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QUADRUPOLAR PLANETARY NEBULAE: A NEW MORPHOLOGICAL CLASS

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ABSTRACT

In the context of the Instituto de Astrofísica de Canarias (IAC) morphological survey of Galactic planetary nebulae (PNs), a new morphological class has been found, and we define their members as quadrupolar PNs. We have found five quadrupolar objects whose lobes are, in pairs, symmetric with respect to two different axes. Among these PNs, three (M2-46, K3-24, and M1-75) have well-defined pairs of lobes; another two (M3-28 and M4-14) are irregular and very possibly quadrupolar. For M2-46, we have measured the extension and the angle between the lobes, and the expansion velocities of the lobes by means of spectroscopic analysis. We propose that these nebulae have been formed by precession of the rotation axis of the central stars, possibly in the presence of a binary companion, associated with multiple shell ejection at the asymptotic giant branch. A simple binary mechanism not associated with precession cannot produce such a morphology.
Subject headings: planetary nebulae: individual (K3-24, M1-75, M2-46, M3-28, M4-14)

1. INTRODUCTION

The morphology of planetary nebulae (PNs) has been studied in recent years to derive indications of the evolution of stars from the asymptotic giant branch (AGB) to the white dwarf (WD) stages. As high-quality narrowband images of PNs have become available, efforts have been made in order to correlate the shapes of the PNs to other parameters of the nebulae themselves and of the central stars (CSs). The aim is to understand the astrophysical scenarios in which the different shapes are produced (see Stanghellini 1995 for a review).

Very recently, we have started a morphological survey on northern PNs at the Instituto de Astrofísica de Canarias (IAC) (Manchado et al. 1996), obtaining narrowband images for 244 PNs through at least two filters corresponding to the Hα + [N II] and [O III] λ5007 emissions. We found that a few of them show a marked quadrupolar shape. They are intrinsically quite different from the point-symmetric PNs classified so far (Stanghellini, Corradi, & Schwarz 1993) in that they definitely show a waist, thus being closely related to bipolar PNs. We classify them as quadrupolar PNs. By quadrupolar PNs, we mean *planetary nebulae with two pairs of lobes, each pair symmetric with respect to a different axis*. Each pair of lobes is very similar to those seen in typical bipolar PNs (e.g., Corradi & Schwarz 1994).

PNs with two or more pairs of unaligned, independent lobes have already been observed, although not identified as belonging to a new morphological class. Icke, Preston, & Balick (1989) have noted that NGC 2440 shows two pairs of lobes. Louise & Pascoli (1985) examined the shape of NGC 2440 and speculated that it could have been produced by a precession mechanism. The mere fact that quadrupolar PNs exist is a good indication that there are asymmetric winds ejected by a rotating star, where a precession mechanism plays a fundamental role.

We describe the observations in § 2. We then present the data in § 3 and our interpretation and discussion in § 4.

2. OBSERVATIONS

The narrowband CCD images were obtained with the 2.56 m Nordic Optical Telescope (NOT) at the Roque de los Muchachos Observatory (La Palma, Spain). For every object, exposures were made in the lines of Hα λ6563 (Δλ 9 Å), [N II] λ6584 (Δλ 9 Å), and [O III] λ5007 (Δλ 50 Å). The pixel size was 0".139 pixel^{-1} with a field of view of 2'.4, and the seeing was 0".6. The long-slit echelle spectra of M2-46 were obtained with the UES on the 4.2 m William Herschel Telescope at the Roque de los Muchachos Observatory. The observational setting is described in Guerrero et al. (1996). The spectral resolution was 6.5 ± 0.3 km s^{-1}. We used a long slit along the major axis of the nebula (P.A. = 18°) passing through the faint central star and a perpendicular slit (P.A. = 108°) at a position 7" toward the north of the central star.

