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THE USE OF LINE EXCITATION MAPPING TO INVESTIGATE PLANETARY NEBULA MORPHOLOGIES

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RESUMEN

Está ahora bien establecido que las nebulosas planetarias circulares, elípticas y bipolares poseen diferentes características físicas y espaciales. No sólo son distintas sus estructuras, sino que también parecen tener distintas temperaturas de Zanstra, abundancias, velocidades de expansión, temperaturas de brillo y alturas de escala sobre el plano Galáctico. Reportamos aquí una manera más sensible para ilustrar las diferencias entre estos flujos. Señalamos que las nebulosas poseen muy distintos cocientes de intensidad de sus líneas de emisión y que esto probablemente sea consecuencia de las distintas masas de sus estrellas progenitoras. Asimismo, recalcamos el potencial del mapeo de los cocientes de intensidad de líneas para analizar otras clases morfológicas, así como para establecer la singularidad de su población y las masas relativas de sus progenitoras. Así, encontramos que las fuentes con chorros poseen a menudo líneas de emisión de baja intensidad con relación al hidrógeno, lo cual sugiere que provienen de estrellas de baja masa. Esta conclusión está sustentada en una variedad de evidencias observacionales independientes. También mostramos que las fuentes irregulares aparentemente representan una clase distinta de flujos. Es probable que las masas medias de sus progenitoras sean mayores que las de las nebulosas planetarias elípticas, pero menores que las de los flujos bipolares.

ABSTRACT

It is now well established that circular, elliptical, and bipolar planetary nebulae (PNe) possess differing physical and spatial characteristics. Not only are their structures quite distinct, but they also appear to possess differing Zanstra temperatures, abundances, expansion velocities, brightness temperatures, and scale heights above the Galactic plane. We report here a further sensitive way in which the differences between these outflows may be illustrated. We shall note that the nebulae posses varying ranges of emission line ratio, and that this is likely to arise as a consequence of their differing progenitor masses. Similarly, we point out the potential of line-ratio mapping for analyzing other morphological classes, as well as for establishing the uniqueness of their populations, and their relative progenitor masses. Thus we find that sources containing jets often possess low line emission intensities relative to hydrogen, suggesting that their progenitors may have low overall masses. This conclusion is supported by a variety of independent observational evidence. We also show that irregular sources appear to represent a distinct class of outflows. It is likely that their mean progenitor masses are greater than those of elliptical PNe, but less than thoseof the bipolar outflows.

Key Words: **ISM: JETS AND OUTFLOWS — ISM: LINES AND BANDS — PLANETARY NEBULAE: GENERAL**

1. INTRODUCTION

It is well known that planetary nebulae possess a broad variety of shapes, although it appears that approximately 85% may be classified as circular, elliptical, or bipolar (Manchado et al. 2000; Phillips 2001a; see also Zuckerman & Aller 1986). Such differences in morphology are not superficial whims of the formation process, but appear to reflect deeper-seated differences between the physical characteristics of these outflows. Thus it is well known that differing morphologies are associated with differing scale heights above the Galactic plane, a trend which reflects the distributions of the stars out of which they were formed (Zuckerman & Gatley 1988; Manchado et al. 2000; Corradi & Schwarz 1995; Phillips 2001b). It also appears that the Zanstra temperature ranges of the nebulae are somewhat different, with BPNe characterized by higher values of T_Z(He II), and circular sources possessing lower temperatures (Phillips 2003a; Corradi & Schwarz 1995). These differences in T_Z are likely to reflect differing central star evolutionary tracks (and rates) within the HR plane.

The abundances of elements are also markedly different, a feature which arises from the differing ages of the progenitors, and a secular increase in abundances within the interstellar medium (ISM) (Perinotto 1991; Phillips 2003b). It is also influenced by the synthesis and ejection of N and He in higher mass stars (e.g., Renzini & Voli 1981; Marigo, Bressan, & Chiosi 1998; van den Hoek & Groenewegen 1997).

Finally, the present author has noted that there appear to be marked preferences in the brightness temperatures of these outflows, with BPNe possessing larger values of T_B(5 GHz), and circular sources leaning towards lower values of this parameter (Phillips 2003c).

These differences in abundance and temperatures are likely to have various consequences for line excitation. Thus, it is well known that line intensities and ratios depend upon the luminosities of the central stars, the densities and masses of the shells, the abundances of elemental species, and the presence or otherwise of dust. It has also been demonstrated that many line ratios vary with He II Zanstra temperatures T_Z(He II), and Stoy temperatures $T_{\rm STOY}$, both of which represent measures of the central star effective temperature $T_{\rm eff}$ (see e.g., Kaler 1978; Phillips 2004a). This latter characteristic has been used to evaluate central star effective temperatures in the absence of more direct observational evidence (e.g., Ferland 1978; Iijima 1981; Zijlstra & Pottasch 1989).

The relations between line ratios, abundances, temperatures, and morphology might be expected to result in systematic differences in line ratio between the differing morphological classes. We shall find, in the following, that this does indeed appear to be the case. Similarly, we shall note that differences in line ratio may represent a guide to nebular progenitor masses $M_{\rm PG}$, and we shall use this to determine that nebulae containing jets are likely to derive from lower mass stars. By contrast, sources having irregular morphologies appear to arise from higher mass progenitors, although it would seem that their masses are not so high as those responsible for the BPNe.

2. THE OBSERVATIONAL DATA BASE

We have, for the present analysis, made use of the shell morphologies determined by Phillips (2003b), in which envelopes were evaluated using both CCD imaging and prior morphological classifications. The morphological scheme is similar to those of Manchado et al. (1996), Hromov & Kohoutek (1968), Gorny, Stasińska, & Tylenda (1997), Corradi & Schwarz (1995), Stanghellini, Corradi, & Schwarz (1993) and others, although it extends to differing (and sometimes more extensive) samples of nebulae. Comparison between the Phillips morphologies and those of other authors suggests that there is a high level of agreement in 83% of cases. The large majority of PNe appear to have bipolar, circular or elliptical outflow envelopes. However, certain other categories of source can also be discerned, including the so-called Gaussian sources of Manchado et al. (1996), and cases which appear to have irregular shell structures. Apart from these, a variety of the shells also appear to contain evidence for point reflection symmetry, jets, ansae, BRET-like activity and so forth, some of which characteristics have been described by López (1997). We shall consider these as a separate class of jet-like source, although the features are contained in what would otherwise be classed as elliptical or circular shell structures.

We have also evaluated emission line ratios for in excess of 300 sources, employing some 3000 line intensities for 15 differing elemental transitions. The emission line intensities are taken from the *Emission Line Catalog* of Kaler, Shaw, & Browning (1997) (ELCAT).

Note that very few of these line intensity measurements are likely to be representative of the shells as a whole (see e.g., Phillips 2004a). Where the measurements are taken with narrow instrumental slits,

