MENZEL 3: A MULTIPOLAR NEBULA IN THE MAKING

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Received 2004 April 23; accepted 2004 June 29

ABSTRACT

The nebula Menzel 3 (Mz 3) has arguably the most complex bipolar morphology, consisting of three nested pairs of bipolar lobes and an equatorial ellipse. Its three pairs of bipolar lobes share the same axis of symmetry but have very different opening angles and morphologies: the innermost pair of bipolar lobes shows closed-lobe morphology, whereas the other two have open lobes with cylindrical and conical shapes, respectively. We have carried out high-dispersion spectroscopic observations of Mz 3 and detected distinct kinematic properties among the different morphological components. The expansion characteristics of the two outer pairs of lobes suggest that they originated in an explosive event, whereas the innermost pair of lobes resulted from the interaction of a fast wind with the surrounding material. The equatorial ellipse is associated with a fast equatorial outflow, which is unique among bipolar nebulae. The dynamical ages of the different structures in Mz 3 suggest episodic bipolar ejections, and the distinct morphologies and kinematics among these different structures reveal fundamental changes in the system between these episodic ejections.

Key words: ISM: kinematics and dynamics — planetary nebulae: individual (Menzel 3)

1. INTRODUCTION

Menzel 3 (Mz 3), the Ant Nebula, is perhaps one of the most stunning bipolar nebulae. The Hubble Space Telescope (HST) color image presented by the Hubble Heritage Program (STScI-PRC01-05, PIs: B. Malick, V. Icke, R. Sahai, and J. T. Trauger) reveals a complex system of three nested pairs of bipolar lobes. These bipolar lobes are roughly aligned along the same axis of symmetry but have vastly different shapes, opening angles, and detailed morphologies. In addition, a faint ellipse of emission aligned along the equator of these bipolar lobes is seen. Not only is the morphology of Mz 3 complex, but its nature is also uncertain. While usually classified as a young planetary nebula (PN), Mz 3 has also been suggested to be a circumstellar nebula of a symbiotic star, based on the high density of its core (Zhang & Liu 2002), its near-IR colors (Schmeja & Kimeswenger 2001), and the spectrum of its central star.

Previous high-dispersion spectroscopic observations of Mz 3 have detected several pairs of bipolar lobes, and their kinematic properties led to the suggestion of episodic bipolar ejections (López & Meaburn 1983; Meaburn & Walsh 1985). More recently, Redman et al. (2000) reported the discovery of fast (500 km s⁻¹) collimated outflows. Detailed modeling of the structure of Mz 3 has been hampered by the limited detector sensitivity or sparse slit coverage of these previous observations. Therefore, we have carried out new long-slit, high-dispersion echelle observations of Mz 3, emphasizing particularly the morphological features that have not been observed previously. These echelle observations, combined with the high-resolution HST narrowband images and Chandra X-ray observations, allow us to produce a complete spatio-kinematic model of Mz 3, adequately representing the three pairs of bipolar lobes and the equatorial ellipse. While our results confirm the previous suggestion that the multipolar structure was produced by episodic bipolar ejections (López & Meaburn 1983; Meaburn & Walsh 1985), we are able to describe the kinematic properties and determine the formation process more precisely. This paper reports our new observations and analysis of the physical structure of Mz 3.

2. OBSERVATIONS

2.1. Archival HST Images

Narrowband WFPC2 images of Mz 3 in the Hα, Hβ, and [N ii] λ6583 emission lines were retrieved from the HST archive (Proposal identifications 6502 and 9050, PI: B. Malick, and Proposal identification 6856, PI: J. T. Trauger). The images used in this work are listed in Table 1 with their integration times, filters, and the location of Mz 3 on the WFPC2 (PC or WFC). These images were calibrated via the pipeline procedure, including the analog-to-digital correction, bias and dark-image subtraction, and flat-field correction. We removed the cosmic rays and combined different exposures obtained with the same filter using standard IRAF routines. The Hα and [N ii] images of Mz 3, displayed in Figure 1, are used to analyze the nebular morphology. The Hα-to-Hβ ratio map of Mz 3, shown in Figure 2 (left), is used to investigate the distribution of intranebular extinction.

