BIPOLAR FLOWS AND JETS FROM STARS OF DIFFERENT SPECTRAL TYPES: OBSERVATIONS

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ABSTRACT. The fact that bipolar flows are widespread among stars of very different spectral types is emphasized. First, the stars associated with the phenomenon are divided into broad types: protostars and pre-main-sequence stars; red giants; symbiotic objects; protoplanetaries; planetaries; novae and cataclysmic variables; and peculiar hot stars. Second, the evidence for circumstellar "disks" or toroids is considered among these different categories of star. Finally, the possible role of binarity is discussed.

1. INTRODUCTION

There were bipolar flows long before there were molecular radio astronomers to tell us that they had discovered them. Optical astronomers knew these already as the class of bipolar nebulae. Defined strictly morphologically, bipolar nebulae are known to constitute a heterogeneous body of objects (Cohen 1983). Some are associated with pre-main-sequence stars or presumed protostars; others with red giants, both oxygen- and carbon-rich; still others are caught in the brief transition from red giant to planetary nebula, the so-called "protoplanetaries"; even some fully-fledged planetaries reveal bipolar structure rather than spherical.

We have always felt intuitively that bipolar nebulae have central stars embedded in equatorial toroids and have undergone recent bipolar mass loss. In most cases it is hard to prove, in the absence of radio molecular data, that a bipolar, usually reflection, nebula is actually driving mass loss through its lobes. Velocity information by optical or near-infrared techniques is often lacking. A rare exception is GL 2688, the "Egg" Nebula in whose lobes directly viewed molecular emission bands (of C_2, C_3, SiC_2) are optically detected (Cohen and Kuhi 1980). The radial velocities of these bands reveal a clear bipolar flow from this carbon-rich F supergiant. In general, bipolarity is assumed to extend from mere morphology to velocity fields if the latter are unknown.

In this talk I want to focus on three aspects of bipolar nebulae and flows. First, let me remind you of the very wide range of spectral

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types of star with which these flows are allied. Second, we will examine some of the recent direct evidence in favor of the existence of circumstellar disks. Finally we will address the possible role of binarity in the creation of bipolars. To highlight the wide range of spectral types of central star it is convenient to divide the unevolved objects into protostellar and pre-main-sequence systems, and the evolved objects into red giants, symbiotic stars, protoplanetaries, planetaries, novae and cataclysmic variables, and other peculiar hot stars. It is important to have a working definition of a "jet" too since this word is experiencing widespread usage now, and not always with the same connotations. I shall use "jet" here to signify a highly confined flow that originates in the immediate vicinity of the responsible star or, if two-sided, includes the star in its body. This definition eliminates random filamentary (HH or otherwise) structures the locations of whose exciting or illuminating stars are not known by any technique, direct or indirect. Opening angles should be at most a few degrees.

2. THE SPECTRAL CHARACTER OF THE ASSOCIATED STARS

2.1 Protostars and Pre-Main-Sequence Stars

Since most presumed protostars are optically unseen I am, perhaps, stretching the title of this talk to include them. However, in a few cases we can detect and even classify reflected stellar spectra, and in still rarer circumstances we do directly see the exciting stars. An obvious subclass of low-luminosity and therefore low-mass protostars is the group that excites Herbig-Haro (HH) Objects. When visible directly these are strong emission-line T Tau stars (e.g. AS 353A, HL and DG Tau) and, indirectly, several HHs scatter the light of stars of this type too (e.g. HHs 30, 55, 100: Cohen, Dopita and Schwartz 1986a). Not all HHs are demonstrably jetlike or bipolar at visible wavelengths. Often only one-sided flows are visible although VLA radio continuum observations indicate the truly two-sided character of the mass loss (e.g. Bieging, Cohen and Schwartz 1984; Bieging and Cohen 1985). Usually the red-shifted jet is lost to optical view because it enters a dark cloud. Likewise the one-sided fan nebulae associated with some pre-main-sequence stars, such as PV Cep and R Mon, arise because an extensive dusty disk overlies one lobe. However, deep CCD frames, especially those in the I-band, or photographs at fortuitous times, can reveal very faint traces of a truly bipolar nebula. Examples of this are the faint southern spike of R Mon recently recorded by Walsh and Malin (1985) and the very faint southern fan of PV Cep detected by Ray (1986). A rather unusual example of a jet in which the blue-shifted lobe is extremely sparse but the red is relatively bright is "DG TauB", discovered by Mundt and Fried (1983) but not physically related to DG Tau. Spectra by Jones and Cohen (1986) of this elegant tapered flow show it to be bipolar and of unprecedentedly low excitation (in one knot the ratio of [SII] (6717+6731) to H-alpha is almost 12:1!).

