RECENT WORK ON BIPOLAR NEBULAE

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Recent results obtained from studies of bipolar nebulae with a variety of techniques are described. Nebular polarization maps and spectropolarimetry, near-infrared spectroscopy, far-infrared photometry, radio maser and continuum work all have contributed to our knowledge of this heterogeneous class of objects. Some are certainly pre-main-sequence; others are likely to represent the rapid transition from red giant to planetary nebula. At least one dust-shrouded carbon star (CIT 6) and one visual binary with an O-star primary (MWC 349) have bipolar structure. Equatorial dusty disks must be common occurrences at different phases of stellar evolution.

Bipolar nebulae (BPNs) represent a class of objects defined purely morphologically. As such, they constitute a very heterogeneous group of nebulae in evolutionary terms (Calvet and Cohen 1978). Fig. 1 indicates the locations of 19 reasonably well-studied BPNs in the Hertzsprung-Russell diagram (HRD). Some nebulae are associated with pre-main-sequence stars; others seem to represent the transition from red giants to bona fide planetary nebulae; still others are well on their way to becoming white dwarfs. (It should be noted that the most problematic aspect of constructing such an HRD is still the determination of distances to individual nebulae; indeed, M2-9 is plotted twice - for 900 pc and again for 50 pc distance (the open circle in Fig. 1; see Kohoutek and Surdej 1980)).

A number of BPNs have been discovered in the past few years. It does seem that, to first order, pre-main-sequence objects can be recognised by their ragged and amorphous outer structures (e.g. see the Centaurus BPN, Wegner and Glass 1979), while highly evolved nebulae appear more highly symmetrical (e.g. GL 2688). Several techniques have been fruitfully applied to the study of BPNs and it is valuable to examine the results of this work. The principal techniques are polarimetric mapping, spectroscopic mapping, spectropolarimetry, infrared spectroscopy, far-infrared photometry, the study of radio molecular masers and continuum monitoring.

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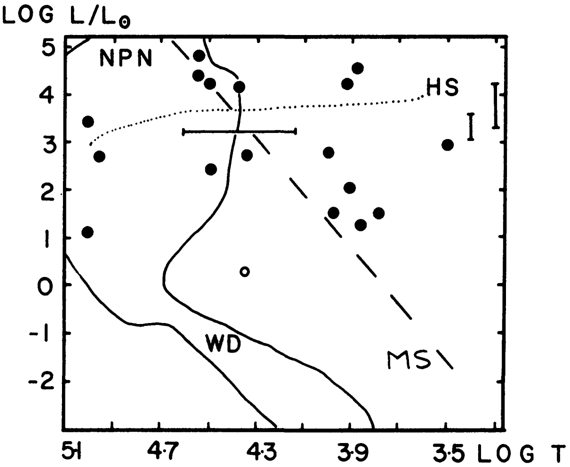

Fig. 1: HRD for 19 BPN. Indicated are the domains of the nuclei of planetary nebulae (NPN) and of the white dwarfs (WD), the main sequence (MS), and a typical evolutionary track for a red giant from Harm and Schwarzschild (1975). Where the temperature of the central star is uncertain, a horizontal bar is plotted; likewise for ranges in luminosity vertical bars are shown. M2-9 is shown at 50 pc (the open circle) and at 900 pc.

All investigators interpret their observations using the same model, namely a central star/infrared object, perhaps optically invisible, surrounded by an equatorial disk of gas and dust, embedded in a more extensive, bipolar nebula that contains small grains that scatter the light of the star in our direction. The photographic structure of some BPNs strongly suggests that that their disks are discernible; for example, M1-92, where the fainter nebular lobe appears truncated by an overlying circular mass. Nebular polarimetric mapping vindicates this view by revealing perturbations of the usual centrosymmetric pattern of polarization vectors in the vicinity of the central object. The centrosymmetric maps are explained as scattering of central starlight by small dust grains. The central disturbances of these patterns, resulting in vectors parallel to the minor axes, are thought to arise by viewing the stars straight through the disks in which are found aligned grains (e.g. Taylor and Scarrott 1980; Perkins, King and Scarrott 1981a; Perkins, King and Scarrott 1981b). Maps of near-infrared polarization reveal an identical situation (e.g. Allen _et al_. 1980a; Staude et al. 1982).