3. ANALYSIS OF INDIVIDUAL PNs

M2-46.—This PN (Fig. 1 [Pl. L8]) has two very well defined pairs of lobes. The outer pair has a total extension of 30" at P.A. 15° and a much smaller pair of lobes up to 15" at P.A. 40°. Although from the figure it seems clear that the two pairs of lobes are not on the same axis, the angle between the two axes of symmetry is quite small, about 25°. The PN has an enhanced central part of 5" width. This is the only object for which we have information on the velocity structure, by means of high-resolution spectral analysis. In Figures 2*a* and 2*b* we show two different diagrams of position versus velocity. Figure 2 (*left*) contains the spectral information acquired with the slit through the symmetry axis; we can infer from this plot that the quadrilobate structure is real. Figure 2 (*right*) shows the velocity field for a slit positioned halfway toward one lobe (see

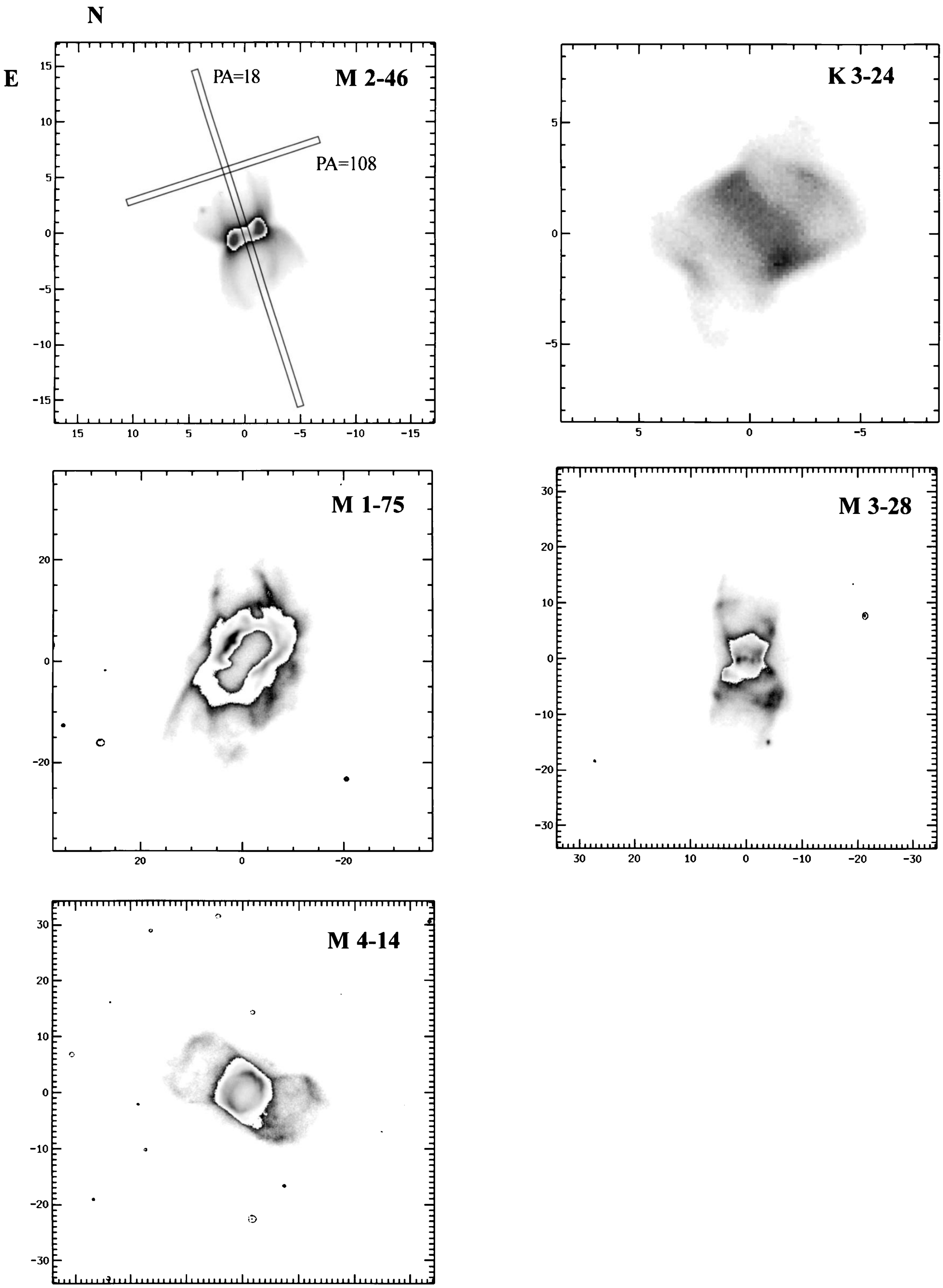

FIG. 1.—[N II] image of M2-46, K3-24, M1-75, M3-28, and M4-14. The picture has been displayed at two levels of intensity to show both the bright and faint features. Scale is in arcseconds. The slit positions corresponding to the high-resolution spectra of M2-46 are also shown.