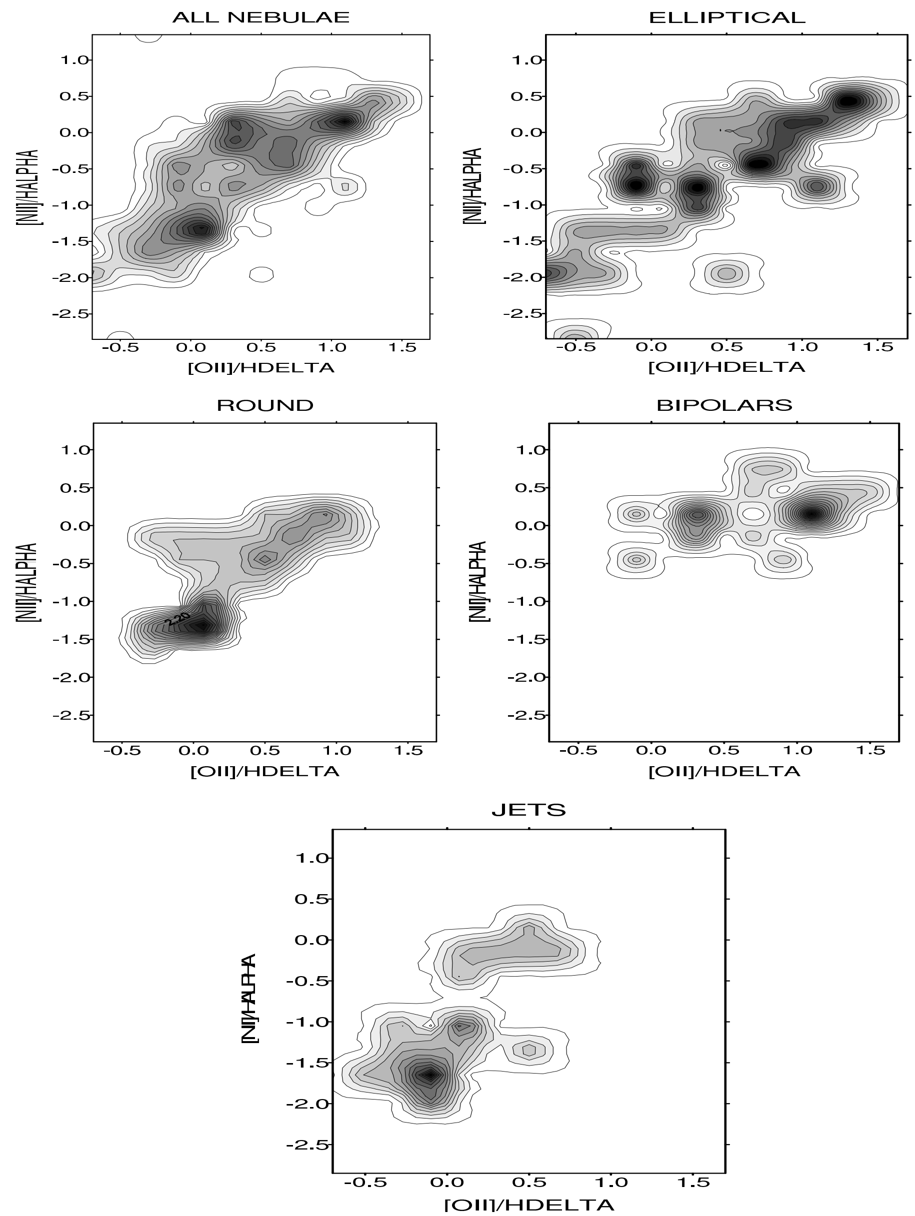

Fig. 1. Distribution of differing morphological classes of PNe within the [N II]/Hα–[O II]/Hδ plane. Line ratios are given in logarithmic units, whilst contour levels are set at linear intervals, and refer to the density of sources within this plane. Note the tendency for bipolar nebulae to be located towards high values of line ratio, and of circular sources to be concentrated towards lower line ratios. Elliptical sources appear to occupy the full gamut of ratios, from the very low to the very high.

for instance, and the slits are centred upon the nebular central stars, then this will tend to bias the results in favour of higher excitation transitions. Similarly, many sources are known to contain low excitation blobs and filaments associated with jets, ansae, and Fliers and the like. The measured line ratios may depend quite strongly upon whether these are located within or outside of the instrumental aperture.

Finally, whilst measures with circular or square apertures can yield more representative intensities, much depends upon the size of aperture employed. Various of the results of Acker and her co-workers (e.g., Acker et al. 1992) were taken with a 4 arcsec aperture, for instance, and this may lead to serious biases where sources are very much larger than this.

It follows that whilst the most of the variation

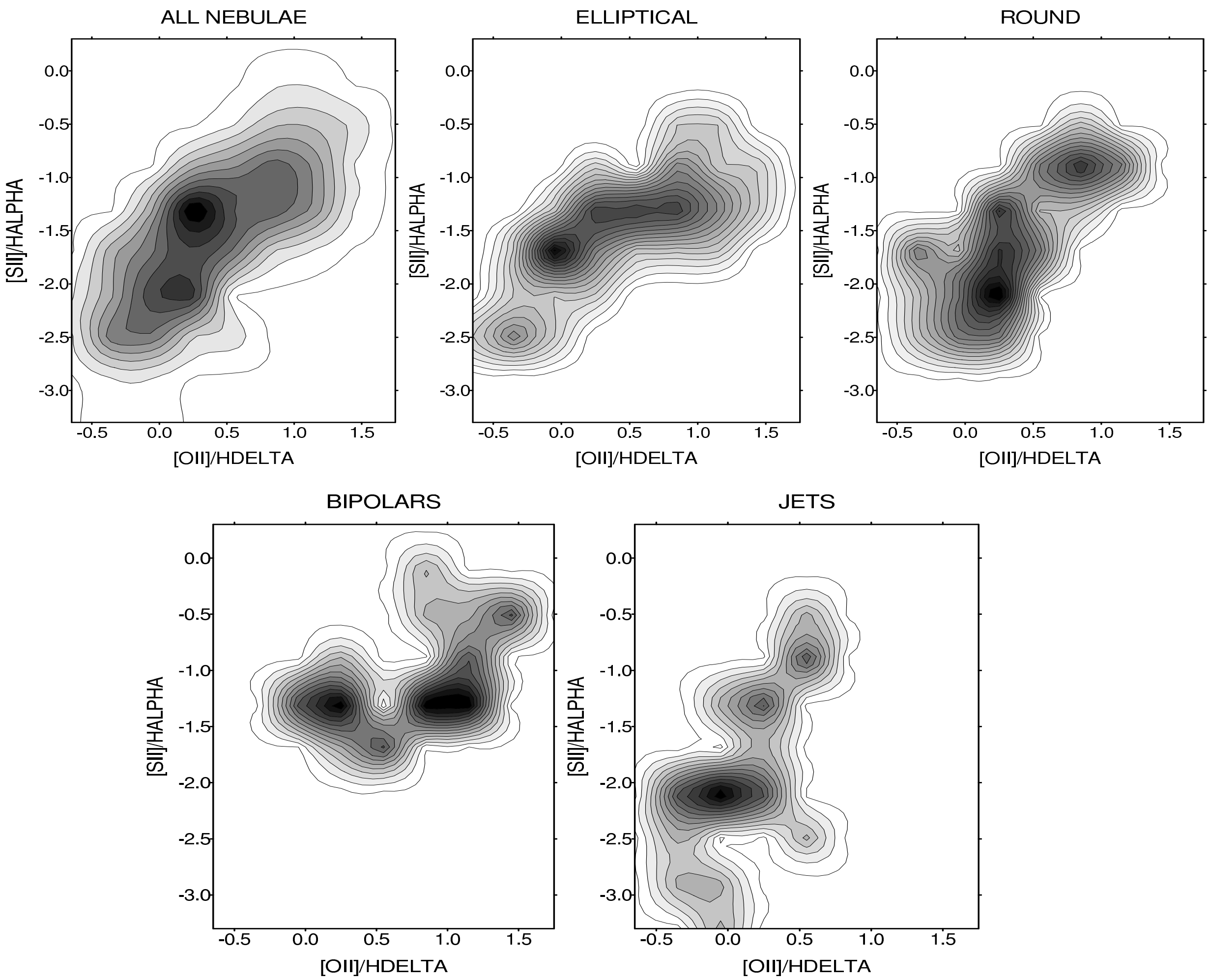

Fig. 2. As in Fig. 1, but for the [S II]/Hα–[O II]/Hδ plane.

in line ratios derives from intrinsic differences between sources, a certain amount of scatter (perhaps $\sim 0.1 \rightarrow 0.2$ dex) may arise from variations in aperture size. In addition, errors arising from continuum subtraction, flux calibration, sky extinction corrections, and photon noise may play their parts in increasing the spread in the results.

We have, for certain nebulae, attempted to perform first order corrections to the catalogue data, in an attempt to partially correct for the deficiencies noted above. Specifically, where the nebulae possess more-or-less uniform Balmer line surface brightnesses (or have surface brightnesses which are not too strongly dependent upon radius), and where there are line ratio estimates for differing portions of their shells, then we have geometrically weighted these ratios to yield a mean shell value. It would be preferable, under ideal circumstances, to sum the ratios over larger numbers of shell positions, and weight these values with respect to the Hβ flux. This is impossible, however, using the data employed here.