The BPN GL 2688 (Ney _et al_. 1975) is rich in molecules, both in the optical and microwave. High-spatial-resolution spectroscopy optically reveals the distribution of molecular emission of C_2, C_3 and SiC_2 across the nebular lobes. These features appear to arise through resonance fluorescence in the stellar radiation field, as for comets in sunlight

(Cohen and Kuhi 1980).

Some BPNs are characterised by very rich atomic emission-line spectra. For these, spectropolarimetry has proved extremely fruitful (Schmidt and Cohen 1981). For the brighter lobe of GL 618 (Westbrook et al. 1975) one sees greatly reduced degrees of polarization at the locations of the emission lines, with rotations in position angle for the very strong forbidden lines (Fig. 2). The permitted lines exhibit the same position angle as the highly polarized continuum so some fraction of this emission arises close to the star and is scattered to us by grains. The degree of polarization, however, is less than that of the continuum, implying that a portion of the permitted line flux is emitted in the lobes themselves. GL 618 has a spectrum that greatly favours the

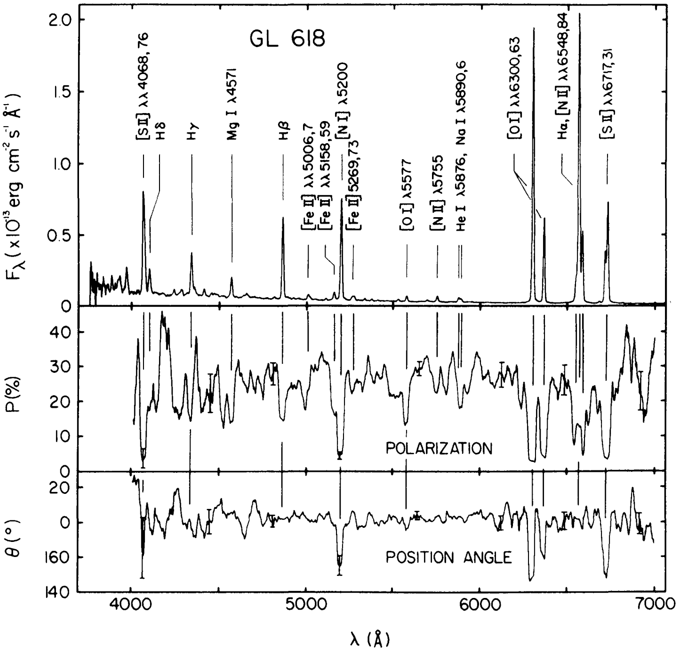

Fig. 2: Spectropolarimetry of the brighter lobes of the BPN GL 618 showing the different characters of polarization for continuum, permitted and strong forbidden lines.

cooling lines of heavy elements. An analysis of the line intensities intrinsic to the lobes enables a model to be constructed of the nebulae in which two very different regimes are found. Ionized, hot (18000K), high-density ($N_e > 20000$ cm^{-3}) filaments occur but neutral (10000K), moderate-density ($N_e \sim 1000$ cm-3) gas is the primary constituent. These zones are identified with unshadowed and shadowed material, respectively (Fig. 3). From both observational and theoretical viewpoints, this BPN fits naturally into present conceptions of the initial development of planetary nebulae where condensations are important. A similar picture

