The spatial orientations of bipolar nebulae

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Abstract. We investigate the spatial orientation of mass outflow axes in post-main-sequence bipolar nebulae. As a consequence, some 71% of nebulae are found to have their outflow axes oriented within $\pm 45°$ of the Galactic plane; a distribution which has a probability level of $5.8 \ 10^{-4}$. There appear to be no clear mechanisms whereby such a non-random distribution may be explained.

1. Introduction

The origins of the multi-various structures of planetary nebulae remains a subject of continuing debate; although it is usually conceded that elliptical, spherical, irregular and other nebular morphologies are likely to derive from the nature of the mass-loss process itself. Thus, rotating stars, binary systems, magnetic fields and radiation pressure are all thought to play a part in creating the observed distributions of nebular emission. The role of larger-scale galactic properties is usually regarded as negligible.

It therefore came as a considerable surprise when Melnick & Harwit (1975) noted significant non-random orientations in the long axes of elliptical nebulae. Of 53 such sources derived from the catalogue of Perek & Kohoutek (1967), some 66% appeared to have major axis orientations within $\pm 20°$ of the Galactic plane. Various mechanisms were proposed by way of explanation, including interaction with interstellar gas, leading to compression perpendicular to the galactic plane, and the influence of the galactic magnetic field. None of these seemed then or in retrospect to be entirely plausible.

Since that time, it has become apparent that a large fraction of planetary nebulae also possess bipolar outflow structures, in which material is collimated along two primary and opposing directions. Archetypal examples of such flows include NGC 6302, Hb5, M2-9 and M3-28. This general morphological subgroup is by no means uniform, and includes a broad range of differing structures; certain nebulae appear to possess extended arms

(cf. NGC 6537, Hb5, He 2-104), whilst others have chaotic sub-structures (NGC 6445, BI Cru, NGC 6302) and, within the limits of our resolutions, comparatively smooth spatial distributions of emission (M 2-9, K 3-72).

In most if not all of these sources, it is supposed that collimation arises through interaction of the outflowing gas with a collar or disk of circumnebular material (e.g. Phillips 1989).

In the following, we investigate the orientation of such nebulae with respect to the galactic plane, and discuss various mechanisms which may be responsible for creating non-random distributions of axes.

2. Analysis of nebular orientations

The sample of bipolar nebulae employed in the present analysis was culled from a variety of published images, including the compilations of Balick (1987), Acker et al. (1992), Schwarz et al. (1992), and Corradi & Schwarz (1995); where orientations appeared ambiguous, careful cross-checks were instigated using POSS, ESO and SERC survey plates. Two primary selection criteria were employed:

1. The nebulae were required to be morphologically similar to the archetypal outflows cited in Sect. 1. In particular, there should be evidence to support bipolar mass-expulsion, leading to regions of preferential emission symmetrically disposed about the central star. Note that we have not included sources in which emission is enhanced along the nebular minor axes, but for which there is no associated evidence for perpendicular mass expulsion. Such nebulae (characterised by Hromov & Kohoutek (1968) as of morphological type 2a/3a) appear to consist of closed shells, and the 'bipolar' features to arise from systematic trends in emission measure within prolate or oblate spheroidal configurations (e.g. Phillips & Reay 1977).

In most cases, the major axis of the bipolar nebula also corresponds to the principal axis of outflow, and it is the orientation of this axis which we describe below. A notable exception to this rule is R Aqr, for which we have used the combined kinematic and morphological analysis of Solf & Ulrich (1985) to define an outflow axis perpendicular to the primary nebular extension.

Finally, we note that a small sub-set of these nebulae appear to be characterised by point-reflection symmetry, whereby asymmetries in one outflow lobe are inversely replicated within the opposing flow. Whilst it is possible that such trends may (for instance) arise from jet activity, the origins of such asymmetries remain ill-determined.

2. The level of outflow collimation is required to be low, and nebular opening angles of order $> 10°$. Thus, whilst a variety of jet outflow sources have recently been discovered (including NGC 6210 (Phillips & Cuesta 1996), NGC 2392 (Gieseking et al. 1985) and others (cf. Soker 1992)), these have higher degrees of collimation, and have not been included in the present analysis. It seems likely that high and low collimation sources possess differing origins.