The line ratios have subsequently been employed to create up to 90 line excitation maps—maps of the distributions of sources with respect to pairs of spectral line ratios. We shall investigate trends for $\sim 1/3$ of these maps in the following analysis, concentrating upon those showing the most informative differences between the various morphological sub-groups. The principal line ratios studied here include [Ne V]λ3426/Hδ, [O III]λ3440/Hδ, [O II]λ3727/Hδ, [Ne III]λ3868/Hδ, He Iλ4471/Hγ, He IIλ4686/Hβ, [O III]($\lambda\lambda$4959+5007)/Hβ, [N II]($\lambda\lambda$6548+6584)/Hα, [S II]($\lambda\lambda$6717+6732)/Hα, and [S II]λ6717/[SII]λ6732 (hereafter referred to as [Ne V]/Hδ, [O II]/Hδ, etc.).

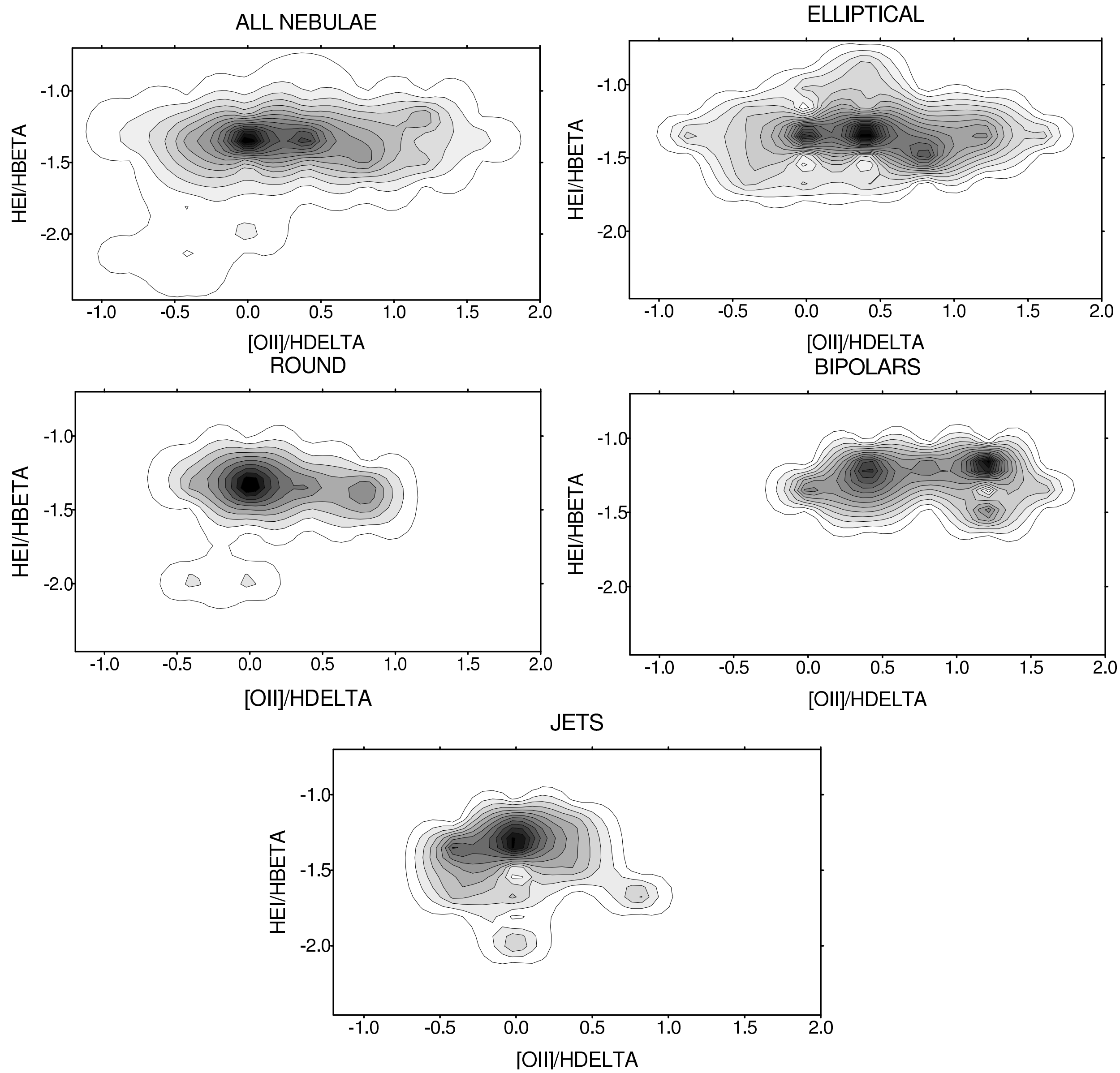

Fig. 3. As for Fig. 1, but for the He I/Hβ–[O II]/Hδ plane.

3. DISTRIBUTIONS OF SOURCES WITHIN THE SPECTRAL LINE PLANES

The variation of shell morphology with respect to emission line ratio is illustrated in Figures 1 to 7, where we have contoured the results with respect to population density. The highest contours (associated with the darkest shading) refer to the largest incidence of sources, the contour interval is linear, and line emission ratios are given in logarithmic units. The lowest contour is set at 5% of peak number density. We have also used a standard Kriging interpolation procedure, as discussed by Journel & Huijbregts (1981).

It is apparent that differing shell morphologies occupy quite differing (but overlapping) regimes. Thus, we find that elliptical nebulae extend over the full gamut of observed values, and overlap the regimes characterising other morphological subgroups. The bipolar sources, by contrast, are located to the upper right of all of the excitation planes, and occur in zones which are relatively compact. This is particularly clear in the [N II]–He II excitation plane (Fig. 5).

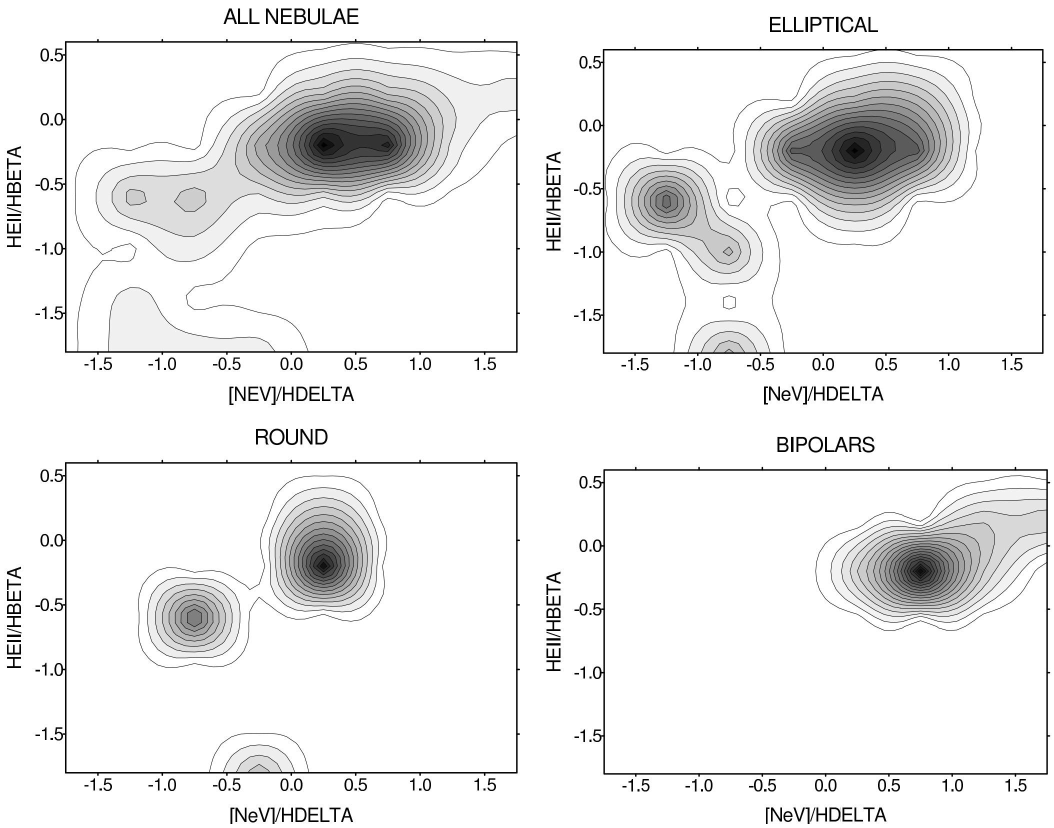

Fig. 4. As for Fig. 1, but for the He II/Hβ–[Ne V]/Hδ plane. Note the presence of at least two subsets of circular and elliptical PNe, having higher and lower values of [Ne V]/Hδ.

