KINEMATICAL ANALYSIS OF A SAMPLE OF BIPOLAR PLANETARY NEBULAE

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ABSTRACT

We present the kinematics of a sample of bipolar planetary nebulae (PNs) which cover a wide range of observed morphologies and collimation degrees, from bipolar PNs (BPNs) with a marked equatorial ring and wide lobes to highly collimated objects. We use an empirical model in order to derive the expansion velocity, collimation degree, and inclination angle of the PN with respect to the plane of the sky. The equatorial expansion velocities measured in the objects in our sample are always in the low-to-medium range (3–16 km s\(^{-1}\)), while their polar expansion velocities range from low to very high (18–100 km s\(^{-1}\)). None of the objects in our sample, even those that show an extreme collimation degree, seem to be (kinematically) younger than \(\sim 10^3\) yr. We compare our results with the state-of-the-art theoretical models for the formation of BPNs. We find good agreement between the observed expansion velocities and numerical models that use magnetic fields with stellar rotation as a collimation mechanism.

Key words: ISM: kinematics and dynamics – planetary nebulae: general – planetary nebulae: individual (Hen 2-428, K3-58, M2-48, Hen 2-437, K3-46, M3-55, WeSb 4, M1-75, M4-14)

1. INTRODUCTION

The interacting stellar winds model, initially proposed by Kwok et al. (1978), is now the widely accepted scenario to explain the planetary nebula (PN) formation. However, it has not yet been unequivocally determined what is the ultimate mechanism responsible for the collimation of the sub-class of PNs that show bipolar or highly collimated morphologies (e.g. Balick & Frank 2002). In the context of the interacting stellar winds model, the formation of a bipolar planetary nebula (BPN) requires a collimation mechanism. An isotropic fast wind interacting with an aspherical mass-loss structure formed during the top of the asymptotic giant branch (AGB) phase is the most commonly invoked scenario, although a collimated fast wind and a spherical AGB structure have also been considered (Lee & Sahai 2003). Despite the fact that models are able to reproduce a wide variety of observed morphologies, it is still not clear how the aspherical mass loss during the AGB (or the axisymmetric fast wind) is produced.

From the numerical standpoint, several variations and additions to the interacting stellar wind model have been developed extensively in the literature under the name of the Generalized Interacting Stellar Winds (GISW) model (Balick 1987; Icke et al. 1989; Soker & Livio 1989; Frank & Mellema 1994; Mellema & Frank 1995; Icke et al. 1992; Mellema 1994). In the GISW model, a fast, tenuous wind from the central star expands into a slow, dense wind whose geometry is assumed to be toroidal. Magnetic fields have also been considered in numerical models; the magnetized wind blown bubble model (MWBB) produces an aspherical mass distribution by including toroidal magnetic fields that constrain the outflow and produce jets in the polar direction (Garciá-Segura & López 2000). Variations to the magnetic approach to generate the AGB aspherical density structure include using a stellar companion rapidly rotating around the central star (Calvet & Peimbert 1983; García-Arredondo & Frank 2004). Although models accurately replicate the PNs shapes, the ultimate question still remains: whether the magnetic field, and/or the stellar rotation, required to develop an aspherical AGB mass loss can be sustained by a single star or if they require the presence of a binary companion (Nordhaus et al. 2007).

In order to distinguish between the physical processes that may play a role in the process of shaping PNs, it is important to have a detailed morphological classification scheme that includes the basic morphological features (Schwarz et al. 1992; Gorny et al. 1997), and also allows for more detailed sub-classes (e.g. the presence of multiple shell PNs, multipolar axis) within each group (Manchado et al. 2000). We should proceed further in the classification and explore the degree of collimation observed in bipolar objects, as this most likely reflects the type(s) and strength(s) of the physical process(es) involved. Finally, the kinematics of the nebula allows us to recover its 3D structure, as it gives access to the extra-dimension hidden in direct imaging.

In this paper, we present high-resolution echelle long-slit spectroscopy of a sample of nine PNs from the Manchado et al. (1996b) catalog that show highly axisymmetric morphologies with different degrees of collimation. Seven of the PNs in our sample are classified as bipolar (K 3-46, K 3-58, Hen 2-428, Hen 2-437, M 2-48, M 3-55, and WeSb 4), and the other two (M 1-75 and M 4-14) present quadrupolar morphologies that are characterized by two pairs of bipolar lobes which are symmetric with respect to two different axes. Two objects in the sample, K 3-58 and M 4-14, also show point-symmetric features. In Section 2 we describe the observations and data reduction, in Section 3 we outline the procedure used in the analysis of the data, and in Section 4 we present the results of the kinematical fits performed to the objects in our sample. Finally, the results are discussed in Section 5 and the conclusions are summarized in Section 6.

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used. The 79 line mm$^{-1}$ providing a spectral resolution of 0.14 Å which corresponds to
a dispersion of 0.07 Å pixel$^{-1}$. The wavelength calibration has an accuracy better than
0.004 Å (0.2 km s$^{-1}$).