In two cases FU Ori stars are believed to excite bipolar flows, namely L1551 IRS5 (early K: Mundt et al. 1985) and HH57 (F8III: Cohen, Dopita and Schwartz 1986b). Optical "jets" sometimes have HH spectra and may reflect red, presumed stellar, continua though these are usually too faint for classification. Some even older T Tau stars, not associated with optical jets or HH objects, lose mass in a bipolar fashion as demonstrated by the frequent blue shifts of nebular [OI] lines in their spectra (Appenzeller et al. 1984).

The nebulous early-type stars first studied by Herbig (1960) and recently reinvestigated by Finkenzeller (1985) also reveal blue-shifted [OI] lines, indicative of non-spherical flow. In some cases these are allied with conspicuous bipolar nebulae, like Lk $H\alpha$-208 and Lk $H\alpha$-233. Polarimetric images of these clearly mark them as reflecting the light of a star within the nebulae [from the clear pattern of centrosymmetric electric vectors: e.g. Shirt, Warren-Smith and Scarrott (1983); Aspin, McLean and McCaughrean (1985); Aspin, Mclean and Coyne (1985)].

There are definite indications of alignments between bipolar flows and the local interstellar magnetic field (e.g. R. J. Cohen, Rowland and Blair 1984). This global organization is shown,too, by the existence of close pairs of parallel flows in the R CrA cloud (from R and T CrA: Ward-Thompson et al. 1985) and in L1551 (from IRS5 and the IRAS object NE of it: Draper, Warren-Smith and Scarrott 1985).

The impact of these non-spherical flows from both proto- and pre-main-sequence stars on their environment is registered through the bipolar patterns of disturbances that extend out into the clouds when mapped in molecules like CO (e.g. Bally and Lada 1983). Probably all stars evolve through a phase of bipolar mass loss early in their lives. Such a conclusion is borne out, also, by the fact that unambiguously young bipolar systems are allied with stars from B8 (lying in a Bok globule: Bruck and Godwin 1984) through the typically K-type spectra of T Tau stars to M3.5 (for HH55's exciting star though the HH is so small that it has not yet been identified as bipolar) or at least to some M-type if Parsamyan 13 is included (Cohen et al. 1983).

2.2 Red Giants

Optical spectropolarimetry shows that extreme carbon stars such as IRC+10216 and IRC+30219 are very highly polarized, up to 30% for GL 2699 (Cohen and Schmidt 1982). For IRC+30219 the abrupt rotation of position angle and virtual nulling of polarization indicate a definitely bipolar scattering nebula. Even for IRC+10216, which has not been observed to show this rotation, there is good agreement between the inferred axis of scattering (E-vector in p.a. 120 deg.) and the elongation recently reported in CCD images (p.a. 30 deg.: Crabtree, McLaren and Christian 1986). Velocities as high as 80 km/s have been noted in IRC+30219 in the form of episodic optical shock spectra (Cohen 1980) although the morphology of this material flow is unknown.

Among the extreme OH/IR stars the system OH0739-14 seems unique in the variety of peculiarities displayed. M9 III (or perhaps I?) starlight is reflected from both lobes of this very red bipolar nebula as is a curious blue continuum probably due to an otherwise unseen hot companion. However, along the axis of this nebula are two HH objects, expanding away from the central star at velocities of ± 150 km/s (Cohen et al. 1985a)! One even shows greatly enhanced nitrogen abundance, relating its material to the central evolved star rather than to the ambient medium.