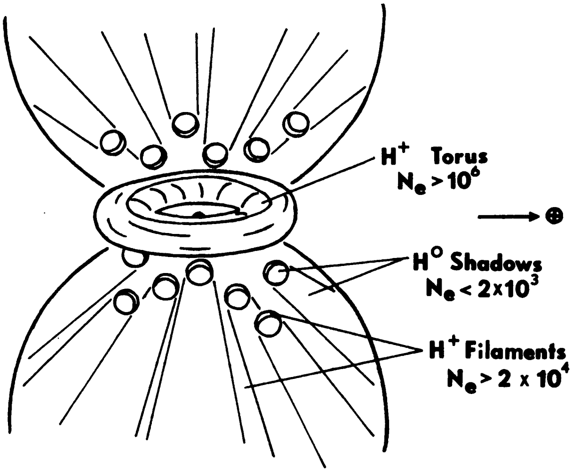

Fig. 3: Model for GL 618 showing the shadowed (neutral) and unshadowed (ionized) zones in the lobes of this BPN.

showing the presence of condensations emerges from spectropolarimetry of M2-9 (Schmidt and Cohen 1981) and nebular polarimetric mapping (King _et al_. 1981).

The near-infrared spectrum of GL 618 is also of great interest as it shows a number of vibration-rotation lines of molecular hydrogen (Thronson 1981). These seem to arise in a shocked zone of T $\sim$2000K, and velocity $\sim$10 km/s, consistent with little ionization of hydrogen. Radial velocity differences between atomic lines in the two lobes have enabled the identification of the blue component of Hα in the brighter lobe as locally ionized matter, whereas the red one is scattered from the central small HII region (Carsenty and Solf 1982). The kinematic analysis suggests an extremely young age for GL 618, perhaps only 600 yr, comparable with the time scale for expansion of the CO molecular shell (1500 yr). Strong support for the view that BPNs like GL 618 are now in rapid evolution comes from the increase in radio continuum flux in only 2 yr (Kwok and Feldman 1981), and the steady brightening of GL 2688 over some 20 yr (Gottlieb and Liller 1976), with some short-term fluctuations (Franz 1980). Short-term variability in the structure of M2-9 may also indicate rapid evolution although Kohoutek and Surdej (1980) favour rotation. Incidentally, these authors present a beautiful picture of M2-9 that reveals an outer very faint loop structure that may illuminate the processes of formation of BPNs.

Substantial infrared flux characterises all BPNs. Airborne far-infrared photometry indicates a grain emissivity like $\lambda^{-1.5}$ for the cool emitting grains, and appreciable long wavelength fluxes speak for circumstellar disks that are greatly extended in temperature range (Kleinmann _et al_.1978). Near-infrared polarimetry (Jones and Dyck 1978) of the BPNs shows a degree of polarization that diminishes with increasing wavelength beyond 1 µm, arguing that the scattering grains are less than about 0.3 µm in radius.

Radio masers are now known to be associated with several BPNs, principally lines of OH. OH0739-14 (Morris and Bowers 1980) is a remarkable OH object, possessing weak emission over a broad velocity range with a prominent narrow spike that moves within this plateau. Although it had not previously been bright enough for optical spectroscopy, one lobe of this BPN was visible beyond 6000Å at a time of strong OH emission. The reflected spectrum (Fig. 4) is clearly that of an extremely cool star, an M9III, the coolest star known within a BPN (Cohen 1981). In fact, OH maser activity extends across the HRD for BPNs from spectral type M9III (OH0739-14), through A2I (Roberts 22: Allen, Hyland and Caswell 1980), to M1-92 (B1V) where it is weakly observed.

GL 2789 has excited considerable controversy as to its distance (Cohen 1977; Humphreys, Merrill and Black 1980). It was first recognised as bipolar from nebular spectropolarimetry (Cohen 1977); it is associated with a CO cloud (Harvey and Lada 1980), and an H_2O maser coincides with its brightest portion (Lada _et al_. 1981). The exciting star is of type late O. Another late O-star that excites and illuminates a BPN is found in Sh2-106. This very complicated region, with several infrared sources, has been extensively mapped in the mid-infrared (Gehrz _et al_. 1982), studied through optical and near-infrared polarimetry (Lacasse _et al_. 1981; Tokunaga, Lebofsky and Rieke 1981), and by optical spectropolarimetry (Staude _et al_.1982). All results are consistent with a single exciting star that drives a bipolar molecular flow away from its equatorial dust disk.