The spectra were obtained in 1995 July and 1996 August at
Northern Galactic PNs (Manchado et al. 1996a). The long-slit
illumination of the slit using sky flat fields obtained with the
same configuration. The wavelength scale and geometrical dis-


tortion were set by a two-dimensional fit to a Th–Ar calibration
lamp. The direction of simultaneously fitting images and spectra of a given nebula in
order to recover the 3D geometry lost by projection effects. As an
illustration, we show in Figure 1 simulated images and position-
velocity (PV) diagrams of a nebula obtained using Equation (1)
for three different inclination angles with respect to the plane of
the sky. From Figure 1, it is clear that the tilt of the simulated
line strongly depends on the inclination angle of the object.
Therefore, the shape of the PV diagram can be used to derive
the inclination angle which may only be assessed from the aspect
ratio of the central ring under the strong assumption that it is
circular. Similarly, Figure 2 shows simulated images and PV
diagrams for nebulae with different γ-factors. In this case, we
see that as γ increases, the shape of the PV diagram becomes
narrower and the line tilt more apparent. Figure 2 also shows
that it is not possible to determine the inclination angle of the
nebula from the projected shape of its cylindrical narrow waist
for γ ⩾ 9. However, it is readily seen that we can determine the
inclination from the line tilt in the PV diagram.

The fitting procedure is an iterative process that is started by
modeling simulated images and PV diagrams with parameters
that are first-order estimates. The set of free parameters includes
the polar and equatorial velocities, $v_p$ and $v_e$, the 1 kpc
kinematical age, the inclination angle of the PN with respect to
the plane of sky, the γ-factor describing the shape of the nebula,
and the radial velocity.

For the objects with a clearly visible central ring structure,
we can estimate both the equatorial expansion velocity and
the radial velocity just by measuring the velocity of the two
brightness maxima at the opposite sides of the ring; the average
of the two velocities gives us the radial velocity, while the
half difference of the velocities gives us a lower limit of the
equatorial expansion velocity. In this case, we can even assess
the inclination of the nebula as the axis ratio of the equatorial
ring is a direct measurement of the inclination angle if we
assume that the ring is circular. Then, the synthetic nebular
image and PV diagram are plotted over the Hα or Hα+[N II]
image and [N II] spectra, respectively. The initial estimates of

BPNs typically have hourglass or butterfly morphology,
meaning that they show two bipolar lobes connected by a narrow
waist. The exact geometry can be very different from one BPN
to another. These differences can basically be described by
the aspect ratio of the bipolar lobes and by the relative width
of the waist with respect to these bipolar lobes. In addition,
the inclination with respect to the plane of the sky affects
the apparent morphology, while the nebular kinematics determines
the observed expansion velocity. In order to determine the
3D geometry and kinematics of the BPNs in our sample, we have
used the empirical model of Solf & Ulrich (1985) which
was originally developed to interpret the velocity field of the
bipolar nebula around the symbiotic star R Aquarii. In this
model, hereafter referred to as the Solf & Ulrich model, the
velocity distribution along a plane going through the main
nebular symmetry axis is described by

$$v(\alpha) = v_e + (v_p - v_e) \sin^\gamma(\alpha)$$

where $\alpha$ is the latitudinal angle from the symmetry axis of
the nebula, $v_e$ is the equatorial velocity, the minimum velocity
along the nebular waist, $v_p$ is the polar velocity, the maximum
velocity of the farthest point from the center of the nebula, and
γ is a geometrical factor that defines the hourglass geometry,
with γ ≈ 1 for round, bubble-like bipolar lobes, and γ ⩾ 1 for
very elongated bipolar lobes.

One advantage of the Solf & Ulrich model is the possibility
of simultaneously fitting images and spectra of a given nebula in
order to recover the 3D geometry lost by projection effects. As an
illustration, we show in Figure 1 simulated images and position-
velocity (PV) diagrams of a nebula obtained using Equation (1)
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image and PV diagram are plotted over the Hα or Hα+[N II]
image and [N II] spectra, respectively. The initial estimates of

5 We use the term 1 kpc kinematical age throughout the text to refer to the
age obtained from the kinematical fitting assuming that the nebula is located at
a distance of 1 kpc. The 1 kpc kinematical age that is determined in the model
explicitly assumes that the lobes and the waist started to grow simultaneously.

6 The distance-corrected kinematical age is the 1 kpc age corrected for the
distance to the object.

7 For the spectral fits, we use the [N II] emission line because of its relative
brightness and small thermal broadening.
4. RESULTS: THE FITS TO THE IMAGES AND SPECTRA

In the following we provide a detailed description of both the data and the best-fit parameters obtained for each object.