The OH maser peculiarity of this system is the presence of a very broad (100 km/s) plateau of weak satellite-line emission below a sharp, powerful spike Morris and Bowers 1980). This spike is believed to be associated with the line of sight to a hot companion embedded in a substantial disk (Morris, Bowers and Turner 1982); a binary was also postulated by Morris (1981) to account for the morphology of the reflection nebula. Other OH/IR sources may be akin to OH0739-14 because of their maser spectra. These include the bipolar reflection nebula M1-92 (spectral type B0: Cohen and Kuhi 1977) which may have similar maser spectral structure (e.g. Davis, Seaquist and Purton 1979). Roberts 22 (A2I: Allen et al. 1980) may be a member of this small group of objects because its 1612 MHz profile might arguably contain a weak, broad plateau of emission although its satellite lines seem to show the characteristic double-spiked spectra of spherically-shelled late-type OH/IR emitters. There is continuing controversy also about whether to include the OH/IR object IRC+10420, a bright, visible F8Ia star that excites strong 1612 MHz emission (cf. Bowers, Johnston and Spencer 1981) with these other two nebulae. Mutel et al. (1979) saw possible evidence in the OH morphology for a disk, perhaps aligned with the elongated optical nebulosity (Thompson and Boroson 1977), but this is not known to be bipolar. Diamond, Norris and Booth (1983) interpret their MERLIN OH maps in terms of bipolar flow but recent near-infrared speckle results (Ridgway et al. 1986) show no convincing evidence for the asymmetry of its dust shell.

2.3 Symbiotic Stars

In this category we include R Aqr and HM Sge. R Aqr is an M7 giant in a rather complex bipolar nebula whose elegant structure was recently explained by Solf and Ulrich (1985) in terms of two episodes of bipolar outflow. Kafatos, Michalitsianos and Hollis (1986) review the ultraviolet excitation and variability of R Aqr. They discuss the curious optical and radio "jet" that emerges from the star and the history of the "new" knot. Mauron et al. (1985) feel from their UV CCD imagery of R Aqr that the appearance of this latter feature does not connote an episode of outflow but is the response of pre-existing material to sudden ionization by the variable hot source. (This "jet" does not align with the major axis of R Aqr's previous bipolar flows but it does roughly coincide with the brightest part of the inner nebula.)

The red giant/symbiotic system, HM Sge, was also studied by Solf (1984) who found evidence from slit spectra for narrowly confined bipolar, high- velocity (200 km/s) mass loss in the form of small regions of forbidden line emission.

2.4 Protoplanetaries

Most newly-found optically-visible bipolar nebulae belong to this class. They are presumably related to the symbiotic stars, or at least to some red giants, while these are evolving into planetaries. Their central stars are hot; their nebulae are usually small and of high density, and it is sometimes hard to separate the protoplanetaries from compact planetaries. Indeed, it may take VLA observations of the latter to recognize their bipolar morphology (e.g. M1-6: Kwok and Purton 1983). Calvet and Cohen (1978) and Cohen (1983) list the protoplanetaries and draw an H-R diagram to show their locations.

2.5 Planetaries

New CCD emission-line images by Balick (1986) indicate that many planetary nebulae, especially the compact ones or those bright in the mid- infrared, have bipolar rather than spherical symmetry. Sometimes the inner nebular structures are quite unlike the outer, as in Abell 30, for example, where the nucleus is embedded in a pair of orthogonal bipolar flows of processed material, perhaps 1500 years old, expanding at roughly 20 km/s from the central star (cf. Reay, Atherton and Taylor (1983).

The bipolar planetary NGC 2346 continues to draw attention. The best picture seems to involve eclipses of a binary system, with unseen hot companion, by an elongated toroidal dust cloud (recently resolved by optical speckle work: Meaburn et al. 1985) that rotates around the stars, orthogonal to which is a bipolar mass flow (cf. Walsh 1983; Roth et al. 1984; Acker and Jasniewicz 1985).

The nebula Mz-3, usually thought of as a fully-fledged planetary (e.g. Lopez and Meaburn 1983), may be interpretable as a protoplanetary according to Meaburn and Walsh (1985) who have studied the kinematics of its inner and outer envelopes. The faintest outer shell shows great line width (up to 450 km/s) compared with the much slower, inner bipolar structure that is expanding at ± 50 km/s.