Finally, it would appear that the circular sources are located to the lower left of many of the figures, and occupy more restricted ranges of ratio than for the elliptical PNe.

The one map in which such trends are not so obvious is that illustrated in Fig. 6. It may be seen from this that [Ne III]/Hδ and [O III]/Hβ vary over only very small ranges. Even here, however, we note that the trends determined above are also to be found. This is particularly apparent if we increase the axial resolution, and zoom-in upon the principal density peaks (see Fig. 7). It is clear that bipolar sources again concentrate towards higher values of [O III]/Hβ and [Ne III]/Hδ, whilst other sources favour lower intensity ratios.

There are at least two separate groupings of circular and elliptical sources within the He II–[Ne V] plane (Fig. 4), suggesting that we may be witnessing two as yet unrecognized morphological subgroups, and/or groupings having low and high central star temperatures. This latter interpretation is consistent with the distribution of He II Zanstra temperatures noted by Phillips (2003a).

Finally, we note that although the large majority of PNe can be classified as being circular, elliptical, or bipolar, other types of morphology also exist. It is sometimes unclear whether these represent distinct nebular subgroups, or are simply variants upon the primary shell morphologies. The present analysis helps us to determine which of these is the case.

One such type of outflow is represented by shells containing jets (see López (1997) for a description of these sources). We find (from Figs. 1 to 3, 6, and 7) that such sources occupy distinct regimes of the line excitation planes. Whilst there is some overlap with the circular sources, it is clear that jet-like sources extend to much lower ratios—and indeed, have source density peaks below those of any other category of outflow. Such trends are unlikely to be biased by jet emission, not least because theoretical shock modeling would imply a precisely reverse tendency (i.e., for higher line ratios [S II]/Hα, [O II]/Hδ and so forth [see e.g., Shull & McKee (1979); Hartigan, Raymond, & Hartmann (1987)].

The distinct nature of these sources can also be represented in histogramic form, as in Figure 8,

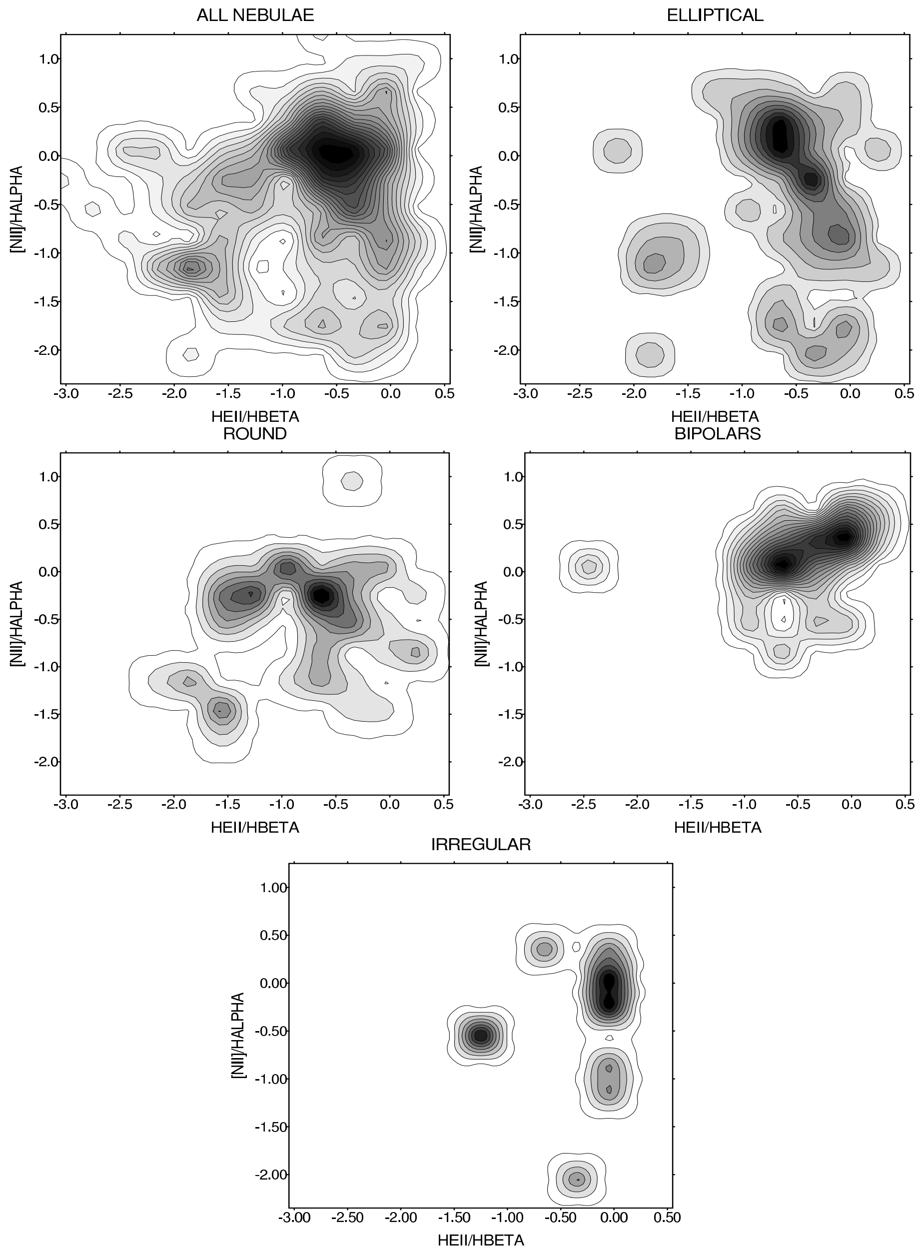

Fig. 5. As in Fig. 1, but for the [N II]/Hα–He II/Hβ plane. It is apparent that the irregular sources tend to congregate towards the right-hand side of the map, where values of He II/Hβ are appreciable.

where we represent the variation in source numbers as a function of log([O III]/Hβ). It is again apparent that the distribution of jet-like sources extends towards lower values of [O III]/Hβ. We shall later find (§ 5) that this may imply exceptionally low progenitor masses.

The curve in Fig. 8 is defined using total of 25 jet outflows; a number which is much less than is used to define the other curves in this figure. It is therefore of interest to evaluate the significance of this trend in a more concrete manner. Is this tendency for jets really different from those of the other morphological classes, and how can this be defined in terms of a specific probability value?

We have, in order to answer this question, undertaken a Kolmogorov-Smirnov analysis of the original data base, in which the significance of trends is assessed on the basis of differences, D, between their