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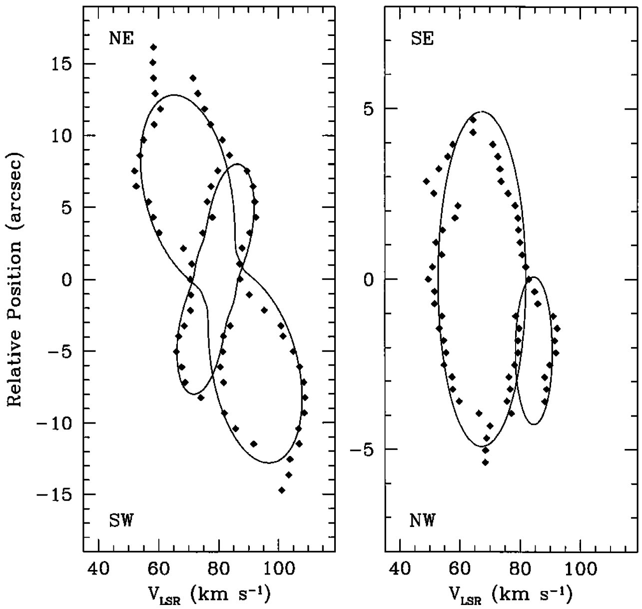

FIG. 2.—(*Left*) Velocity vs. position plots from the [N II] λ6584 line of M2-46 for P.A. = 18°. Black points are the observed data, while solid lines represent the fit of the Solf & Ulrich (1985) model with $\gamma = 3.5$, $V_p = 40$ km s^{-1}, and $\gamma = 4.5$, $V_p = 25$ km s^{-1}, respectively, and $V_e = 7$ km s^{-1} for both lobes. (*Right*) Same as left panel, but for P.A. = 108°.

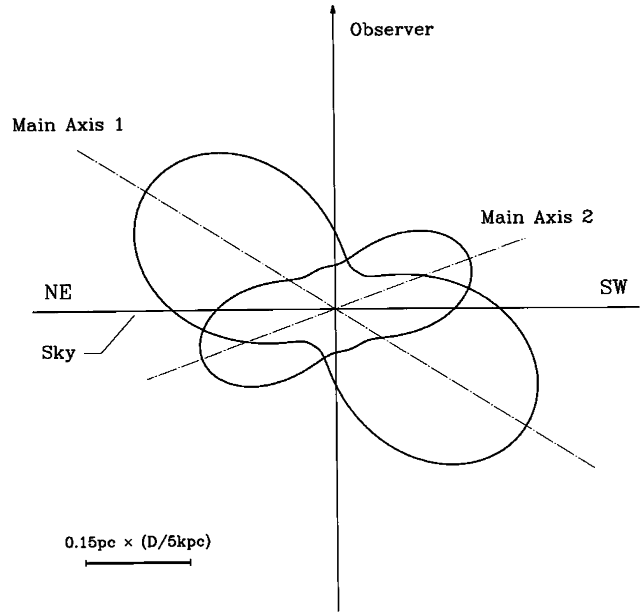

FIG. 3.—Schematic representation of the proposed model for M2-46. The main nebular axes are tilted 60° and 110° with respect to the line of sight. The spatial scale corresponds to a distance of 5 kpc (see text).

slit position in Fig. 1). In both figures a simple model of a bipolar expanding nebula (Solf & Ulrich 1985) has been fitted. In this model

$$V_{\rm exp}(\phi) = V_e + (V_p - V_e)|\cos\phi|^{\gamma},$$

where ϕ is the colatitude angle, varying from 0° at the pole to 90° at the equator, V_e and V_p are the equatorial and polar velocities, and γ is a shape parameter. Both of the panels in Figure 2 show the excellent agreement of the model with our observations. For the outermost lobe, a polar velocity of 40 km s^{-1} and an inclination angle, in the line of sight, of 60° were estimated, while for the innermost lobe, the values were 25 km s^{-1} and 110°. We see that the lobes have different velocities, and while the large lobe is approaching the observer in the southwest position, the small lobe is receding along the line of sight. Figure 3 shows a model of the four lobe positions with respect to the line of sight and the plane of the sky. The synthetic morphology (Fig. 4), which was obtained by projecting the proposed model over the plane perpendicular to the line of sight, is in excellent agreement with the observed morphology (Fig. 1). Combining the angles in the line of sight (50°) and in the perpendicular plane (25°), we find that the angle between the two pairs of lobes is 53°.