2.6 Novae and Cataclysmic Variables

The old nova V603 Aql was studied spectroscopically in great detail. From these data it is possible to construct a clear picture of the morphology of its nebular shell and to recognize this as built up from a series of successive biconical ejections from the nova within its accretion disk (Weaver 1974). This system was recently reinvestigated by Haefner and Metz (1985) who give details of the binary and the accretion disk.

The novalike cataclysmic variable PG1012-029 shows a non-rotating component to its line profiles that dominates the character of the eclipses of the secondary (Honeycutt, Schlegel and Kaitchuk 1986). These authors attribute this component to a bipolar wind from the accretion disk.

2.7 Peculiar Hot Stars

If we study the peculiar hot star, MWC 349, we will continue this bipolar/biconical theme. This star has a vast literature of peculiarities. I shall confine my remarks here to its VLA maps at 5 GHz (Cohen et al. 1985b) and 15 GHz (White and Becker 1985). The 5 GHz map clearly shows an interaction between the winds of MWC 349B, a B0III, and MWC 349A, the bright central component. Further, despite the good fit of the visibility function to a spherical mass loss law, this central component patently shows non-sphericity in the form of what appear to be biconical projections. At the higher frequency it appears bipolar.

3. EVIDENCE FOR CIRCUMSTELLAR DISKS

3.1 Photometric and Polarimetric Imagery

Usually the fainter lobes of bipolar nebulae are also redder. It is therefore easy to believe that the fainter lobes are more heavily extinguished by local obscuration, perhaps due to overlying circumstellar dust disks. There are even indirect clues to this in the shapes of some of these lobes whose boundaries, closest to the central stars, are concave towards the stars (e.g. M1-92). Slightly more direct evidence comes from the breakdown of the centro- symmetric pattern of polarization vectors in the vicinities of the stars, or from the presence of fan-shaped regions of low polarization (due to optically thick scattering in a toroid by grains aligned parallel to the disk plane: cf. Aspin et al. 1985a,b). In Lk Hα-208, Shirt, Warren-Smith and Scarrott (1983) detect an extensive disk partially overlying the southern nebular lobe by their photometric and polarimetric imaging.

We might extend the imagery discussed here to include use of the speckle technique on MWC 349 which Leinert (1986) found to be elongated in a north-south direction at 2.2 and 3.8 microns, the same axis as indicated by radio synthesis observations.

3.2 Spatial Variations in Extinction

In particularly fortunate circumstances one can even "see" dust disks by their obscuration of background stars. This technique works for Mz 3 (Cohen et al. 1978).

Another method worthy of discussion is valuable in the protostellar context where the exciting star of an HH chain is not seen optically but its location can be inferred either from the position of an infrared source or from the brightness of scattered starlight within different HH knots. From the Balmer decrements in the HH nebulae one can deduce approximate extinctions, dominantly foreground since the emission lines arise in situ. The ratio of infrared to optical luminosities, or the depth of the 10 μm silicate absorption feature, can be used to estimate the direct line-of-sight extinction to the central star. Often it is found that the very large central extinctions drop precipitously within a very few arc seconds towards the HHs. Examples of this effect are given in Table 1. They indicate that there is centrally a higher density of absorbing material than can arise in the foreground interstellar medium. While it is conceivable to contrive a model in which this is intracluster (associated with the dark cloud material) rather than circumstellar (strictly local to the exciting star) this is only plausible if objects suffer very deep embedding and only one lobe (the blue-shifted one) of the bipolar flow is visible. It would not apply to "DG TauB", in which both red- and blue-shifted flows are clearly visible, nor to DG Tau which star is itself visible, nor to HH57 where, again, both lobes are clearly seen. Therefore one can establish that a relatively thin region of high obscuration exists towards the HH-exciting star that does not extinguish the nearby HH knots appreciably. A dusty disk would account for this.