The optical spectrum of "The Red Rectangle", illuminated by HD44179 (Cohen et al. 1975), has been found to contain a wealth of so far unidentified apparently molecular emission features (Schmidt, Cohen and Margon 1980). In the nebular lobes (Fig. 5) the spectrum is dominated by a broad diffuse peak with several groups of sharp emissions, some resolved. None of these structures is polarized, indicating that their source(s) are found within the lobes and that their emission merely dilutes the scattered starlight. It is tempting to identify the sharper features as due to gaseous species, and the diffuse peak as due to solid-state resonances when these gaseous molecules are bound into grains. As yet, however, no satisfactory matches have been found with known molecular spectra.

A feature common to several BPN is the presence of nebular spikes; for example, those of the Rectangle, of GL 2688, and of Parsamyan 22. Nebular polarization maps in the visible suggest that, for HD44179, these arise because of enhanced dust density on a biconical surface (Perkins _et al_. 1981c). On rather general theoretical grounds (Icke 1981) it has been argued that mass loss from an object embedded within an accretion disk would result in biconical outflow, independent of the driving mechanism. Stellar winds have been favored as producing some BPN by means of expanding circumstellar shells (M2-9: Walsh 1981), or intermittent outflows of

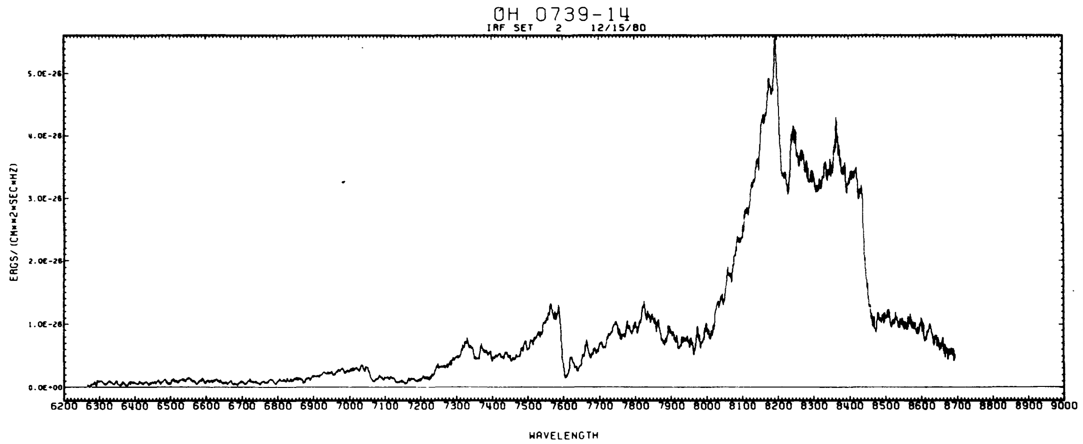

Fig. 4: Red spectrum of the embedded star of the BPN OH0739-14 as reflected from its southern lobe; the spectral type is M9III.

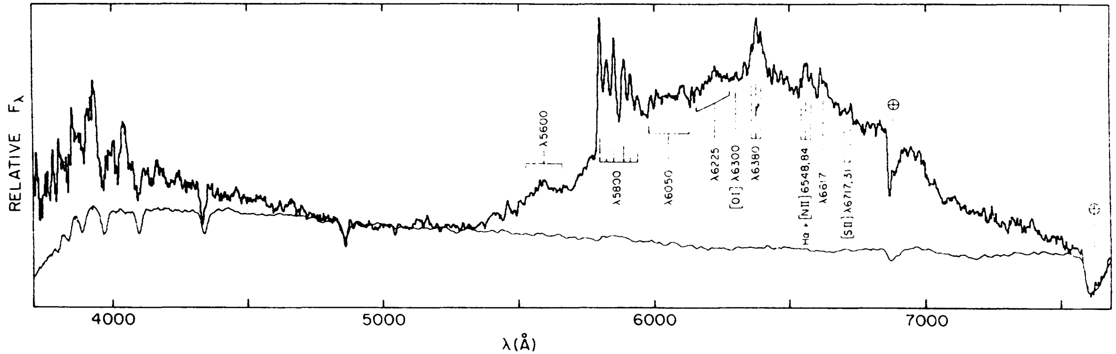

Fig. 5: Optical spectrum of the nebulosity associated with HD44179. Lower spectrum is that of the central star; heavy line refers to the nebular spectrum.

