted lines of low-ionization species. Aside from Hα and [N II], most of its circumstellar lines exhibit P Cygni profiles. Hence high-dispersion observations of nuclear Fe, Si, and Ca lines in M2-9 could be revealing.

V1329 Cygni (alias HBV 475) is described as an eruptive symbiotic star with a period of about 964 days by Wallerstein *et al.* (1988). These authors have shown that the star has exhibited major changes in its spectral character and the shapes of its line profiles on timescales of weeks to years. There are superficial similarities in the spectra of V1329 Cygni and the nucleus of M2-9, and both are associated with bipolar flows. V1329 Cygni, RR Tel, RT Ser, V1016 Cyg, and probably PU Vul are members of a common class of stars.

Calvet and Cohen (1978) have suggested that the central stars of CRL 2789, M1-92, MZ-3, M2-9, and CRL 618 form a sequence in their relative strengths of Fe^{+} and Fe^{++} lines. All of these objects are isolated bipolar nebulae whose central stars inhabit the same region of the H–R diagram.

c) Summary

In summary, M2-9 is a butterfly nebula whose symmetry axis lies very close to the plane of the sky. The high degree of symmetry, the unmistakable presence of a neutral disk around the star, the presence of bright, easily observed emission lines from many different species, and a bright central star make the nebula an ideal test case for comparing models of the hydrodynamics of interacting winds from evolved stars losing mass (e.g., Balick *et al.* 1987; Icke *et al.* 1989; Soker 1988) with an easily studied test case.

M2-9 has been classified as a PN based on the standard morphological criteria and the position of its central star in the H–R diagram. However, M2-9 may have an evolutionary history distinct from other PNs. It exhibits knots of emission along the edges of the lobes with very large proper motions. The spectrum of the nucleus of M2-9 has little in common with the spectra of the nuclei of other PNs. Nuclear emission lines share more similarities with those of η Car, the nova RR Tel, some symbiotic stars, the P Cyg star AG Car, and other stars prodigiously losing mass than with the nuclei of other PNs.

The luminosity and color of the nucleus of M2-9 place it in a region of the H–R diagram populated by proto-PNs. Such stars are prone to instabilities. Emission lines such as [Fe II] and [Fe III], as well as a very broad Hα, argue that the star, perhaps in consort with a very compact companion star, has recently and possibly violently ejected a portion of its envelope. For example, a recent thermal pulse in the bright, visible OB star might have dumped mass onto the surface of an unseen compact companion resulting in the ejection of a novalike circumstellar shell. López and Meaburn (1983) and Meaburn and Walsh (1985) reach a very similar conclusion for the case of MZ-3.

Whatever its nature, the nucleus of M2-9 shares many characteristics with very close mass-transfer binary systems. Clearly, the nucleus should be observed carefully in the ultraviolet and monitored for changes in its brightness and spectral character. Repeated high-dispersion observations would also be of interest. The small knots with large proper motions might be the result of occasional outbursts. If so, the last ejection may have occurred as recently as the early 1950s (see Kohoutek and Surdej 1980).

It is a sincere pleasure to thank the many people at the NOAO who capably assisted with the observations. H. L. Preston's efforts to calibrate the data are greatly appreciated. SIMBAD, the database of the Strasbourg Astronomical Data Center, was used to research the spectrum of AG Car. Financial support for the observations was provided by NOAO and NSF grant no. AST 86-12228. Image processing at the University of Washington is made possible by grants from the NSF (AST 83-10552) and the Digital Equipment Corporation. This paper was written during a *gezellig* summer visit to Leiden University, which was graciously supported by the Netherlands Foundation for the Advancement of Pure Research (NWO) through grant no. B78-251 and NSF grant no. INT 87-14186.

REFERENCES

Allen, D. A., and Swings, J. P. (1972). Astrophys. J. **174**, 583.
Aspin, C., and McLean, I. S. (1984). Astron. Astrophys. **134**, 333.
Aspin, C., McLean, I. S., and Smith, M. G. (1988). Astron. Astrophys. **196**, 227.
Balick, B. (1987). Astron. J. **94**, 671.
Balick, B., Gately, I., and Zuckerman, B. (1989). In preparation.
Balick, B., Preston, H. L., and Icke, V. (1987). Astron. J. **94**, 1641.
Becker, R. H., and Fesen, R. A. (1988). Astrophys. J. Lett. (submitted).
Bignell, R. C. (1983). In *Planetary Nebulae*, IAU Symposium No. 103, edited by D. R. Flower (Reidel, Dordrecht), p. 69.
Calvet, N., and Cohen, M. (1978). Mon. Not. R. Astron. Soc. **182**, 687.
Calvet, N., and Peimbert, M. (1983). Rev. Mex. Astron. Astrofis. **5**, 319.
Carlson, E. D., and Henize, K. G. (1979). Vistas Astron. **23**, 213.
Ciatti, F., and Mammano, A. (1975). Astron. Astrophys. **38**, 435.
Feibelman, W. A. (1984). Astrophys. J. **287**, 353.
Garcia, M. R. (1986). Astron. J. **91**, 1400.
Icke, V., Preston, H. L., and Balick, B. (1989). Astron. J. **97**, 462.
Kohoutek, L., and Surdej, J. (1980). Astron. Astrophys. **85**, 161.
López, J. A., and Meaburn, J. (1983). Mon. Not. R. Astron. Soc. **204**, 203.
Meaburn, J., and Walsh, J. R. (1985). Mon Not. R. Astron. Soc. **215**, 761.
de Muizon, M., Strom, R. G., Oort, M. J. A., Claas, J. J., and Braun, R. (1988). Astron. Astrophys. **193**, 248.
Oliverson, N. A., and Anderson, C. M. (1982). In *The Nature of Symbiotic Stars*, edited by M. Friedjung and R. Viotti (Reidel, Dordrecht), p. 71.
Penston, M. V. (1988). Preprint.
Schmidt, G. D., and Cohen, M. (1981). Astrophys. J. **246**, 444.
Seitzer, P., Reed, R., and De Veny, J. (1988). *The Gold Camera—a CCD Spectrometer for the KPNO 2.1-Meter Telescope. Preliminary Manual* (NOAO Operations Division, Tucson).
Soker, N. (1988). Astrophys. J. (in press).
Stahl, O. (1986). Astron. Astrophys. **164**, 321.
Swings, J. P., and Andrillat, Y. (1979). Astron. Astrophys. **74**, 85.
Thackery, A. D. (1977). Mem. R. Astron. Soc. **83**, 1.
van den Bergh, S. (1974). Astron. Astrophys. **32**, 351.
Wallerstein, G., Solf, J., Mikolajewska, J., Crampton, D., and Brugel, E. (1988). Preprint.
Walsh, J. (1981). Mon. Not. R. Astron. Soc. **194**, 903.
Westbrook, W. E., Becklin, E. E., Merrill, K. M., Neugebauer, G., Schmidt, M., Willner, S. P., and Wynn-Williams, C. G. (1975). Astrophys. J. **202**, 407.