Galactic coordinates and orientations for individual nebulae are summarised in Table 1. Errors in these orientations depend upon the precision with which the outflow axis may be defined, and are generally less than $\pm 3°$. It would appear, as a result, that the distribution of outflow vectors is distinctly non-uniform; most nebulae appear to possess inclination angles which are comparatively low. In particular, the mean vectorial direction of this sample is $+12.7° \pm 5.6°$, whilst fully 71% of nebulae have major axes oriented within $\pm 45°$ of the galactic plane. Using binomial statistics, it is possible to show that the probability of such a distribution arising by chance is only $5.8 \ 10^{-4}$.

Finally, although it is clear that BI Cru, He 2-104 and R Aqr are post-main-sequence bipolar outflows, their symbiotic nuclei place them apart from other nebulae in this study. If these sources are deleted from the more general sample, then the mean concentration towards the galactic plane is very slightly enhanced, and the probability level increases fractionally to $6.9 \ 10^{-4}$.

3. Discussion

The distribution of axes described in Sect. 2 comes as a surprise, not least because there appear to be few mechanisms whereby such trends may be induced.

Thus, one might imagine that where the primary collimation of these flows is taken to arise from circum-nebular disks, and these disks derive in turn from nuclear binary systems (Bond & Livio 1990), then a preferential orientation of binary systems might give rise to non-random outflow statistics. A problem in this case, however, is that there appears to be little evidence for preferential orientation among optical or eclipsing binaries (van de Kamp 1958; Huang & Wade 1966; Rudy 1979; Finson 1933). Similarly, one might anticipate that the formation of binary systems within the turbulent elements of molecular clouds would, if at all, lead to angular momentum vectors broadly perpendicular to the galactic plane; parallel, that is, to the galactic angular momentum vector. Such non-randomising tendencies would in turn be countered by a variety of destructive processes, including collisions and gravitational interaction between the individual turbulent elements.

It is interesting, in this respect, to note that Phillips (1996) has found a strong tendency for the angular momentum vectors of molecular clouds Ω_C to be oriented parallel to the galactic angular momentum vector Ω_G. Similarly, Benz (1984) has noted a tendency for merged clumps within theoretical cloud structures to acquire values Ω_{CL} perpendicular to Ω_C. It would therefore seem plausible to expect a similar distribution of vectors Ω_{CL} to that displayed by bipolar outflows.

A problem with this latter hypothesis, however, is that a comparable analysis of angular momentum vectors in molecular clumps and hot spots yields very little evidence for systematic trends in orientation (Phillips 1996).

Similar problems are also encountered where disks derive from the rotation of individual stars; the deduced orientation of stellar rotation vectors appears random (Huang 1967a,b; Slettebak 1949; Huang & Struve 1954; Abt et al. 1972), and any non-random tendency might be expected to lead to disk minor axes (and collimated mass-outflow axes) perpendicular to the galactic plane.

Other possibilities cited by Melnick & Harwit include the influence of the galactic magnetic field, and shock interaction with the interstellar medium. Whilst both of these mechanisms may have some minor role to play in the case of elliptical sources, it seems clear that the energetics of the bipolar outflow phenomenon are such as to preclude such relatively minor constraining mechanisms. In particular, we note that the typical volume kinetic energies of BPN are of order $\sim 2 \ 10^{-8}$ ergs cm^{-3}, whilst the energy density of the intercloud magnetic field is $B^2/8\pi \sim 1.5 \ 10^{-12}$ ergs cm^{-3}, some 10^4 times smaller. Although some correlation has been noted between the orientations of pre-main-sequence bipolar outflows and the Galactic magnetic field (Cohen et al. 1984), this appears to be perpendicular to the trend for post-main-sequence sources noted above, and arises in a substantially different ambient medium (see Mouschovias & Paleologou (1980) and Konigl (1982) for theoretical discussions of this question).

Finally, and by contrast, a further disordering mechanism may arise during comparatively late phases of nebular evolution, and derive from precession of the collimating zone. It is apparent, for instance, that certain more highly collimated flows show evidence for pulsed mass-loss, together with temporal re-orientation in the axis of ejection (e.g. Phillips & Cuesta 1996; Miranda & Solf 1992; Lopez et al. 1993, 1995). The evidence in the case of lower collimation flows is somewhat more equivocal, although it appears that one source at least (NGC 2440) may also share this pathology (Cuesta & Phillips 1996).