high mass loss rate from very hot central stars (Mz-3: López and Meaburn 1982). Even the complex "poly-polar" nebula NGC 6302 has been interpreted in this light (Barral et al. 1982). In order to produce adequate ionization in Roberts 22, with an A2I central star, appeal was made to sudden deceleration of a rapid outflow at the inner edge of the torus, producing a shock (Allen et al. 1980b). Several independent models for different BPNs require mass loss rates of order 10^{-4} to 10^{-5} $M_\odot$/yr, a magnitude suggestive of a short-lived phenomenon.

Another mechanism advanced in the context of stars that have driven out bipolar CO flows is that of supersonic expansion through a de Laval nozzle, in the direction of a decreasing density gradient (Königl 1982). This picture unifies conical/fan and biconical/bipolar cometary nebulae (Cohen 1982) since one nebular lobe is often deeply embedded in a dust cloud. Within this framework, the displacement between fan-tip and associated infrared object (e.g. for PV Cep, Cohen et al. 1981; for R Mon, Cohen and Schwartz 1982) is explained - the fan-tip apparently representing the nozzle above the star/infrared source. The association between ambient cloud and BPN has been probed by a 2.6-mm CO occultation of Lk Hα-208 (Good et al. 1981). No compact molecular source (e.g. a disk) was resolved.

Stimulated by OH0739-14, Morris (1981) proposed that in a binary with primary evolving up the red giant branch, and achieving its tidal radius before corotation with the secondary, the primary envelope could be ejected and would sink to the equatorial plane. Such a model would predict that BPNs would evolve into planetaries whose nuclei would be binaries that ultimately become cataclysmic variables. In this context, it may be of interest to note the 16-day period for the spectroscopic binary nucleus of NGC 2346 (e.g. Méndez and Niemela 1981).

It is remarkable that so many diverse objects are found to possess a bipolar structure. Let me conclude with two very recently discovered examples of this diversity. GL 1403 (CIT-6) is an extreme carbon star, embedded in a thick circumstellar dust shell, whose spectropolarimetry presents an intriguing phenomenon (Cohen and Schmidt 1982), namely abrupt rotation of position angle through 90 degrees, accompanied by almost a nulling of polarization at the same wavelength (Fig. 6). GL 1403 also exhibits a strange, smooth, blue continuum, not typical of extreme carbon stars, and due to thermal emission by hot (2000K) grains viewed over the poles of the star. The red continuum is starlight scattered through an equatorial dust disk (in whose plane we lie) and hence polarized orthogonally to the blue spectrum.(Fig. 7).

MWC349 is a highly intriguing late O star with a curiously slow wind and associated with radio continuum emission. Very recently, deep VLA maps (Cohen et al. 1982) have been made at 6 cm that clearly demonstrate MWC349 to be a binary, not merely an optical double star. Complex gas streaming is seen (Fig. 8). However, the radio contours that surround the primary are conspicuously square, with corners "pinched out" along the diagonals. This morphology is strikingly reminiscent of the optical

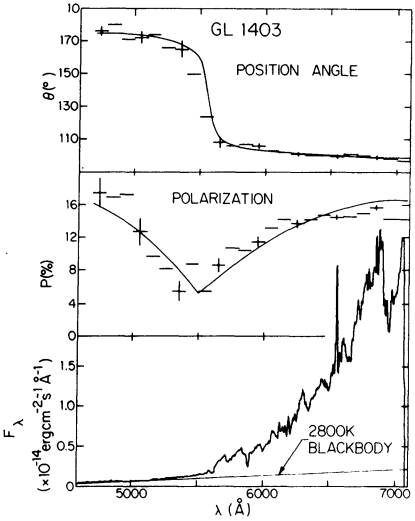

Fig. 6: Spectropolarimetry of the extreme carbon star GL 1403 (CIT-6).