From the radial velocity of the PN, we can estimate the distance by placing the PN in the Galaxy and read off its distance from a Galactic rotation curve (e.g., Sellwood & Sanders 1988). A $V_{\rm LSR} = 79.0$ km s^{-1} was measured, which leads to a distance of $D = 5$ kpc. By using this distance, the lobe sizes (15″ and 7″.5), and by deprojecting the lobes from the plane of the sky (60° and 110°), we infer a lineal extension of 0.42 and 0.19 pc for each lobe. Combining these sizes with the expansion velocity (40 and 25 km s^{-1}), we calculated a dynamical age of 10,200 and 7500 yr for both lobes. Though these ages may have some uncertainties, mainly due to the distance determination, it is absolutely certain that the time lap between the ejections of the two lobes (interlobe time-lap) should be very short, of the order of a few thousand years. A smaller distance will make the interlobe time-lap even shorter.

K3-24.—Very obviously quadrupolar, this nebula has two pairs of almost identical lobes, measuring 12″ at P.A. = −20° and 11″ at P.A. 100° (Fig. 1). The lobe pairs are rotated with respect to one another by about 60° on the plane of the sky. For this nebula, we can only give a very rough estimate of the interlobe time-lap: we assume a lobe velocity of 20 km s^{-1}, then by using the shortest and longest distances in Acker et al. (1992), we find an interlobe time-lap between about 700 and 1500.

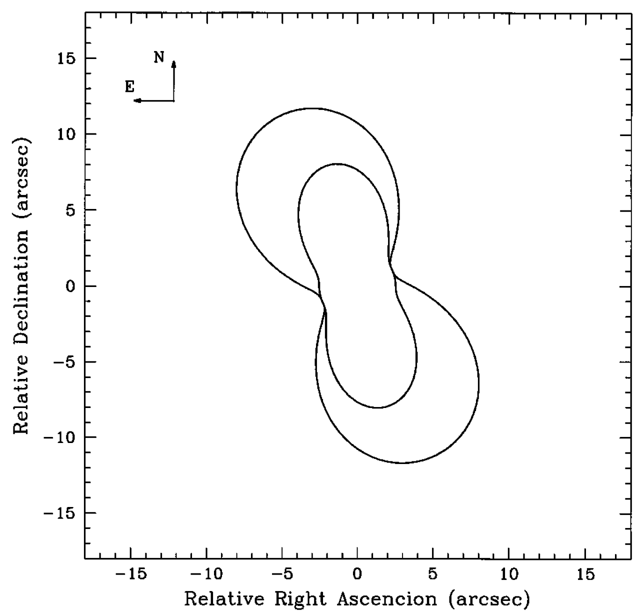

FIG. 4.—Synthetic morphology according to the proposed model for M2-46.

M1-75.—We had already analyzed this nebula (Fig. 1) as a very peculiar object with a very high nitrogen-to-oxygen ratio (Guerrero, Stanghellini, & Manchado 1995). The narrowband image in Guerrero et al. (1995) was taken with the IAC80 telescope, while in the present paper we show the NOT [N II] image: the improved resolution discloses the previously undetected quadrupolar morphology. The major pair of lobes extends to 64″ at P.A. = −30°, while an inner pair of lobes has a total length of 42″ at P.A. = 10°. The morphology is also characterized by a very marked ring from where the lobes depart.

M3-28.—Even if the two pairs of lobes are not clearly visible here (Fig. 1), we speculate that this object is very similar to M1-75, with a different orientation on the plane of the sky. The lobes have a total extension of about 20″ at P.A. = 30° and 17″ at P.A. = −30°.