2.2. Archival Chandra X-Ray Observations

The Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-Ray Observatory was used on 2002 October 23 to obtain a 40.8 ks exposure of Mz 3 (Observation identification: 2546; PI: J. H. Kastner). Mz 3 was positioned at the nominal aim point of the ACIS-S array on the back-illuminated S3 CCD. We retrieved the level 1 and level 2 processed data from the Chandra Data Center and further processed the data using the Chandra X-Ray Center software CIAO version 3.0.2 and the Calibration Data Base (CALDB) version 2.25. The background count rate is consistent with the
quiescent background\textsuperscript{4} for most of the observing time. Only two background “flares” of short duration occurred. After excluding these high-background periods from our analysis, the net exposure time was reduced to 39.6 ks. We used this dataset to extract an image in the 0.5–1.8 keV band at a resolution of $\sim 1'' 0$ and superposed the X-ray contours on the HST WFPC2 H$\alpha$ image in Figure 2 (right) to illustrate the relative distribution of X-ray-emitting gas and the ionized nebular material.

\begin{table}
\centering
\caption{Archival HST WFPC2 Observations of Mz 3}
\begin{tabular}{|l|c|c|c|}
\hline
Emission Line & Exposure Time (s) & Location & Program ID \\
\hline
H$\alpha$ & 350 & PC1 & 9050 \\
H$\alpha$ & 900 & WF3 & 6856 \\
H$\beta$ & 1300 & WF3 & 6502, 6856 \\
[N II] & 1300 & PC1 & 9050 \\
[N II] & 900 & WF3 & 6856 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{4} Reported by Markevitch (2001); available at http://cxc.harvard.edu/contrib/maxim/bg/index.html.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{MZ3_image}
\caption{HST WFPC2 images of Mz 3 in the H$\alpha$ (top) and [N II] $\lambda 6583$ (bottom) emission lines. The different morphological components of this nebula are marked as described in the text: BL1 are the inner bipolar lobes, BL2 are the cylindrical lobes, BL3 are the conical lobes, and EE is the equatorial ellipse. Both the H$\alpha$ and [N II] images are displayed at two intensity contrasts and spatial scales to highlight these different morphological components.}
\end{figure}
2.3. Echelle Observations

High-dispersion spectroscopic observations of Mz 3 were obtained on 2002 June 23 and 24 using the echelle spectrograph on the CTIO 4 m telescope. The spectrograph was used in the long-slit mode to obtain single-order observations of the Hα and [N ii] λ6548, 6583 lines for an unvignetted slit length of 3''. The 79 line mm⁻¹ echelle grating and the long-focus red camera were used, resulting in a reciprocal dispersion of 3.4 mm⁻¹. The data were recorded with the SITe 2K CCD with a pixel size of 24 μm. This configuration provides a spatial scale of 0''26 pixel⁻¹ and a sampling of 3.7 km s⁻¹ pixel⁻¹ along the dispersion direction. The slit width was set to 0''9, and the resulting instrumental FWHM was 8 km s⁻¹. The angular resolution, determined by the seeing, was better than 1''2.

The echelle observations were made with the slit oriented along different position angles and placed at various offsets from the central star, in order to sample the complex morphological features of Mz 3. The slit positions and exposure times of these observations are given in Table 2. Although both Hα and [N ii] lines are available, only the [N ii] λ6583 line is used to analyze the kinematics of Mz 3 because of its smaller thermal width. The echellograms of the [N ii] λ6583 line are presented in Figure 3, where an [N ii] image is also presented with the slit positions superposed.

3. RESULTS

The HST narrowband images of Mz 3 reveal three pairs of bipolar lobes and one elliptical feature along the equator of these lobes; they are marked in Figure 1 as BL1, BL2, BL3, and EE, respectively. These features are also detected in the echellograms and marked correspondingly in Figure 3. In §§ 3.1–3.4, we discuss detailed morphologies and kinematics and propose spatio-kinematic models for each of these structures in Mz 3.