*Hen 2-428.* Hen 2-428 (Figure 3) is a BPN with a noticeable equatorial ring and two open hourglass bipolar lobes of which the northern one is brighter and more extended. The central star, unusually bright for BPNs, has a known binary companion (Rodríguez et al. 2001). For this nebula, we acquired long-slit echelle spectra along P.A.s, 77° and 157° (see Figure 3). We note that the spectrum taken along P.A. 77° is off-center and passes through the bright knots in the equatorial ring. Therefore, the basic spectral fitting relies on the spectrum at P.A. = 157° which has an adequate signal-to-noise ratio in the central region and the brightest northern lobe to constrain the fit. From our best fit, we get an equatorial expansion velocity, \( v_e \), of 16 km s\(^{-1}\), and a polar velocity, \( v_p \), of 80 km s\(^{-1}\). A value of \( v_e = 15 \) km s\(^{-1}\) was obtained for this object by Rodríguez et al. (2001).

*Hen 2-437.* Hen 2-437 (see Figure 4 (top)) is a very elongated PN that does not show a central ring structure. These morphological features make it very difficult to constrain its equatorial velocity and to reproduce the spectral shape with the Solf & Ulrich model. Since there is almost no tilt in the central maxima of the [N\(\text{II}\)] echellogram along P.A. 77°, we assume that the nebula has a small inclination angle, lying almost in the plane of the sky.

The geometry of the nebula is thus constrained by its morphology, and the nebular contours can be reproduced relatively well by using an extremely high \( \gamma \)-factor. Given the difficulties in reproducing the spectral shape of Hen 2-437, it was not possible to derive firm results. We give a set of the most likely values: the inclination angle is small, within 2°, the polar velocity can be constrained to be between 50 and 100 km s\(^{-1}\), and the equatorial velocity has to be small, of the order or lower than 10 km s\(^{-1}\).

*K 3-46.* K 3-46 (Figure 4 (bottom)) has a well-defined hourglass geometry with a prominent equatorial ring and a marked waist. For this nebula, we obtained very low expansion velocities from the fit to the PV diagram, with \( v_e < 3 \) km s\(^{-1}\) and \( v_p \sim 18 \) km s\(^{-1}\). We note that it was not possible to find an optimal fit, and Figure 4 (bottom) indeed suggests that our simulated fit would require a larger central ring. We also note that the kinematical age of K 3-46 is of 24,000 yr which is, as we will discuss later, the highest value obtained in our sample.

*K 3-58.* At a first glance, K 3-58 shows a classical bipolar morphology (Figure 5), but its conspicuous ring is rather irregular and the bipolar lobes show point-symmetry. All these components are clearly detected in the [N\(\text{II}\)] echellogram obtained along P.A. 90°, with the brightest emission peaks located on the equatorial ring. Inside the main lobes, a secondary structure reaches approximately up to one half of the length of the main lobes. This secondary structure, that is clearly present in the spectral data as bright emission peaks, may have originated from a later ejection to the one that shaped the main lobes. From the fit we obtain \( v_e = 38 \) km s\(^{-1}\) and \( v_p = 12 \) km s\(^{-1}\). Interestingly, the ratio between the equatorial and the polar velocities is relatively small for this object.

*M 1-75.* M 1-75 (Figure 6) is the first object classified as quadrupolar (Manchado et al. 1996b). M 1-75 with its complex morphology and extremely high He abundances and the N/O ratio is a candidate for a peculiar stellar evolutionary path (Guerrero et al. 1996). The nebula does not show a circular...
Figure 3. Kinematical fitting of the Hen 2-428 for a slit P.A. of 167° (top) and for a slit P.A. of 77° (bottom). The narrowband image, extracted from the Manchado et al. (1996b) catalogue, has been rotated to the P.A. of the slits along which the spectra were obtained. The angular scale of images and spectra has been matched to allow an easy comparison of images and spectra. Also note that the PV diagrams have been corrected for the local standard of rest (LSR) velocity. In order to display the complete structure of the spectral line, the contrast of the spectra is adjusted, so the faintest parts can be seen.

The spectra for M 1-75 was obtained along the main symmetry axis of the two pairs of bipolar lobes, namely along P.A. 150° and 176°. The former spectrum (Figure 6 (top)) proved more useful to guide our spectral fit, as it provides information for both pairs of bipolar lobes. The data taken at the second P.A. have been used for control purposes only and is shown at the bottom of Figure 6.

The large lobes, along P.A. 150°, can be well fitted by using \( \gamma = 6 \) and an inclination angle of 87° as determined from the spectra. Since these lobes seem to lie close to the plane of the sky, but an irregular annular structure at the central regions. Since the equatorial ring is clearly not circular, it cannot be used to assess the inclination angle of the nebula with respect to the plane of the sky.
of the sky, a change in just $2^\circ$ is very noticeable for such an elongated shape, and the inclination angle can be constrained well. The expansion velocities obtained for the largest pair of lobes are relatively low, with $v_e = 8$ km s$^{-1}$ and $v_p = 55$ km s$^{-1}$.