M4-14.—The outermost edges of two pairs of lobes are clearly seen in Figure 1. The inner edges are not so distinct, possibly because the innermost edges are interacting. The extension of both lobes seems similar, about 25″ at P.A. = 45° and P.A. 90°; therefore, the interlobe time-lap must be very small.

4. DISCUSSION

When the star reaches the asymptotic giant branch thermal pulsating (TP-AGB) phase, it ejects its envelope to form a PN. The PN forms when a tenuous fast wind (∼1000 km s^{-1}) emitted by the PN central star interacts with the slow (∼10 km s^{-1}) and dense wind, ejected at the end of the AGB phase (the so-called "superwind"). In particular, it has been shown by means of hydrodynamical two-wind models that the interaction between symmetrical and asymmetrical stellar winds produces an asymmetrical nebula (Kwok 1982; Kahn 1983). The mechanisms that can account for an asymmetrical wind are the rotation of the central star and the presence of a binary companion (see Livio 1995). Another way to induce asymmetry in a PN is the presence of a toroidal magnetic field (see a review in Chevalier 1995).

The quadrupolar PNs in our sample have some very definite characteristics: (1) they have an enhanced waist; (2) they have two pairs of lobes of different elongations; and (3) the two pairs of lobes are off-axis of (projected) angles between about 40° and 60°. All these nebulae are definitely asymmetric, in the sense that each pair of lobes defines an equatorial plane that is perpendicular to the lobe axis. Thus, a mechanism for asymmetry to be induced is a necessary step toward our interpretation. Whatever this mechanism may be, it is associated with a mechanism that changes the axis of symmetry between two subsequent nebular ejections. Therefore, we have to investigate processes that produce two preferential planes. A common envelope scenario has to be ruled out, because this will only produce one preferential plane. In the next two sections we present the possible scenarios to explain the observed morphology.

4.1. *Triple System*

Stable triple systems are possible (Herczeg 1982), as long as the third star's orbit is more than 3.5 times the size of the smaller orbit. In this case, it may happen that the closest stars will undergo a common envelope (CE) phase, forming a disk. This disk will precess under the influence of the third star, and, if the star suffers two consecutive ejections, it will produce a quadrupolar PN. According to our survey, at least five PNs among the 244 are quadrupolar. This figure is obviously a lower limit to the real number of quadrupolar PNs, most of whose structures would be hidden because of their projection on the plane of the sky.

That means at least 2% of the PNs are quadrupolar. According to Batten (1978), at least 15% of the stars may have triple systems; therefore, the statistics seem reasonable. However, this possibility is doubtful at best, since in only one of the five quadrupolar PNs (M2-46) is a central star seen. Though extinction may be invoked as the reason why the stars are not seen, this is not the case for M4-14 and M1-75, where the central ring is not edge-on. It is hard to explain how up to four PNs have a triple system, when none of the stars are seen. Therefore, we believe that this explanation is hardly plausible, or at least cannot account for all the observed quadrupolar PNs.

4.2. *Precessing Star*

For the five PNs in our sample, there are indications of high N/O enhancement. In particular, M1-75 has one of the highest N/O abundance ratios ever found in a PN (Guerrero et al. 1995); M2-46 shows a N/O enhancement of over 6 times the solar value (Köppen, Acker, & Stenholm 1991); K3-24, M3-28, and M4-14 have [N II] λ6584–to–Hα line ratios of 1.6, 1.7, and 1.8, respectively (Acker et al. 1992). These values are among the highest found in PNs and indicate high nitrogen enhancement. There is a known correlation between high N/O ratios, bipolarity, and high progenitor masses larger than 2.4 $M_\odot$—the so-called type I PN (e.g., Peimbert 1978). Therefore, we can tentatively infer that all these quadrupolar PNs have progenitor stars with masses larger that 2.4 $M_\odot$. Calvet & Peimbert (1983) pointed out that such stars will have a high rotation velocity ($\langle v \rangle \sim 100$ km s^{-1}) and propose a model in which a toroid is formed in the equator of the star and a subsequent mass loss produces the bipolar shape. Bjorkman & Cassinelli (1993) have shown that the escape velocity drops at the equator of a rotating star, thus increasing the mass loss in the equator and forming a disk. This disk will collimate the mass loss, forming a bipolar lobe. This scenario has been modeled by Langer et al. (1996) for η Car, and the authors were able to reproduce the bipolar shape with a single star.