### Table 2

| Offset (arcsec) | Position Angle (deg) | Exposure Time (s) |
|----------------|----------------------|------------------|
| 0…………………..| 8                    | 600              |
| 2 west…………… | 43                   | 900              |
| 0…………………..| 52                   | 900              |
| 3 north…………. | 98                   | 1800             |
| 4 south…………. | 98                   | 1800             |
| 8 south…………. | 98                   | 1800             |
| 14 south…………| 98                   | 1800             |
| 19 south…………| 98                   | 1800             |
| 26 south……….. | 98                   | 1800             |
| 0…………………..| -28                  | 900              |
Fig. 3.—The [N ii] λ6583 image (top left) and echellograms of Mz 3 along nine different slit positions. The slit positions of the echelle observations are superposed on the [N ii] image. The different morphological components of this nebula are marked on the echellograms. Note that the spatial scale of the image and echellograms are not coincident. Note also that velocities have been referred to the systemic velocity of Mz 3.
The [N ii] $\lambda$6583 image (left) and echellogram along P.A. 8° (right) of Mz 3. Both the image and echellogram have the same orientations and spatial scales to make a fair comparison easy. The arrows indicate the locations in the image and the echellogram of the knots at the tips of the innermost bipolar lobes described in the text. Contrast in the image has been chosen to highlight these features.

derived from the Hα/Hβ ratio map shown in Figure 2 (left), support this hypothesis: the Hα/Hβ ratio is higher on the northern lobe than on the southern lobe, and therefore extinction toward the northern lobe is higher, indicating larger amounts of intervening material. In addition to the surrounding material that obscures the northern BL1 lobe, the central star of Mz 3 is embedded in a thick, extended shell detected through the mid-infrared emission of dust (Quinn et al. 1996).

This Hα/Hβ map discloses additional clues on the distribution of absorbing material within Mz 3. Hα/Hβ, i.e., the extinction, is especially enhanced at the projected edge of the lobes and along the bright optical filaments, suggesting that the expanding lobes carry large amounts of dust and suffer from self-absorption. In agreement with Smith’s (2003) conclusions based on the different amounts of extinction derived from infrared H i and [Fe ii] lines, we conclude that a significant fraction of the extinction toward Mz 3 is local rather than interstellar. The local nature of the extinction in Mz 3 and its nonuniform distribution affects the morphology of the diffuse X-ray emission, which is anticorrelated with the amount of extinction (Fig. 2), as typically observed in other PNe (Kastner et al. 2002).

To determine the dynamical age and inclination of the polar axis for each of the BL1 lobes, the shell morphology and position-velocity relation need to be analyzed and modeled quantitatively. We have adopted a simple expression to approximate the radial expansion velocity of an hourglass as a function of the latitude angle, $\theta$ (Solf & Ulrich 1985):

$$v(\theta) = v_e + (v_p - v_e) \sin(|\theta|)^{\gamma},$$

where $v_e$ and $v_p$ are the expansion velocities at the equator and pole, respectively, and the exponent $\gamma$ sets the lobe geometry. We have also assumed a homologous expansion so that

$$r(\theta) = v(\theta)\Delta t,$$

where $\Delta t$ is the time since the lobe was formed.

Using the model outlined above, we have determined $v_e$ and $v_p$, the age, the exponent $\gamma$, and the inclination with respect to the sky and P.A. of the symmetry (polar) axis of each of these bipolar lobes. The best fits for the southern and northern BL1 lobes are shown in Figure 5, and the parameters of these fits are listed in Table 3. As expected from the different morphological and kinematic properties of the southern and northern lobes, the best-fit parameters to each lobe are not exactly the same, although both fits have similar inclination of the symmetry axis with respect to the plane of the sky, 15°–20°, and kinematic age, $^5 600 \pm 50(D/kpc)$ yr, where $D$ is the distance in kiloparsecs to Mz 3.

If the bright knots at the tip of the bipolar lobes share their inclination angle, then the true deprojected velocity of these knots is in the range between 90 and 150 km s$^{-1}$. For comparison, we have also included in Table 3 the parameters of the best fit to the northern lobe, considering the extension and kinematics of the converging blister at its polar cap. The shorter kinematic age of the northern lobe when its blister is considered is suggestive of acceleration of the gas motions caused by a blowout process.