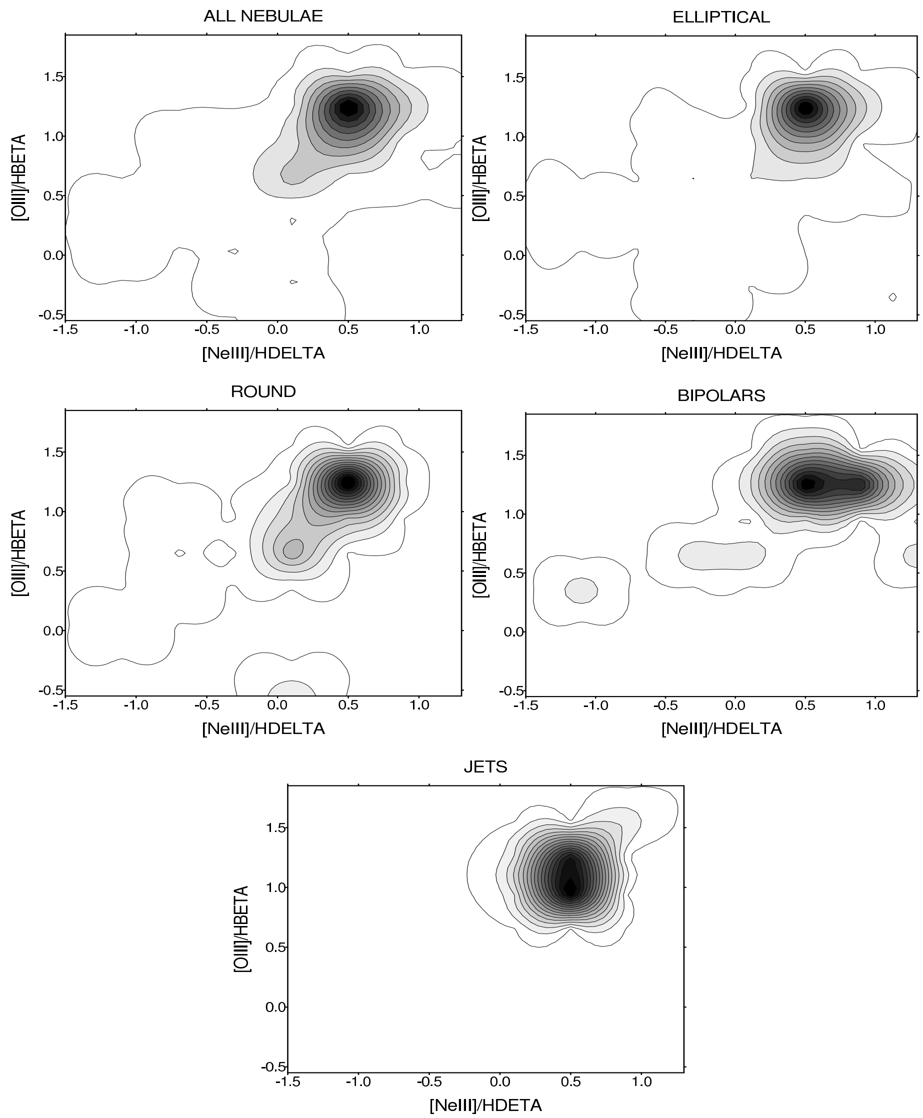

Fig. 6. As in Fig. 1, but for the [O III]/Hβ–[Ne III]/Hδ plane. Note the very restricted ranges of line ratio characterizing most PNe.

cumulative number distributions. This is used to define a probability coefficient P, such that low values of P imply significant levels of difference. We find that when the distribution of jet containing sources is compared to that of all of the sources combined, then one obtains a value $D = 0.28$, and a probability $P \simeq 0.05$. Similar results ($P \sim 0.13 \rightarrow 0.16$) are found when one compares the distribution of jets to those of elliptical and round PNe. These values for P suggest that the curves are indeed different, although the level of significance is relatively modest.

Finally, we note that certain nebulae appear to display strong (and spatially non-symmetric) variations in emission, and are usually classified as irregular. Such outflows are also, in many cases, observed to possess a filamentary appearance. A listing of certain of these nebulae is included in Table 1, where we also include details of He II and H I Zanstra temperatures (in units of 10^3K; Phillips 2003a), and adopted values of log([N II]$\lambda\lambda$6548+6584/Hα) and log(He IIλ4686/Hβ). Note that there appear to be two sequences of published temperatures for NGC 5189, and we have quoted mean values of T_Z for these separate trends. Most of these nebulae appear, for the present, to be incapable of being included within the main morphological categories cited above. This situation may however change. The referee has pointed out that two of the sources

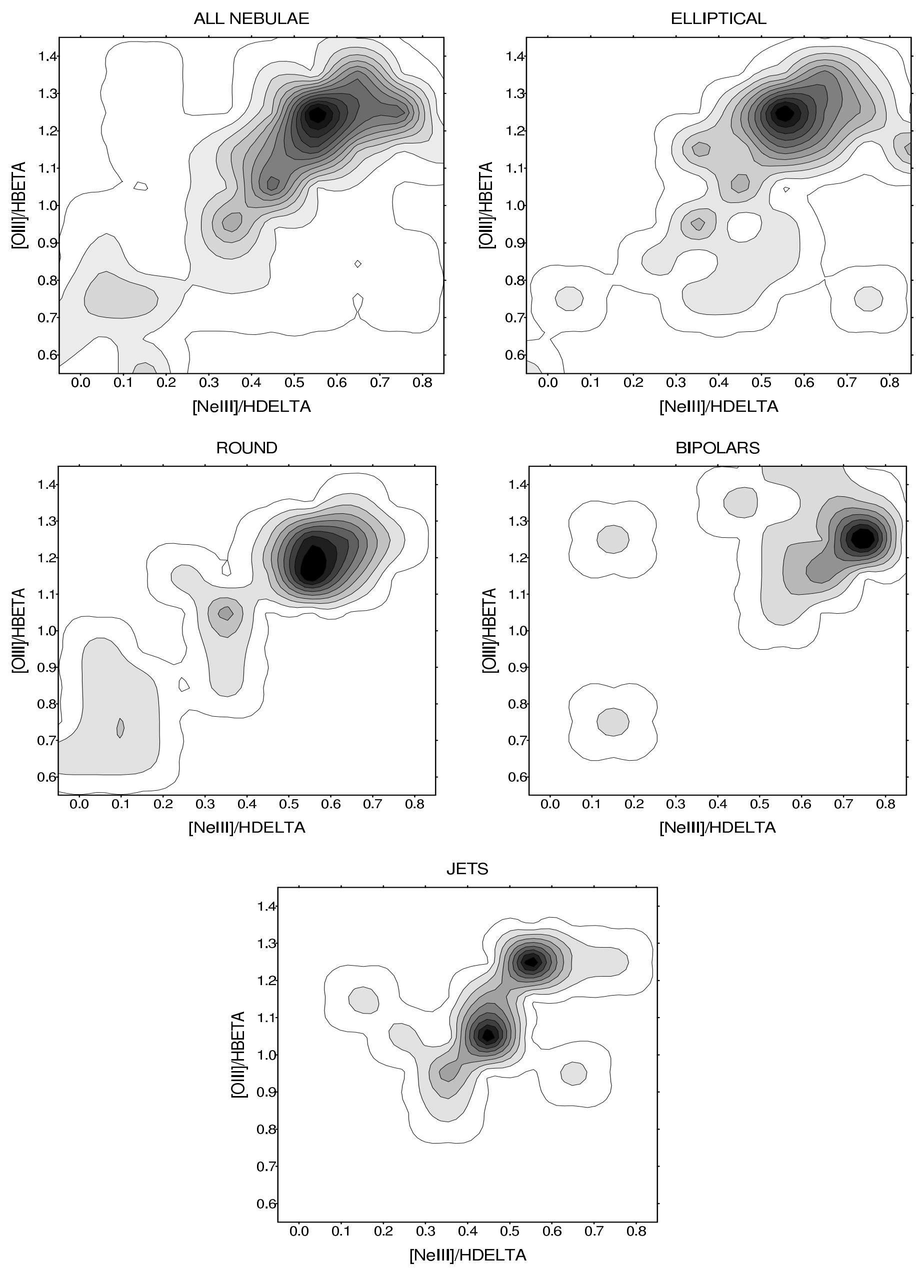

Fig. 7. As in Fig. 6, but at much higher resolution (note the change in axial ranges). We note similar tendencies for the jets and bipolar sources to those noted in previous figures.

on our original list (M 1-41 and BV 5-1) are likely to be bipolar outflows (Bohigas 2001; Kaler, Chu, & Jacoby 1988). This change of classification is a result of deeper and more sensitive imaging. It is therefore possible that similar changes of classification may occur for certain other sources as well. Apart from these cases, it has also been claimed that IC 2149 is bipolar (Vázquez et al. 2002), and that Sh 2-71, A77, and Hu 1-2 are elliptical.