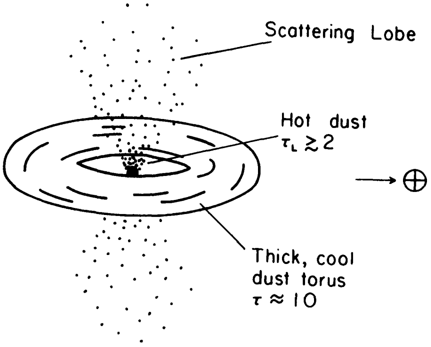

Fig. 7: The bipolar model proposed for GL 1403.

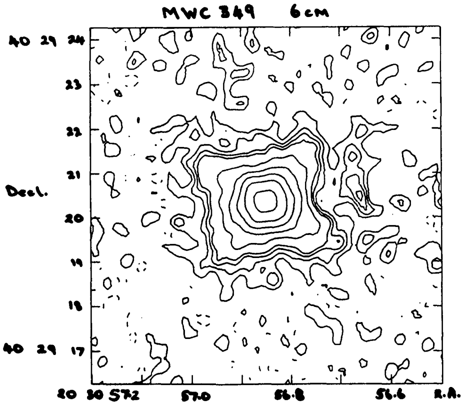

Fig. 8: VLA 6-cm map of the binary MWC349 showing the squaring of the contours around the primary which may represent a biconical surface flow akin to that in The Red Rectangle.

structure of The Red Rectangle. This serves to indicate that equatorial dusty tori are common occurrences at very different phases of stellar evolution. Consequently, bipolar nebulae are also abundant, although apparently representative of phenomena of very short duration.

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DOPITA: Some of the bipolar nebulae show spectra like those of Herbig-Haro objects whose spectra can be well reproduced by low velocity shocks. The same idea might help in understanding bipolar nebulae spectra.

COHEN: For nebulae such as GL 618, this might be fruitful, but many bipolar nebulae show just reflection spectra.

KALER: In GL 618, are the emission lines unpolarized and what are the errors?

COHEN: The permitted lines are polarized at a level of about 10% ± 1%. The forbidden lines are about 3% polarized, but this is attributable to the interstellar medium.

SURDEJ: Do you think that the outer loops of bipolar nebulae are produced by magnetic fields?

COHEN: It is quite possible that this is the case.

CARSENTY: We have recently found that the motions in M2-9 cannot be attributable to rotation for the N and S lobes would be rotating in opposite senses.

COHEN: Good! Then I can remove the open circle from Fig. 1 representing M2-9 at a distance of 50 pc.

BLACK: Is it true that for the bipolar nebulae which you claim to be excited by O-stars, the spectral type rests solely on counting ultraviolet photons?

COHEN: It really depends on the distance: if you have a credible distance, then you have an estimate of the bolometric luminosity. For some nebulae, you have to rely on photon-counting. Of course, even if you do see absorption lines, as in GL 2789, you may be looking only at a shell spectrum.

NUSSBAUMER: Could the shapes of bipolar nebulae arise from magnetic confinement? Material may be carried away from the stars along open magnetic field lines as in the case of the Sun.

COHEN: Yes; in fact, it may be possible to interpret bipolar nebulae in terms of supersonic expansion through a de Laval nozzle under magnetic confinement.

LEAVER: Are the axes of bipolar nebulae aligned with the Galactic magnetic field direction?

COHEN: I believe that it has been claimed that the orientations of nebular disks or axes are correlated with the Galactic plane or the direction of the local Galactic magnetic field. However, I am not convinced that this is true of the entire sample of bipolar nebulae.