The kinematics of the small lobes cannot be constrained as accurately because their geometry in the image is not well defined. We have assumed, for simplicity, that the small and large pairs of lobes have identical morphologies, and therefore we use the $\gamma$-factor determined for the large lobes, $\gamma = 6$. The range of inclination angles we then obtain is between $60^\circ$ and $70^\circ$. Using an inclination angle of $65^\circ$, we obtain expansion velocities of $v_p = 45$ km s$^{-1}$ and $v_e = 12$ km s$^{-1}$.

M 2-48. M 2-48 (see Figure 7 (top)) does not show an equatorial ring, but a pinched waist. The pair of collimated lobes ends in a pair of bow shocks that were analyzed in detail by
Figure 5. Same as Figure 3 for K 3-58 for a slit P.A. of 90° (top) and for a slit P.A. of 14° (bottom). As for Hen 2-437, white contours are used for the brightest regions of the spectral line.

López-Martín et al. (2002). The collimated morphology of the bipolar lobes of M 2-48 requires us to use a high $\gamma$-factor ($\sim$8). The narrow central waist of M 2-48 does not allow us to determine the inclination angle from the geometry of the ring and, therefore, as mentioned in Section 3, we have to rely on the line tilt in the observed PV diagram. We reproduce well the geometry of both image and spectra by using an inclination angle of $\sim$80°, with the northeastern lobe receding from us. We derive a radial velocity of 16 km s$^{-1}$, a $v_e = 10$ km s$^{-1}$, and a $v_p$ of 100 km s$^{-1}$ which is the largest value in our sample. The inclination angle and expansion velocities obtained are consistent with the determination by López-Martín et al. (2002).

M 3-55. Despite being very faint, M 3-55 displays a clear symmetric shape (Figure 7 (bottom)). We obtain for M 3-55 a low expansion velocity, lower than 6 km s$^{-1}$ in the equator and...
about 19.5 km s$^{-1}$ along the polar directions. M 3-55 also has the lowest $\gamma$-factor of all the objects within our sample which is not surprising given that it has a relatively wide ring and round lobes.

M 4-14. Manchado et al. (1996b) classified M 4-14 (Figure 8 (top)) as a PN with quadrupolar morphology (based on imaging). Here, we also remark on the noticeable point symmetry of its bipolar lobes. To fit the cylindrical waist of M 4-14, a high $\gamma$-factor ($\gamma = 5$) is needed. From this fit we obtain $v_e = 11$ km s$^{-1}$ and $v_p = 65$ km s$^{-1}$.

M 4-14 has a $[\text{N II}]/H\alpha$ ratio of among the highest found in PNs, indicative of a high nitrogen enhancement and high N/O ratio, that are known to be correlated with bipolarity (Peimbert & Torres-Peimbert 1983). The chemical abundances, expansion velocity, and geometry factor $\gamma$ make M 1-14 and M 1-75 very similar.
WeSb 4. WeSb 4 is a large, somehow diluted object, that shows one of the most irregular morphologies among the objects in the sample (Figure 8 (bottom)). The narrowband image does not display a clear hourglass shape that, on the other hand, is evident in the much deeper spectrum. In the spectrum we detected weak, and more extended emission than in the optical images. From the image and [N II] echellograms along P.A. 69° and 159°, we derive an inclination angle of 50°, and a $v_e$ of 14 km s$^{-1}$, and $v_p$ of 95 km s$^{-1}$. WeSb 4 has one of the highest $v_p$ in our sample.

5. DISCUSSION

We summarize in Table 2 the parameters obtained from the best fits to the data. Column 2 gives the size of the lobes and waist as measured from the maximum extension of the 3σ contour levels extracted from the images obtained by Manchado et al. (1996a). The polar and equatorial expansion velocities are given in Columns 3 and 4, respectively, the 1 kpc kinematical age is given in Column 5, the inclination angle in Column 6, and the
$\gamma$-factor in Column 7. Below the values obtained from our best fit (when the synthetic PV diagram passes through the intensity maxima in the spectral data and the simulated image tightly traces the nebular geometry), we have listed the range of values that still provide reasonable matches (when we can still provide a fit that passes through the main features) to the images and spectra in order to provide an estimate of the uncertainties in our fits.

The equatorial velocities range from very low values (3 km s$^{-1}$ for K 3-46) to typical expansion velocities (16 km s$^{-1}$ for Hen 2-428). None of the objects in our sample has high, $\sim$40 km s$^{-1}$, equatorial expansion velocities such as those found by Corradi & Schwarz (1993) in the BPNs CTS 1 and Hen 2-84. The polar velocities cover the whole range, from very low (18 km s$^{-1}$ in K 3-46) to medium/high (100 km s$^{-1}$ in M 2-48).