TABLE I

System	Stellar Extinction	HH Extinction	HH from Star (")
L1551 IRS5	30:	7	< 3
DG Tau	5.4	0.4	8
"DG TauB"	8	0.6	2
HH57 star	5	1:	10

3.3 Near-Infrared Imagery

The highly evolved, almost recombined, planetary nebula Abell 30 was found by Cohen and Barlow (1974) to have a centrally-peaked distribution of mid-infrared-emitting dust grains. Subsequent study by Cohen et al. (1977) showed that, between the Rayleigh-Jeans distribution of the exceptionally hot nucleus and the steeply rising 160K component, there is a population of hot grains whose aperture dependence at 2 and 3 μm seemed closer to r than to r-squared. This could indicate an inclined dusty disk rather than a more spherical distribution of hot grains. Raster maps at 2 and 10 μm (Dinerstein and Lester 1984) have shown that, indeed, such a disk exists. Similarly, for the bipolar nebula NGC 6302, Lester and Dinerstein (1984) near- and mid-infrared rastered images support the conclusion that a dust disk lies around the central star, orthogonal to the bipolar flow axis of this nebula. This infrared work nicely corroborates both the optical polarimetry by King, Scarrott and Shirt (1985) and the VLA observations by Rodriguez et al. (1985), all of which conclude in favor of a similarly oriented disk that must have both dusty and ionized components.

At longer wavelengths (50/100 μm) Cohen and Schwartz (1984) report the existence of a structure, associated with the "Infrared Nebula" in the Cha 1 association, that is spatially-resolved in one dimension (perpendicular to the major axis of the reflection nebula) but unresolved parallel to the "flow". Similarly, for HH-exciting stars, Cohen, Harvey and Schwartz (1985) have discovered 100 micron structures that represent flattened emitting regions, resolved orthogonal to the flows of HH objects but not in the flow directions. One particularly conspicuous flattened zone is associated with the potential FU Ori star that excites HH57. Another surrounds the exciting star of the HH7-11 system. The intrinsic radii deduced for these flattened structures are of order several thousand A.U., with temperatures of the cool dust around 45K.

3.4 Radio Aperture Synthesis Observations

Highly promising results are emerging from aperture synthesis maps of bipolar nebulae made either at centimeter wavelengths with the VLA (typically in ammonia lines) or in millimeter wave syntheses in molecules sensitive to high densities (e.g. CS or HCN). A good example of the value of these data can be gleaned from new observations of GL 2688. Rieu, Winnberg and Bujarrabal (1986) find a disk in ammonia surrounding the infrared source that lies between the lobes whereas other molecules like CO and even HC_7N show emission entirely surrounding the nebula or at least elongated parallel to the flow direction, respectively. He even detects an ammonia "jet", orthogonal to the disk and moving into the northern lobe. Bieging and Rieu (1986), working with the 3 mm HCN lines, also note a disk around the waist of GL 2688 with essentially the same diameter as the ammonia toroid. Spectra of the disk reveal spatial differences with velocity with a pattern indicative of rotation of the HCN structure.

4. THE ROLE OF BINARITY

4.1 Protostars and Pre-Main-Sequence Stars

At 15 GHz, L1551 IRS5 is resolved into two components that Bieging and Cohen (1985) interpret as a potential binary. The projection of the inferred orbital plane is closely orthogonal to the central 5 GHz contours in the "jet" or extended emission. The jet appears to emanate from the brighter (the northern) of these two high-frequency sources.

A similar situation occurs for T Tau. The stronger of the two radio components lies immediately south of the star and there is an HH object with perceptible proper motion that is moving to the west, essentially orthogonal to the line connecting T Tau N and S.

Mundt and Fried (1983) have suggested that the easternmost blob of "DG TauB" is elongated roughly perpendicular to the westward line of knots and that this elongation represents a potential binary. However, Jones and Cohen (1986) do not confirm the elongation in their direct CCD image and argue that the exciting star of this system lies <u>between</u> two bright knots, rather than inside any knot. This is much more plausible, for if "DG TauB" were such a well-developed, confined flow it must be very young. If so, nothing should be visible directly in the vicinity of its exciting star. The binary status of this exciting star should, therefore, be withdrawn.