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$^5$ The distance to Mz 3 is highly uncertain. Hereafter we have chosen to show explicitly the dependence of the kinematic age on distance.
3.2. BL2: The Cylindrical Bipolar Lobes

The bipolar lobes of BL2, the outer bipolar lobes 1 (OBL1) in Redman et al. (2000), have an almost rectangular morphology, with the P.A.s of the western and eastern edges having a difference as small as ~5° (Fig. 1). The lobes have a width of ~24″ and a length up to ~85″ for the northern BL2 lobe, i.e., the aspect ratio is 7:1. Their edges are rather straight, bending inward only at the location where these lobes contact the inner BL1 lobes. The detailed morphology of BL2 shows a complex system of long filaments extending radially outward. These filaments originate from a collection of knots at the base of the BL2 lobes that form a cavity-like structure just outside the BL1 lobes (Fig. 4).

The [N ii] echellogram of the BL2 lobes along P.A. 8° (i.e., roughly the BL2 symmetry axis) shows two velocity components with a velocity gradient of ~1.1 km s⁻¹ arcsec⁻¹ (Fig. 2). The difference in velocity between these two components, ~110 km s⁻¹, does not change significantly with the position along the symmetry axis of these lobes. Along the orthogonal direction, the echellograms at P.A. 98° and offset 14″, 19″, and 26″ show hollow position-velocity ellipses in BL2 (Fig. 2). Material in these lobes is thus mostly confined in the thin walls of hollow cylinders. This material cannot just flow along the walls of the cylinder, as a cross section of such a cylinder would have exactly the same observed velocity. Instead, the apparently constant velocity split implies that the section of the cylinder expands with a constant ~55 km s⁻¹ expansion velocity. Meanwhile, the velocity along the walls increases with the distance from the central star and must be faster than the transversal velocity; otherwise the lobes would not show the high aspect ratio, ~7:1, that characterizes them.

The Hubble law–like expansion of the BL2 lobes suggests that these lobes were made in a single, explosive event. As the difference in velocity between the blue- and redshifted components at a given location of BL2 is the same, ~110 km s⁻¹, the kinematic age of BL2 can easily be derived assuming that the 24″ width of BL2 is simply due to expansion along this direction. The kinematics are well reproduced using a cylinder tilted with respect to the plane of the sky with fixed 55 km s⁻¹ expansion velocity across its section and linearly increasing velocity along the walls (Fig. 6). The best-fit model has an inclination of 20° ± 5° against the sky plane, in agreement with the previous value reported by Meaburn & Walsh (1985), and a kinematic age of 1000 ± 100(D/kpc) yr. At the maximum distance of 85″ from the central star of Mz 3, the deprojected expansion velocity is ~320 km s⁻¹.

3.3. BL3: The Conical Lobes

We have named the pair of bipolar lobes with conical shape BL3, called the outer bipolar lobes 2 (OBL2) by Redman et al. (2000). These lobes have an opening angle of ~50°, and their limbs point directly to the central star of Mz 3. In the images in Fig. 1, the conical lobes BL3 are composed of multiple knots with long, radial tails stretching out up to 60″ from the central star of Mz 3. The distribution of these knots and filaments is looser than that of the filaments in BL2. Indeed, the knots and filaments in BL3 look disconnected, more like individual streams of material than part of a continuous structure.