Before leaving the theme of source identification, it is worth remarking that such complex structures can also act as Rorschach patterns, and lead observers to identify patterns in the outflows which are little more than psychological artifacts. Even where minor symmetries are confirmed, however, it is clear that the shells are disordered over a broad range of size scales, and that this is the primary characteristic defining their morphologies. At least some of

TABLE 1

PLANETARY NEBULAE WITH IRREGULAR MORPHOLOGIES

Source	G.C.	T_Z(H I) 10^3 K	T_Z(He II) 10^3 K	log(He II/Hβ)	log(N II/Hα)
Pe 1-17	024.3 − 03.3	···	···	−0.155	0.163
Sh 2-68	030.6 + 06.2	120.0	···	···	···
Sh 2-71	035.9 − 01.1	29.5	···	−0.174	0.493
NGC 6765	062.4 + 09.5	38.0	93.0	−0.174	0.371
A 71	084.9 + 04.4	111.0	132.6	−0.538	0.296
Hu 1-2	086.5 − 08.8	58.7	111.1	−0.054	0.111
A 77	097.5 + 03.1	···	80.1	···	···
DeHt 5	111.0 + 11.6	$<$ 40	···	−0.092	···
IC 2149	166.1 + 10.4	31.1	49.0	···	−0.755
K 2-1	173.7 − 05.8	76.0	138.0	0.057	−0.907
K 2-2	204.1 + 04.7	158.0	113.0	−1.155	−0.487
NGC 2452	243.3 − 01.0	79.2	121.5	−0.062	−0.447
He 2-11	259.1 + 00.9	89.0	···	···	···
NGC 5189	307.2 − 03.4	72.5	109.8	−0.030	0.019
		45.5	80	···	···
He 2-119	317.1 − 05.7	···	···	−0.484	−1.939
A 36	318.4 + 41.4	22.8	70.0	0.068	···
He 2-155	338.8 + 05.6	51.0	73.0	−1.268	−0.694
Hf 2-1	355.3 − 04.0	···	···	−0.102	−0.343

this incoherence may be due to the interaction of jets and the primary envelopes, and it is therefore of interest to note that two of the outflows (Hu 1-2 and Pe 1-17) have been associated with BRET like activity (see López (1997) for a discussion of this phenomenon).

It is apparent, from Fig. 5, that the distribution of these nebulae differs from that of all other sources. The range of [N II]/Hα is comparable to that for the elliptical nebulae, and somewhat broader than is observed for circular PNe. However, the He II/Hβ ratios are systematically high—more so than is the case for the BPN. This tendency is also noted in the histogram in Figure 9, where we illustrate the variation of source numbers with respect to He II/Hβ.

It is of interest, yet again, to evaluate the significance of the trends in Fig. 9. Although the total number of irregular sources is low (14), it is surely interesting (and significant) that fully 60% are located within a single narrow peak. A Kolmogorov-Smirnov analysis shows that when this trend is compared to that for all of the sources combined, then one obtains a difference parameter D = 0.449, and an associated probability P = 6×10^{-3}. This increases to P = 0.029 (D = 0.442) when one compares the trend to that for bipolar outflows alone. So here again, it would appear that the histogramic difference between these trends has a reasonable level of significance.

It is apparent from the foregoing, therefore, that line ratio mapping may represent a useful way of discriminating between the differing nebular types. It also suggests that the physical appearances of these sources may reflect deeper-seated physical differences. We discuss, in the following sections, what this might imply for the masses of their progenitors.

4. THE CORRELATION BETWEEN PROGENITOR MASSES AND LINE EXCITATION

Relative emission line ratios depend upon a variety of interconnected mechanisms, and these may yield results which are not always intuitively obvious. Nevertheless, there are various qualitative arguments to suggest a relation between observed line ratios and progenitor mass. These imply that particular morphologies should be associated with specific regimes within the line excitation planes, as is found from our analysis in § 3. They also suggest that a

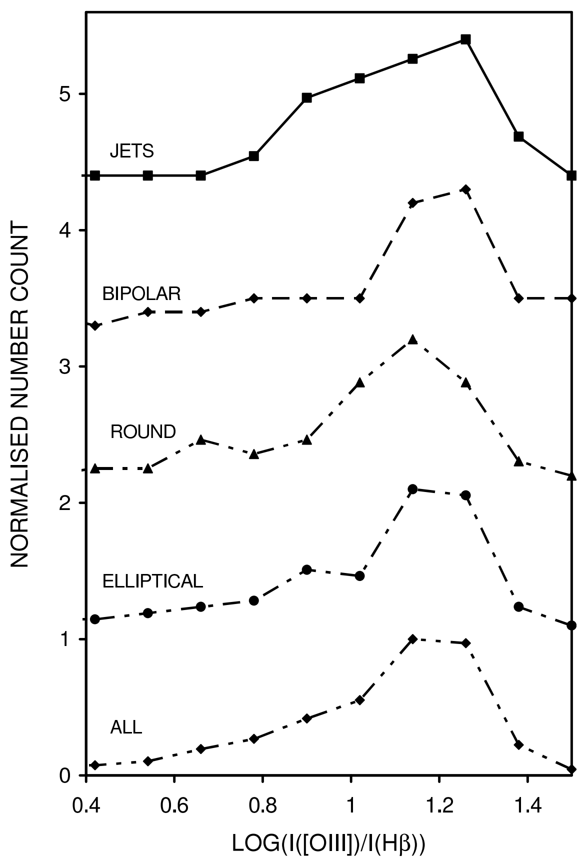

Fig. 8. The distribution of differing morphological classes with respect to [O III]/Hβ. Note the tendency for jets to be located towards lower values of this ratio.

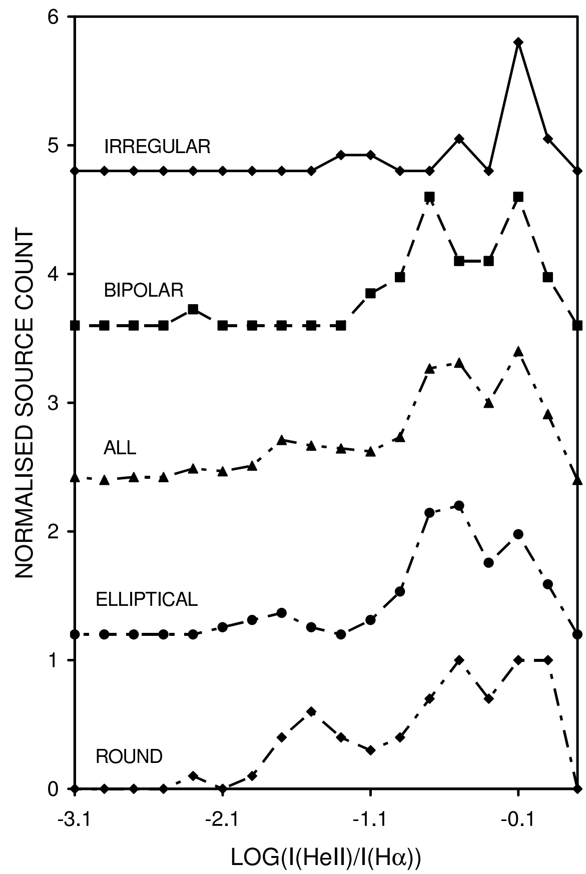

Fig. 9. Histogram of the number distribution of differing morphologies with respect to He II/Hβ. Note the extreme concentration of irregular sources towards higher values of He II/Hβ.

line ratio analysis may be of help in identifying the progenitor masses of other nebular subgroups.

We describe, below, various of the mechanisms which appear to be of most importance in defining such relations:

(a) It is relevant, in the first place, to note that certain line ratios increase in strength with increasing Zanstra (or Stoy) temperatures. This correlation has been used to assess T_Z and T_{STOY}, and stellar effective temperatures T_{eff} where direct measures are unavailable (see e.g., Ferland 1978; Iijima 1981; Zijlstra & Pottasch 1989). Kaler (1978) for instance finds that [O III]λ5007/Hβ and [Ne III]λ3868/Hβ increase with increasing T_{STOY}. Similarly, Phillips (2004a) has determined that He II/Hβ, and a broad range of other (more or less complex) line ratios increase with T_Z(He II). Whilst most of these correlations are rather poor, and subject to considerable levels of scatter, it would appear that some such correlation applies for the majority of emission line ratios considered here. The transitions of He II and [Ne V] represent particularly extreme examples of this tendency, since softening of the radiation field causes them to be undetectable towards lower values of T_Z.

This variation in the ratio between collisionally excited and permitted line intensities is also consistent with the results of various theoretical analyses. Pottasch & Preite-Martinez (1983), for instance, have noted that the ratio between the luminosities of collisionally excited transitions and that of Hβ is expected to increase with increasing central star temperature. The most extreme of these trends occurs for higher excitation PNe.