Figure 8. Same as Figure 3 for M 4-14 for a slit P.A. of 40° (top) and WeSb 4 for a slit P.A. of 159° (bottom). As for Hen 2-437, white contours are used for the brightest regions of the spectral line of M 4-14.
The PNs analyzed in this paper can be classified into three different groups, according to their morphology and kinematics. The first group formed by Hen 2–428, K 3-46, K 3-58, M 3-55, and M 4-14 consists of BPNs with notable central rings. For these objects, we have a direct estimate of their equatorial expansion velocities measured from the spectral emission of the ring (as it was described in Section 3). A second group is formed by the highly collimated objects Hen 2-437 and M 2-48 having the highest polar expansions and elongated bipolar morphology typical mostly for younger PNs. Finally, the third group is formed by the somewhat deteriorated objects with poorly defined morphologies; M 1-75 and WeSb 4. The PNs belonging to this third group are expected to be more evolved since they have the highest kinematical ages. Although K 3-46 also has a large kinematical age, we did not include it in this group of evolved objects. We suspect that its large kinematical age is probably a consequence of deceleration in the course of its evolution.

### 5.1. PN Ages

Our spatio-kinematical study provides a direct estimate of the kinematical age that can be used to assess the nebular age. It is important to keep in mind in this comparison the very likely possibility of acceleration or deceleration of the nebular material due to the complex interaction between the ionization and dynamics of the shell driven by the hot bubble. As a result, kinematical ages often do not match the age of the central stars, as shown theoretically by Villaver et al. (2002), who proved that kinematical ages overestimate the age in young nebulae and underestimate it for evolved ones. Moreover, the definition of the PN age is a rather tricky concept. It can be considered that a PN is born when the central star supplies enough photons capable of ionizing the nebula. However, the kinematical age is a dynamical concept that tells us when the gas started moving. At the time of nebular ionization the gas is already moving and the photoionization itself is expected to change the gas dynamics. In addition, the gas velocity as inferred from models (Villaver et al. 2002) is not constant. If the gas has been accelerated the kinematical ages are underestimated and the opposite is true if the gas has suffered deceleration. The age obtained in Table 2 is one of the parameters of the fitting and it is obtained under very simplistic assumptions, namely that the lobes and the waist were formed at the same time and they have been moving at a constant velocity since then. Therefore, the ages determined this way are just an order of magnitude approximation to the time since the formation of the nebula (both dynamically and from ionization).

The kinematical model assumes the same age for the lobes and the waist of a nebula. As a consequence, the larger lobes always have larger expansion velocities. Note that under this simplistic assumption we are excluding the possibility that the lobes were formed before the waist.

In Table 2 we provide the 1 kpc kinematical ages. Here, we have estimated the “real” ages by multiplying the 1 kpc kinematical ages derived from our fits by the individual distances. It is well known that PNs distances are poorly determined, however they are a necessary parameter for the age estimation. It is important to note that the ages determined in Table 3 are the ones given in Table 2 but scaled to the distance to the nebula. We have used the distances obtained from the Galactic rotation curves of Burton (1974) when possible, as these distances are considered to be the most reliable. In some cases, our data were out of the range covered by the rotational curves, and therefore the distance estimate was not viable through this method. This also applies for M 2-48, for which this method gives ambiguous results, and for M 1-75, for which the distance derived from this method (5.4 kpc) is

| PN name | Hα sizea (") | v_e (km s^-1) | v_p (km s^-1) | Kinematical age (yr) | Inclination angle (°) | γ |
|---------|---------------|---------------|---------------|---------------------|----------------------|-----|
| Hen 2-428 | 63 × 18 | 80 | 16 | 2400 | −75 | 1 |
| Hen 2-437 | 45 × 4.6 | ... (5) | ... (5) | ... (5) | ... (5) | 1800 | 90 |
| K 3-46 | 81 × 36 | 18 | 3 | 11000 | −70 | 0.9 |
| K 3-58 | 23.0 × 12.7 | 38 | 12 | 1800 | −600 | 5 (2.2) |
| M 1-75 | 69 × 23b | 55 | 8 | 2700 | 87 | 6 |
| M 1-75c | ... | 45 | 12 | 2400 | 65 | 5.5 |
| M 2-48 | 42.6 × 5.7d | 100 | 10 | 1160 | −79 | 8 |
| M 3-55 | 11.1 × 8.2 | 19.5 | 6 | 1800 | 40 | 0.6 |
| M 4-14 | 27 × 8.5 | 65 | 11 | 1500 | 38 | 5 |
| WeSb 4 | 77 × 18d | 95 | 14 | 3400 | 50 | 6 |

**Notes.**

a The size of the lobes and waist.

b Ring size 24.0 × 13.1.

c For the smaller pair of lobes.