Further information on the kinematics and structure of BL3 can be derived from the echellograms at P.A.s 43°, 52°, and ~28° through the central star and at P.A. 98° and offset 14″, 19″, and 26″ to the south of the central star of Mz 3 (Figs. 3 and 7). In the echellograms at P.A.s 43°, 52°, and ~28°, the knots and filaments composing BL3 appear as tilted straight features with different slopes on the position-velocity space. The structure and kinematics of BL3 in these echellograms is somehow confused by that of BL2, but the echellograms at P.A. 98° resolve unambiguously BL3 from BL2. In these echellograms, the velocities of the knots and filaments of BL3 are mostly distributed, but not completely confined, along ellipses. The radial velocities of these ellipses, as well as the velocity differences between their red- and blueshifted sides, increase radially from the central star of Mz 3. The distribution in the position-velocity space of these knots and filaments suggests that, unlike BL2, material in BL3 is not completely

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**TABLE 3**

| Fit of the Physical Parameters of BL1 |
|--------------------------------------|
| Bipolar Lobe, t_p (km s⁻¹), t_v (km s⁻¹), i (deg), P.A. (deg), Kinematic Age (yr) |
|--------------------------------------|
| Southern lobe, .......... | 100, 15, 15, 8, 600 |
| Northern lobe, .......... | 80, 15, 20, 12, 600 |
| Northern lobe and blister, .. | 140, 15, 20, 10, 520 |

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6 Actually, these are not cylinders, as they open gradually with distance from the central star, but the angle of divergence, ~5°, is too small to affect significantly the model fits.
Fig. 6.—Some \([\text{N} \text{ ii}] \lambda 6583\) echellograms of Mz 3 along selected slit positions marked on the figure. The echellograms are superposed by the position-velocity plots derived from the best model fit for the cylindrical bipolar lobes BL2 described in § 3.2.

Fig. 7.—Some \([\text{N} \text{ ii}] \lambda 6583\) echellograms of Mz 3 along selected slit positions marked on the figure. The echellograms are overlaid by the position-velocity plots derived from the best model fit for the conical bipolar lobes BL3 described in § 3.3.
confined to the walls of the conical lobes. This is illustrated by the feature seen in the echellograms at P.A. 98° and offset 14″ and 19″ south at relative position about −15″ and $(v - v_{sys})$ about −100 km s$^{-1}$ (Figs. 2 and 7). This feature looks like a small velocity ellipse whose spatial size and difference in velocity increase from the echellogram at offset 14″ south to that at 19″ south, suggesting that this filament is opening into a conical structure.

The kinematics of the knots and filaments of BL3 derived from these echellograms show that their expansion velocity follows a Hubble law. We have modeled the kinematics of the BL3 lobes, assuming that they have a conical shape with opening angle $\sim 50°$ and that the expansion velocity is directed along the walls of the cone and increases linearly outward from the central star of Mz 3. Following this model, we have fit the observed kinematics (Fig. 7) and derived an inclination angle of the symmetry axis with the plane of the sky of $12° \pm 3°$. The deprojected expansion velocity at 60° from the central star would be $180 \pm 30$ km s$^{-1}$, and the kinematic age of BL3 is $1800 \pm 200$ (D/kpc) yr. The inclination angle and kinematic age derived from this fit have greater uncertainty than those fitting BL1 and BL2, because the discrete nature of BL3 makes difficult to judge the goodness of the fit and to determine the best-fit parameters.

3.4. EE: The Equatorial Ellipse

The HST images of Mz 3 displays an additional feature unnoticed in previous images, a closed ellipse with size $82″ \times 32″$ oriented along P.A. $\sim 85°$, i.e., almost along the nebular equator (Fig. 1). This structure, referred to as the Equatorial Ellipse (EE), is delineated by filamentary arcs especially prominent at the northeast and southwest of Mz 3.

EE is revealed as dramatic high-velocity arcs in the echelette observations along the slits oriented at P.A. 98° and offsets 3″ north and 4′, 14′, and 19′ south of the central star, as well as in the slits at P.A.s 8′, 52′, 43′, and −28′ (Fig. 3). The measured expansion velocity is close to $200$ km s$^{-1}$ with respect to the systemic velocity. It is interesting to note that the arcs in the echellograms of the slits passing through the central star are disrupted by radial filaments of BL3. It is also interesting to note that the arcs detected in the echellograms at P.A. 98° and offsets 3″ north and 4″ south show marked point symmetry.