4.2 Red Giants and Symbiotic Stars

In at least one model of symbiotics, the red giant is one component in a binary with a compact hot companion. Such a model was favored by Solf (1984) for HM Sge and this system exhibits bipolar high-speed mass outflow. The symbiotic R Aqr shows clear evidence of episodes of parallel bipolar ejection (Solf and Ulrich 1985), although its "jet" is not in this same direction. For OH0739-14 the blue continuum reflected by the nebular lobes speaks for the presence of a blue companion. The maser model by Morris, Bowers and Turner (1982), that might apply not only to this OH/IR source but also to M1-92 and Roberts 22, requires that the strong spike of emission comes from the line of sight through the equatorial disk toward the hot star. Therefore, it is possible that all these bipolar OH/IR systems contain binaries.

4.3 Protoplanetaries

So far there is no evidence in favor of binary central stars in any of the established protoplanetary nebulae.

4.4 Planetaries

The photometric variations of NGC 2346 have been interpreted by many authors as due to eclipses by a dust cloud orbiting the central star. The only visible star is too cool to ionize the nebula so there must be an unseen hot component within the nebula, perhaps within the dust toroid. 19W32 is a bipolar planetary with a central star that is a close (<1") double (Kohoutek 1982). The brighter component does not lie at the nebular center of symmetry and the fainter star is definitely hot. Perhaps this the faint blue star is the true exciting star and the bright object just lies in the foreground.

4.5 Novae and Cataclysmic Variables

Implicit in the models for these systems is a binary with an accretion disk surrounding the active star.

4.6 Other Peculiar Hot Stars

We have already cited the strange high luminosity object, MWC 349. The VLA map at 5 GHz indicates a region of interaction apparently between the winds from the two hot stars, MWC 349A and B (B0III). This interaction suffices to demonstrate the binary nature of MWC 349 and, again, the axis of radio bipolarity is clse to orthogonal to the projected orbital plane of the two stars, in spite of their great separation.

HD 44179, the star associated with the "Red Rectangle" nebula is a very close but visual binary, ADS 4954 (Cohen et al. 1975). Speckle observations of this star in 1981 (Meaburn and Walsh 1983) successfully detected the companion, seen last in 1962. Even allowing for the ambiguity of 180 in position angle the most plausible orbit is not related to the orientation of the inferred dust disk nor of the nebular spikes.

5. CONCLUSIONS

In conclusion, it appears that our intuitive picture of bipolar nebulae as systems incorporating sizable equatorial toroids around the central star is substantially correct. This toroid may have cool dusty, or molecular, or ionized components, or any combination of these. Its orientation is almost invariably perpendicular to the major axis of the nebula. An appreciable number of stars associated with bipolar nebulae are known to be binaries in which, usually but not always, the inferred orbital plane is orthogonal to the direction of outflow.

Questions still remain about the "disks" and whether they play any significant role in the dynamics of the bipolar flows. For the HH-exciting stars it is, perhaps, more fruitful to think in terms of static confinement of a flow that originates at the protostellar core but must pass through a still-infalling region of gas and dust in order to penetrate to the ambient medium. Such a picture may well provide confinement, if not collimation, of HH jets (Shu 1987). For the novae like V603 Aql, it is hard to avoid the feeling that activity within the accretion disk is the probable cause of the successive ejections of biconical surfaces. Cohen et al. (1985a) have built a model for the evolved OH/IR object, OH0739-14, in which the binary creates the highly supersonic HH objects.

In the context of the extreme carbon stars and, for that matter, OH0739-14 too, it is a continuing curiosity (Cohen 1985) that the ancient molecular shells (of CO or OH) indicate a more or less spherical flow while more recent mass loss has somehow generated both an equatorial toroid and a bipolar outflow. What is the true chronology of the morphology of mass loss in these extremely cool giants?

Certainly the great variety of stellar spectral types allied with bipolar flows indicates that the mechanism, or mechanisms, of non-spherical mass loss are easy to establish and may depend upon common ingredients such as a convective stellar configuration, global mass loss in the presence of an equatorial toroid, a binary system and an accretion disk around the currently active component, stellar rotation, and the circumstellar or interstellar magnetic fields.

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