d Size in the [N ii] image.
Table 3
Estimated Kinematical Ages

| PN name      | $V_r$ (km s$^{-1}$) | 1 kpc kinematic age (yr) | Statistical distance (kpc) | Reference | Rotation curve distance (kpc) | Adopted distance (kpc) | Estimated age (yr) |
|--------------|---------------------|--------------------------|---------------------------|-----------|------------------------------|------------------------|-------------------|
| Hen 2-428    | 72                  | 2400                     | 2.7                       | CaKa71    | 2.2                          | 3.4                    | 5280              |
| K 3-46       | 66                  | 9000                     | 2.15                      | CaKa71    | 2.2                          | 2.2                    | 19350             |
| K 3-58       | 21                  | 1800                     | 6.6                       | CaKa71    | 6.2                          | 6.2                    | 11070             |
| M 1-75       | 7                   | 2700                     | 2.6–3.7                   | CaKa71    | 5.3                          | 3.4                    | 9099              |
| M 2-48       | 16                  | 1160                     | 3.42                      | CaKa71    | 1.5–7.7                      | 4.2                    | 4872              |
| M 3-55       | 30                  | 1800                     | 3.56                      | CaKa71    | 2.8                          | 2.8                    | 5040              |
| M 4-14       | 49                  | 1500                     | 3.7                       | CaKa71    | 3.7                          | 3.7                    | 5550              |
| WeSb 4       | 69                  | 3400                     | ...                       | ...       | ...                          | ...                    | 15980             |

References: [CaKa71], Cahn & Kaler (1971); [Ma84], Maciel (1984); [Ca76], Cahn (1976); [Ac78], Acker (1978); [Da82], Daub (1982); [AGNR84], Amnuel et al. (1984); [CKs91], Cahn et al. (1992).

unreasonable and gives a lengthy kinematic age for a PN. When it was not possible to estimate the distance from the rotational curves, we have used the statistical distances from Cahn et al. (1992) when available. Otherwise we have used the distance from Cahn & Kaler (1971) or, as a last resort, an average of available distances in the literature. We note that the values given by Maciel (1984) are systematically lower than the values given by others. Therefore, Maciel’s distances have not been used for the averages.

In Table 3, Column 1 gives the PN name, Column 2 the radial velocity, Column 3 the kinematic age at 1 kpc obtained from the model fitting, Column 4 the statistical distances taken from Acker et al. (1992), Column 5 the reference to the statistical distance, Column 6 the distances estimated from the galactic rotation curve (Burton 1974), and Column 7 the distance used to estimate the kinematical age which is given in Column 8.

The distance-corrected kinematical ages range between $\sim 5,000$ and $\sim 20,000$ yr. Intuitively, it is expected that younger PNs would have better-defined morphologies than the older ones. This appears to be the case for almost all the objects analyzed. Hen 2–428, M 2–48, M 3–55, and M 4–14 are relatively young, with kinematical ages $\sim 5,000$ yr, and all have well-defined morphologies. M 1–75 and especially WeSb 4 are older, with kinematical ages $\sim 10,000$ yr, and their morphologies are not sharp.

In old objects such as WeSb 4, ionization-driven instabilities which act on a timescale comparable to the kinematical age of the nebula might be responsible for the development of irregular shapes (Cliffe et al. 1995).

There are two objects in our sample for which a relation between their age and their morphology is not straightforward. K 3–46, the oldest PN in our sample ($\sim 20,000$ yr), and K 3–58, a relatively old PN, have sharp morphologies. One possibility is that the distances used are wrong, which would not be a surprise given the high uncertainties involved in PN distance determinations. Another possibility for K 3–46 is that it has experienced deceleration, in which case the age given in Table 3 would be an underestimation of the real age of the object.

Adopting a distance of 1 kpc to Hen 2–437, we obtain a kinematical age between 750 and 2000 yr. The age of Hen 2–437 is consistent with those of high-collimated PNs (Lee & Sahai 2003).

5.2. Comparison with Numerical Models

Quite often the comparison between theoretical models and observed objects is based only on a morphological match since this is the only available information in most cases. From our experience in matching published models to data, we have found that it is possible to find models that can simulate the morphology of a PN but with different velocities to those measured; in this case we need to know whether the model can simultaneously reproduce the morphology and kinematical properties that, in the case of bipolar PNs, are parameterized by the expansion velocity, the physical nebular size, and geometry (the $\gamma$-factor). Note that, in the model of Solf & Ulrich, the expansion of a BPN is homologous, i.e., in its expansion, the nebula keeps its proportions, as well as the ratio between the polar and equatorial velocities.

Only the models by García-Segura et al. (1999) and García-Segura & López (2000) provide enough information on the evolution of the morphology for different collimation parameters for us to compare to our data. In the García-Segura et al. (1999) models (hereafter, GS99), the velocity ratio between the equator and the poles depends on the shaping mechanism, while the absolute values of the velocities depend on the initial velocity of the slow wind. Therefore, when evaluating the ability of
the theoretical models to match our observations, we are more interested in comparing the nebular shapes and velocity ratios rather than the absolute velocity values.