(b) Similar correlations are also expected between line ratios and elemental abundances. Richer & McCall (1995), for instance, have found that peak values of [O III]λ5007/Hα are dependent upon abundances O/H, and similar correlations may be noted between [N II]λ6584/Hα and N/H. This latter relation is illustrated in Figure 10 for the case of Galactic PNe, where we have used values of [N II]λ6584/Hα taken form ELCAT, and abundances and PNe types taken from Maciel & Chiappini (1994) and Phillips (2003b). Such abundance weighting of the line ratios is likely to be particularly important for BPNe, for which the abundances of He and N are known to be enhanced (Phillips 2003b). This likely explains the extreme placement of these sources in Fig. 5.

(c) Another factor of importance in defining line ratios is the role of nebular electron density. Thus, we note that forbidden line transitions are subject to collisional de-excitation when densities exceed a critical value n_{CR}. Values of this parameter vary between 8.6×10^4 and 7×10^5 cm^{-3} for the principal forbidden lines of nitrogen and oxygen. More concretely, Osterbrock (1989) has noted that when nebular densities increase to $n = 10^4$ cm^{-3}, then the ratio [O II] $\lambda\lambda$3726+3729/Hβ will decrease by an order of magnitude or so. Similar changes are expected for [N II] λ6584, [O III] λ5007 and other transitions as densities increase still further.

This dependency between line strength and density implies a correlation with progenitor mass as well. To see how this arises, we note that where central stars derive from higher mass progenitors, then they are expected to evolve much more rapidly within the HR plane (e.g., Vassiliadis & Wood 1994). This takes them up to peak effective temperatures in a very short period of time, and implies that shell surface brightnesses will be appreciable at a relatively early stage of their evolution (Phillips 2003c). Given that shell densities also decline with increasing evolutionary time period, it follows that the densities of these higher mass outflows are expected to be larger than average.

Such an analysis is borne out by the results of more detailed theoretical modeling. Marigo et al. (1998), for instance, find that the highest shell densities are associated with the largest progenitor masses.

A further important characteristic of PNe shells is their tendency to be most observable close to the evolutionary turn-over period (Phillips 2003c); the phase at which temperatures, luminosities and ionizing fluxes are close to their maximum values, and the central star hydrogen burning envelope is close to exhaustion (e.g., Schonberner 1993). This implies that higher mass nebulae are not only expected to reach high surface brightnesses relatively rapidly, at which point shell densities are high, but that there is a high likelihood of the sources being detected at this phase of their evolution.

It follows that higher mass PNe may actually display reduced forbidden line strengths, in contrast to most of the trends noted in § 3.

(d) Apart from these relations between observationally derived parameters, we also note that Zanstra temperatures and abundances would be expected to be related to the masses of the progenitor stars. In the first place, it is now accepted that elements such as He and N are more abundant where progenitor masses are appreciable (e.g., Perinotto 1991; Phillips 2003b). This correlation arises from the dredging of core synthesized materials during phases of asymptotic giant branch evolution (e.g., Renzini & Voli 1981; Marigo et al. 1998; van den Hoek & Groenewegen 1997). Such correlations also apply for a broad range of other elemental species, although for somewhat differing reasons. It would appear, for instance, that the abundances of elements within the ISM are increasing with time (e.g., Perinotto 1991; Maciel 2001). Stars formed more recently will therefore contain higher overall abundances. Since massive stars evolve more rapidly than lower mass stars, and form planetary nebulae more quickly, one then expects that the PNe of these stars will also reflect these higher levels of abundance. The reverse occurs for lower mass stars.

All in all, therefore, one expects there to be an approximate correlation between abundance and progenitor mass, with higher abundances implying larger values of M_{PG}.

(e) A similar correlation is likely to apply for temperature, and arise from evolution within the HR plane. Higher mass stars evolve more rapidly than their lower mass counterparts (evolutionary times vary as approximately $T_{EV} \propto M_{CS}^{-6.5}$ where one assumes the hydrogen burning tracks of Vassiliadis & Wood (1994)). They are also characterized by differing evolutionary tracks, and attain higher temperatures and luminosities. Phillips (2003a) has recently noted that this implies a dependency between central star temperatures and progenitor mass, such that higher mass progenitors are associated with higher mean values of T_{eff}.

(f) As noted in the introduction, there appears to be a difference between the physical and spatial properties of the various morphologies. These are, in all likelihood, reflective of differences in the masses of the progenitor stars. Bipolar PNe appear to have higher elemental abundances, for instance, and this is probably indicative of higher than average progenitor masses (Phillips 2003b). It is also found that circular sources derive from lower mass stars, whilst elliptical outflows may arise from almost any

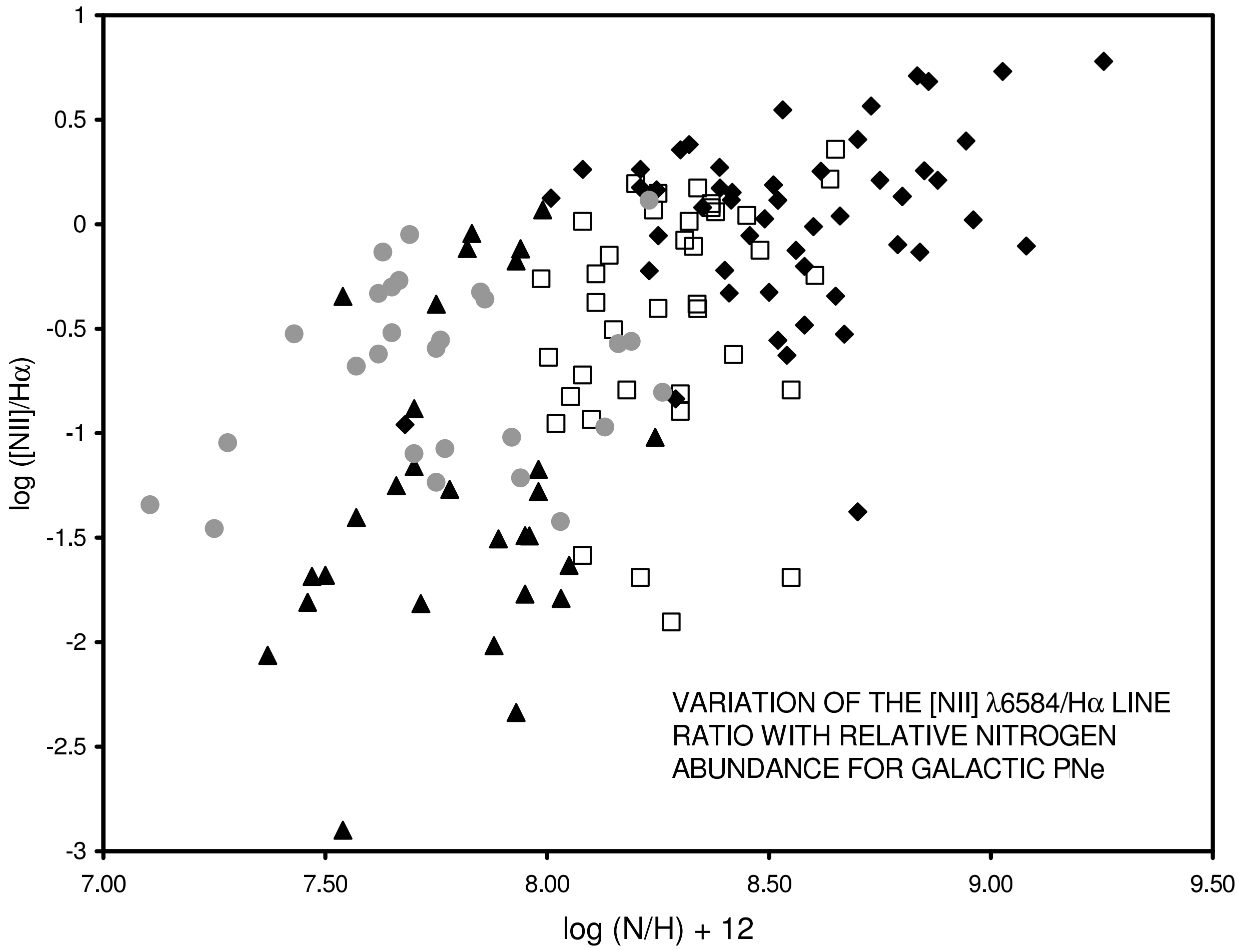

Fig. 10. Variation of relative nitrogen abundance with [N II]/Hα for Galactic planetary nebulae. We have identified Type I (filled lozenges), Type IIa (open squares), Type IIb (filled triangles), and Type III (grey filled circles) PNe.

mass of star. Similar conclusions are arrived at from studies of mean nebular heights above the Galactic plane (Zuckerman & Gatley 1988; Manchado et al. 2000; Corradi & Schwarz 1995; Phillips 2001b), tendencies in brightness temperature (Phillips 2003c), and mean trends in Zanstra temperature (Phillips 2003a). It should be emphasized however that this is not a hard-and-fast rule.