It appears, in brief, that there are no clear mechanisms whereby we might replicate the non-random distribution of axes in Sect. 2 – and several means whereby such tendencies might be diluted. This, in turn, may presumably imply that we lack some fundamental understanding of the mass-loss process in these sources; a deficiency which should be seriously considered in further theoretical analyses of such outflows.

Finally, it should be noted that the proportion of sources with orientation close to the galactic plane may be seriously underestimated in an analysis of this kind. Where, for instance, an

Table 1. Galactic orientations of bipolar nebulae

Source	I	b	I_p†	Source	I	b	I_p†	Source	I	b	I_p†
IC 4634	000.3	+ 12.2	−71.2	We 1-4	201.9	− 04.6	−42.7	He 2-84	300.4	− 00.9	−44.2
M 1-28	006.0	+ 03.1	+32.1	K 3-72	204.8	− 03.5	−12.0	Th 2-B	307.0	− 01.2	+18.0
NGC 6445	008.0	+ 03.9	+30.6	M 1-8	210.3	+ 01.9	+88.4	MyCn 18	307.5	− 04.9	+70.0
NGC 6309	009.6	+ 14.8	+26.2	NGC 2346	215.6	+ 03.6	+17.5	He 2-1 11	315.0	− 00.3	+33.8
NGC 6537	010.1	+ 00.7	+03.0	IRAS 07131	217.4	+ 04.5	−42.3	He 2-104	315.4	+ 09.4	+53.4
M 2-9	010.8	+ 18.0	−33.9	IRAS 09371	221.9	+ 42.7	+07.0	He 2-119	317.1	− 05.7	+20.5
M 3-28	021.8	− 00.4	−28.2	M 1-16	226.7	+ 05.6	+09.3	He 2-114	318.3	− 02.0	+74.8
Na 2	025.9	− 10.9	+47.5	Kl-10	229.6	− 02.7	−39.3	IC 4406	319.6	+ 15.7	−01.9
M 4-15	061.3	+ 03.6	+67.8	M 1-13	232.4	− 01.8	+05.5	Mz 1	322.4	− 02.6	+87.9
M 2-48	062.4	− 00.2	+41.5	NGC 2440	234.8	+ 02.4	−69.0	He 2-123	323.9	+ 02.4	+11.2
R Aqr	066.5	− 70.3	+41.7	M 3-2	240.3	− 07.6	+75.0	He 2-141	325.4	− 04.0	−18.0
K 3-46	069.2	+ 03.8	+59.9	NGC 2818	261.9	+ 08.5	−42.8	He 2-145	331.4	+ 00.5	+62.9
CRL 2688	080.2	− 06.5	−31.0	He 2-25	275.2	− 03.7	+68.8	Mz 3	331.7	− 01.0	+44.9
NGC 7026	089.0	+ 00.3	−53.4	NGC 2899	277.1	− 03.8	−01.7	He 2-186	336.3	− 05.6	−23.9
SH 1-89	089.8	− 00.6	−09.4	He 2-36	279.6	− 03.1	+32.0	NGC 6072	342.1	+ 10.8	+30.0
A 79	102.9	− 02.3	+44.0	He 2-52	285.7	+ 01.1	+01.0	NGC 6302	349.5	+ 01.0	+42.5
NGC 650	130.9	− 10.5	+29.3	Hf 48	290.1	− 00.4	+31.2	19 W 32	359.2	+ 01.2	+14.0
CRL 618	166.4	− 06.5	40.4	He 2-64	291.7	+ 03.7	−21.6	Hb 5	359.3	− 00.9	+47.0
J 320	190.3	− 17.7	+23.8	BI Cru	299.7	+ 00.1	−57.2	−	−		−

† Orientation of nebular oufflow axes with respect to the galactic plane.

outflow source possesses an intrinsic orientation i_g with respect to the galactic plane, and the inclination of axis G to the plane of the sky is θ (where G is the projection of the outflow axis onto the galactic plane), then the projected inclination of the outflow axis in the plane of the sky (i.e. the value observed here) is given by $i_p = \tan^{-1}(\tan i_g / \cos \theta) > i_g$.

Although it is possible that non-random deviations also apply to the distribution of nebulae in θ, it is clear that the level of orientation noted here must constitute a distinct lower limit. It is likely, in brief, that the distribution of axes with respect to i_g possesses an even lower statistical likelihood than has been noted for i_p.

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