To compare the models with the observations, we need a parameter that can quantify the degree of collimation. The $\gamma$-factor in the Solf & Ulrich geometrical model is an appropriate parameter to account for the degree of collimation observed. The shape in the GS99 models is controlled using different values of $\sigma$ (the ratio of the magnetic to the kinetic energy density in the fast wind) and $\Omega$ (the ratio of the stellar rotational velocity to the critical breakup velocity).

In order to allow a better comparison between the models and the parameters derived from the observations we have determined the Solf & Ulrich parameters ($\gamma$-factor) that correspond to the GS99 simulated cases. We find that low-$\sigma$ and low-$\Omega$ values produce shapes that are similar to those generated by low values of $\gamma$ ($\gamma < 1$) (see Figure 5 in GS99). The GS99 cases with low-$\sigma$ and high-$\Omega$ values are equivalent to medium-$\gamma$ values, while high-$\sigma$ and high-$\Omega$ values result in very collimated objects, with high-$\gamma$ values.

For categories J–K in GS99, the morphology develops using only rapid star rotation rates, while for categories Q–V the additional help of magnetic fields is required. Hen 2-428, K 3-46, and M 3-55, which have the lowest $\gamma$ (1, 0.9, 0.6, respectively) factors in our group, compare well to categories J–K of GS99. Both the observed objects and the corresponding theoretical simulations are reproduced with $\gamma$-factors around 1 and, although our PNs do not have the same absolute expansion velocities as the GS99 cases, this is not a critical issue as lower expansion velocities in GS99 magneto-hydrodynamic (MHD) simulations could be obtained by choosing lower initial velocities for the slow wind. In fact, the ratio of expansion velocities for K 3-46 and Hen 2-428 situates them in categories Q–R, but their $\gamma$-factor and morphology place them into the J–K group. It must be noticed that the central star of Hen 2-428 in a binary system (Rodríguez et al. 2001). It is tantalizing to consider that the presence of the binary companion may have influenced the nebular shaping, resulting in a BPN with enhanced polar velocities with respect to the BPN that would have been collimated by a single, rotating star.

In general, the expansion velocities in GS99 are rather high compared to those observed in our sample. However, M 1-75, M 4-14, and WeSb 4 have similar expansion velocity ratios (i.e. equatorial to polar expansion velocity) and morphologies as the PNs in categories Q–R in GS99. These 3 PNs have $\gamma$-factors between 5 and 6. In fact, M 4-14 even coincides in its kinematical age and value of its expansion velocities with the theoretical models to match our observations, we are more interested in comparing the nebular shapes and velocity ratios rather than the absolute velocity values.

M 2-48 is more collimated than the previous objects and fits into categories S–T, while Hen 2-437 would go even higher, to the class U in GS99. Such highly collimated objects, with lobes of wedge-shaped polar regions, are not well reproduced by the Solf & Ulrich model and therefore our derived velocities carry a large uncertainty.

Careful inspection of the images of M 2-48 and Hen 2-437, which have the highest collimation factors in our sample, reveals traces of a dusty disk in the equatorial region, a feature not visible in the low-$\gamma$ objects. Similar features were already detected in various young, highly collimated objects (e.g. Sahai et al. 2006) and suggest the existence of thick equatorial disks.

Finally, we are left with K 3-58 a rather peculiar object since it has an expansion ratio and $\gamma$-factor that lie outside the cases modeled by GS99. K 3-58 presents a cylindrical equatorial ring which is wider than the one obtained for the J–L categories of GS99, and it shows lobes that are rounder than those in the R–V classes. The best fit to the morphology and kinematics of this object can be found in Figure 5 of García-Segura & López (2000). The nebula simulated there has almost identical expansion velocities to those which we measure. In this model, the point-symmetric shape is accomplished with a tilt between the magnetic collimation axis and the bipolar wind outflow.

To summarize, we find that objects with low-$\gamma$ values generally compare well with the GS99 models which are mainly shaped by stellar rotation. The possible exceptions are PNs formed in binary systems that will present low-$\gamma$ but somewhat higher expansion velocities (Hen 2-428), while high-$\gamma$ objects show high polar expansions and agree well with the simulations obtained using strong magnetic fields and high rotational velocities.

6. CONCLUSIONS

Although all of our objects are bipolar/quadrupolar, they differ significantly in their morphology and kinematics. Morphologies range from bubble-lobed (Hen 2-428) to highly collimated (Hen 2-437) PNs. The sharpness of the nebular shapes also varies from well-defined objects to those with somewhat deteriorated shapes (WeSb 4). This variety is reflected in the range of geometrical $\gamma$-factors (from 0.6 to 20) which might differentiate between the physical processes that originate them.

We find that the objects from our sample present as well a variety of expansion velocities, from low (3 km s$^{-1}$) to medium (16 km s$^{-1}$) equatorial expansions, and from low (18 km s$^{-1}$) to medium/high (100 km s$^{-1}$) polar expansion velocities. The disagreement between the spectral data of K 3-46, hardly revealing signs of equatorial expansion, and its image, showing a wide central ring, indicate the possibility of deceleration in this nebula. This deceleration may reveal the interaction of the nebular material with a dense equatorial disk.