The bipolar source M 2-9 has been classified as a type III outflow, for instance, but has abundances which appear inconsistent with an origin in higher mass progenitors (e.g., Maciel & Koeppen 1993), and is most likely to derive from a symbiotic binary (Schmeja & Kimeswenger 2001). Similarly, sources characterized as being circular may have intrinsic structures which are very much different; they may represent bipolar sources viewed along their polar axes, or ellipsoidal sources viewed along their axes of symmetry.

Finally, we note that stellar mass is not the only determinant of how particular outflows develop, and it is clear that central star binarity may be crucial in explaining BPNe and other symmetric structures (e.g.. Bond 2000).

Despite these caveats, the bulk of the evidence appears to favour a broad correlation between morphology and mass, and we shall assume this to be the case in the analysis which follows.

(g) It may finally be remarked that line ratios are also likely to depend upon the structural and kinematic properties of the outflows. The BPNe appear, for instance, to contain particularly high velocity winds (Corradi & Schwarz 1995), and there is evidence that this may lead to internal shocking and the enhancement of various forbidden line transitions (e.g., Phillips & Cuesta 1998). By the same token, the presence of neutral envelopes is expected to foster charge exchange reactions, and may also lead to UV shadowing within the principal ionized shells. Both of these mechanisms are likely cause enhancement of lower excitation transitions. Since bipolar nebulae appear to contain larger proportions of neutral gas (Huggins et al. 1996), one might then expect that such effects will be prominent within this particular class of PNe.

Finally, it is possible that the geometries of these sources play an important role in defining overall line strengths and ratios. In particular, the ionization and density structures of biconical outflows are likely to be significantly more complex than is the case for spherical shells. This may have a strong effect upon line ratios, and contribute to the differential positioning of these sources within the line ratio maps.

It follows, from the discussion above, that certain nebular characteristics appear to be mutually correlated. We note that:

• Certain line ratios increase in strength with increasing central star temperature, a correlation which applies for many of the transitions considered here.

• Many line strengths also depend, more-or-less directly, upon the abundances of the elements.

• Both Zanstra temperatures and abundances appear to vary with the masses M_{PG} of the progenitor stars.

• It appears likely that the morphologies of PNe are related to M_{PG}. Bipolar outflows are associated (on average) with higher values of M_{PG}, circular sources with lower values of this parameter, and elliptical sources appear to arise from almost any mass of star.

Taking all of these factors into account, one then expects that circular sources should, in the mean, be weighted towards lower values of line ratio (i.e., the lower left hand sides of the excitation planes). Similarly, it would appear likely that bipolar sources will be biased towards higher line ratios (the upper r.h.s. of the planes), and elliptical sources should extend over the entire observed range of line ratios. These tendencies may also be reinforced by the role of shocks and neutral material, although the densities of higher mass sources may have a counterbalancing effect, and lead to a reduction in certain forbidden line intensities.

It is encouraging to note that these trends are, for the most part, confirmed in the figures illustrated here (see § 3).

It therefore seems that the placement of nebulae in the excitation planes may give an approximate indication of the masses of their progenitors, and that this might also be of use when investigating other morphological subgroups. We discuss two such cases in the following section.

5. THE CHARACTERISTICS OF IRREGULAR SOURCES, AND NEBULAE CONTAINING JETS

We have noted, in § 3, that sources containing jets appear to possess particularly low emission line ratios. This suggests that this grouping of sources may be physically distinct, and that such jets are not simply add-ons to what would otherwise be mainstream PNe. Such a conclusion is also suggested by the analysis of Phillips (2002), who noted that the mean velocity of expansion for these sources was low, and differed from those of other PNe.

Such a result would also seem to suggest, given the discussion in § 4, that the sources may have lower progenitor masses than almost any other category of outflow. This conclusion is supported by a at least two other pieces of observational evidence. Thus Phillips (2003b) has noted that not only are shell abundances modest (and comparable to those for circular PNe), but also that mean Galactic latitudes are appreciable, and significantly greater than those for circular PNe.

A further category of nebula is frequently described as irregular, and it is unclear whether this, too, represents a separate category of outflow. It may be possible, presumably, that they represent distorted variants of more mainstream structures. Our present results help us to clarify this issue.

It is apparent, from § 3, that these sources possess differing line emission properties from the majority of PNe; a result which suggests that we are indeed witnessing a separate category of outflow. Although the range in [N II]/Hα is broad, and comparable to that for elliptical PNe, the ratios He II/Hβ are high. This may imply that whilst the central stars have high effective temperatures T_{eff}, the progenitors are not so massive as to lead to appreciable nitrogen enrichment of the envelopes.

There is some ancillary evidence to support this interpretation. Thus we find that the mean Galactic latitude of the sources is of order $<b>$ = $5.26°\pm0.79°$ (if one removes the single high latitude source NGC 6026); a value which is somewhat greater than the estimate for BPNe ($< b > \simeq 3.38°\pm0.42°$), and significantly less than those of elliptical and circular PNe (between 8° and 12°). Similarly, the available He II Zanstra temperatures of these sources (some 11 in total) indicate a mean value $< T_Z(\mathrm{He\,II}) > \simeq 99$ kK; a value which is intermediate between that of the BPNe ($< T_Z(\mathrm{He\,II}) > \sim 118 \rightarrow 138$ kK (Phillips 2003a)) and those for circular and elliptical PNe ($< T_Z(\mathrm{He\,II}) > \sim 81 \rightarrow 92$ kK).

It may therefore be that this category of outflow is sandwiched between the lower mass circular and elliptical PNe, and the higher mass bipolar nebulae.

It would appear in conclusion, therefore, that such an analysis may be of use in investigating differing morphological structures. Their placement in the line excitation planes offers a quick first way of determining the uniqueness of these shells, and of assessing the masses of the progenitors. Although such an investigation cannot, on its own, be relied upon to give definitive answers to these questions, it may nevertheless act as a useful pointer towards the possible origins of the sources.

6. CONCLUSIONS

There are various lines of evidence to suggest that circular, elliptical and bipolar sources represent physically distinct structures, and arise from differing masses of progenitor star. In particular, it is clear that the Galactic distributions, mean abundances, expansion velocities, surface brightnesses, and central star temperatures of these sources all differ in the mean. We have also pointed out that there is another way by which one may detect differences between these outflows. We find that the distribution of morphologies within line excitation planes are often markedly different, with bipolar PNe characterized by high line ratios, and circular sources residing at the opposite end of the range. Only elliptical outflows appear to possess the full range of line excitations. These differences are likely to reflect the varying progenitor masses of the sources, and suggest that such analyses may be useful for identifying other morphological subgroups as well.

We have, with this in mind, investigated the distribution of jet-like and irregular sources within a variety of line excitation planes. The results are interesting, and imply that both groups represent distinct physical entities. The jet-like sources appear to be characterized by the lowest ranges of line ratio, which probably suggests that their progenitor masses are low as well. This conclusion is supported by measures of Zanstra temperatures, elemental abundances, and the mean Galactic latitude. In addition, the irregular nebulae appear to have characteristically high values of He IIλ4686/Hβ, although the range in [N II]($\lambda\lambda$6548+6584)/Hα is very much greater. They therefore share line excitation properties with both elliptical and bipolar outflows. How one should interpret these latter trends is at present unclear, although it would seem these sources are again likely to represent a distinct physical subgroup. It is also likely that their mean progenitor masses are appreciable, albeit somewhat less than those of the BPNe, and that levels of nitrogen enrichment are modest.

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