If the star or the disk is precessing, and if two shells are ejected within the precessing period, the four lobes that we see will form. In order to account for the precession, a external torque is needed. However, as we lack evidence that the central star belongs to a multiple system, we cannot know the origin of this external torque. In Figure 5 we envisage a possible geometrical scenario for the formation of quadrupolar PNs, where a binary companion provides the external force to produce the precession of the star, if rotating, or of the disk encircling the primary star. The orbital plane is perpendicular to the precession axis, while the rotation axis forms an angle α with the precession axis.

In the case of M2-46 we have a three-dimensional analysis of the nebular motions and a good indication of the time elapsed between ejections ($t \sim 2700$ yr). According to Figure 5, the aperture of the precession cone (α), the time (t), the

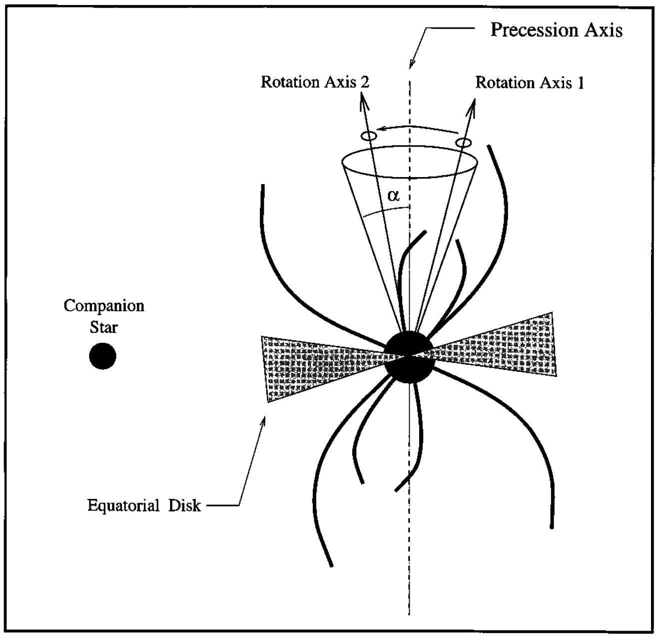

FIG. 5.—Proposed model for the formation of a quadrupolar nebula, see text for explanation.

angle between ejections ($\phi \sim 53°$), and the precession period (T) can be related as

$$\sin^2 \alpha \cos \left(2\pi \frac{t}{T}\right) + \cos^2 \alpha = \cos \phi . \qquad (1)$$

Therefore, the precession period is less than ~18,500 yr. When in a binary system one of the stars has a disk, the precession period of the disk can be expressed as

$$T = \frac{4}{3} (M_1 + M_2)^{1/2} \frac{d^3}{M_2 r^{1.5} \cos \alpha} , \qquad (2)$$

where M_1 and M_2 are the masses of the primary and secondary, respectively, in units of $M_\odot$, r is the disk radius, d is the binary separation in AU, and α is the precession angle. For a value of 8000 yr (which implies $\alpha = 30°$ according to eq. [1]), and assuming a radius of 100 $R_\odot$ for the equatorial disk and a primary star of 0.85 $M_\odot$, it is necessary to place a 0.30 $M_\odot$ secondary star at a distance of 8 AU from the primary. A Jupiter-like planet (~0.001 $M_\odot$) would need to be located at 1.3 AU.

We also have some independent indication that M1-75 was produced by a binary star (Guerrero et al. 1995). In conclusion, we state that the planetary nebulae M2-46 and M1-75 were generated by a precessing rotating star, for the latter the torque provided by the binary companion. More work needs to be done on the other objects of this morphological class for a sound interpretation.

Although models explaining quadrupolar morphology have never been developed, the precession of a source ejecting clumps of material has been used to explain the formation of point-symmetric PNs (Cliffe et al. 1995). Few other objects can be explained this way, the authors infer, and they give a list of a few PNs from the Corradi & Schwarz (1993) sample that are named bipolar/point-symmetric. We feel that the definition of bipolar/point-symmetric is confusing and that the point-symmetric PNs that show (symmetric) strings of clumps should have a different formation history than the quadrupolar PNs.

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