The estimates of kinematical ages, derived using distances inferred from the Galactic rotation curve or otherwise statistical distances, vary from middle-age to old with possible significant errors originated from distance errors and non-uniform expansions. The data agree rather well with the state-of-the-art theory for PN collimation, however, we cannot exclude the origin of the possible shaping mechanisms i.e. whether rapid star rotation, and/or magnetic fields are originated by single or binary systems. We suggest that the $\gamma$-factor used to fit the Solf & Ulrich model could roughly indicate which shaping process is actually at work.

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REFERENCES

Acker, A. 1978, A&AS, 33, 367
Acker, A., Marcout, J., Ochsenbein, F., Stenhholm, B., & Tylenda, R. 1992, Strasbourg-ESO Catalogue of Galactic Planetary Nebulae, (Garching: European Southern Obs.), 1992
Amnuel, P. R., Guseinov, O. K., Novruzova, K. I., & Rustamov, I. S. 1984, Ap&SS, 107, 19
Balick, B., & Frank, A. 2002, ARA&A, 40, 439s
Balick, B., Preston, H. L., & Icke, V. 1987, AJ, 94, 1641
Burton, W. B. 1974, in Galactic and Extragalactic Radio Astronomy, The Large Scale Distribution of Neutral Hydrogen, ed. G. Verschuur, & K. I. Kelleman (Berlin: Springer)
Cahn, J. H. 1976, AJ, 81, 407
Cahn, J. H., & Kaler, J. B. 1971, ApJS, 22, 319
Cahn, J. H., Kaler, J. B., & Stanghellini, L. 1992, A&AS, 94, 399
Calvet, N., & Peimbert, M. 1983, RevMexAA, 5, 319
Cliffe, J. A., Frank, A., Livio, M., & Jones, T. W. 1995, ApJ, 447, L49
Corradi, R. L. M., & Schwarz, H. E. 1993, A&A, 278, 247
Daub, C. T. 1982, ApJ, 260, 612
Frank, A., & Mellema, G. 1994, ApJ, 430, 800
García-Arredondo, F., & Frank, A. 2004, ApJ, 600, 992
García-Segura, G., Langer, N., Różycka, M., & Franco, J. 1999, ApJ, 517, 767
García-Segura, G., & López, J. A. 2000, ApJ, 544, 336
Gorny, S. K., Stasinska, G., & Tylenda, R. 1997, A&A, 318, 256
Guerrero, M. A. et al. 1996, ApJ, 464, 847
Icke, V., Balick, B., & Frank, A. 1992, A&A, 253, 224
Icke, V., Preston, H. L., & Balick, B. 1989, AJ, 97, 462
Kwok, S., Burton, C. R., & Fitzgerald, P. M. 1978, ApJ, 219, L125
Lee, C.-F., & Sahai, R. 2003, ApJ, 586, 319
López-Martín, L., et al. 2002, A&A, 388, 652
Maciel, W. J. 1984, A&AS, 55, 253
Manchado, A., Guerrero, M. A., Stanghellini, L., & Serra-Ricart, M. 1996a, The IAC Morphological Catalog of Northern Galactic Planetary Nebulae (La Laguna, Spain: Instituto de Astrofisica de Canarias (IAC)), 1996, Foreword by Stuart R. Pottasch, ISBN: 8492180609
Manchado, A., Stanghellini, L., & Guerrero, M. A. 1996b, ApJ, 466, L95
Manchado, A., Villaver, E., Stanghellini, L., & Guerrero, M. A. 2000, in ASP Conf. Ser. 199, Asymmetrical Planetary Nebulae II: From Origins to Microstructures, 17
Mellema, G. 1994, A&A, 290, 915
Mellema, G., & Frank, A. 1995, MNRAS, 273, 401
Nordhaus, J., Blackman, E. G., & Frank, A. 2007, MNRAS, 376, 599
Peimbert, M., & Torres-Peimbert, S. 1983, in IAU Symp. 103, Planetary Nebulae, 233
Rodríguez, M., Corradi, R. L. M., & Mampaso, A. 2001, A&A, 377, 1042
Sahai, R., Young, K., Patel, N. A., Sánchez Contreras, C., & Morris, M. 2006, ApJ, 653, 1241
Schwarz, H. E., Corradi, R. L. M., & Melnick, J. 1992, A&AS, 96, 23
Soker, N., & Livio, M. 1989, ApJ, 339, 268
Soker, N., & Rappaport, S. 2001, ApJ, 557, 256
Solf, J., & Ulrich, H. 1985, A&A, 148, 274
Steffen, W., & López, J. A. 1998, ApJ, 508, 696
Villaver, E., Manchado, A., & García-Segura, G. 2002, ApJ, 581, 1204