It is clear from these results that Mz 3 shows an equatorial outflow moving at high velocity. Its three-dimensional geometry, however, is difficult to envision because of the fragmented information revealed by the observations and the likely interaction of EE with BL3. In the following, we consider four different geometrical models for this outflow: (1) an extended equatorial disk, (2) a ring collimating a bipolar ejection, (3) a pair of wide-opened bipolar lobes, and (4) an oblate ellipsoid-like shell.

Although equatorial disks have been proposed to play an important role in the collimation of bipolar PNe, there is no detection of high-velocity equatorial disks in PNe. An example of equatorial disk can be found in the bipolar nebula around η Car, which shows an equatorial structure that seems to be an extended equatorial disk (Smith 2002). If EE in Mz 3 were a circular equatorial disk, then the expansion law with radius on the disk can be inferred from any echellogram of a slit passing through its center simply by applying a scaling factor that depends on the inclination of the disk with respect to the line of sight, because all velocities along such a line share the same inclination angle with the line of sight. For a circular disk, its inclination angle can be derived from the observed minor-to-major axes ratio of the projected ellipse. The size of EE of $82″ \times 32″$ corresponds to an inclination against the plane of the sky of the rotation axis of the circular disk of $\sim 23°$. Using this value for the inclination of the disk and the information on the expansion velocity law on the slit at P.A. 52° passing through the center of Mz 3, we have determined the expansion law with radius on the disk, which is plotted in Figure 8. The velocity in the disk decreases smoothly with radius up to a given radius, where the velocity decreases sharply. Using this velocity law, we have produced the position-velocity plots expected for significant slit positions (Fig. 9). The model deviates significantly from the position-velocity arcs observed along P.A. 98° with different offsets from the central star (Fig. 9). We conclude that EE cannot be interpreted as an expanding disk.

A detailed study of the spatio-kinematic properties of an expanding ring collimating a pair of bipolar lobes is presented by Solf & Ulrich (1985) for the bipolar nebula around the symbiotic Mira variable R Aqr. In an expanding ring, the ring itself projects an ellipse onto the sky, long-slit echellograms along the ellipse major axis show two arcs in the position-velocity space, one shifted to the blue and the other to the red, and long-slit echellograms along the ellipse minor axis reveal a characteristic hourglass-shaped line. The morphology and kinematics of Mz 3 observed in the echellograms of the slits along P.A. 98° are compatible with these model expectations; however, the slit at P.A. 98° and offset 26″ south of the central stars does not detect emission outside the observed ellipse, nor do the slits at P.A.s 52°, 43°, 8′, and −28′ show the expected hourglass shape. We conclude that an expanding ring that collimates bipolar lobes is not appropriate for the three-dimensional geometry of EE.

We have also considered the possibility that EE is composed of a pair of wide-open, champagne-glass–shaped bipolar lobes tilted with respect to the line of sight so that the flow vector points almost directly to us at the location of the equatorial waist. This model would explain the observed kinematics: at locations near the central star, the observed velocity is large because the line of sight is close to the direction of the flow vector, whereas at increasing distances from the central star, the lobes bend and close so that the direction...
of the flow vector diverges from the line of sight and the observed velocity decreases. The projection of these lobes onto the plane of the sky, however, would not produce an elliptical shape, but two intertwined arcs pointing at opposite directions, as observed, e.g., in the central regions of MyCn 18 (Sahai et al. 1999). We thus disregard this model as the three-dimensional geometry of EE.

Finally, we consider an oblate shell that expands much faster along the equator than along the poles and whose symmetry axis is close to the plane of the sky. Assuming a homologous expansion for this shell, we have produced synthetic position-velocity plots that can be compared with the observed ones to determine the best-fit parameters (Fig. 10). The best-fit shell model is a flat ellipsoid whose symmetry axis is tilted against the line of sight by 70° ± 5°, and the ellipsoid has an equatorial expansion velocity \( \approx 200 \text{ km s}^{-1} \), a polar velocity \( \approx 70 \pm 20 \text{ km s}^{-1} \), and a kinematic age 1000 ± 50(D/kpc) yr. This model satisfactorily explains the high-velocity arcs observed in the slits at P.A. 98°. It also accounts for the disruption of EE by BL3, which has bored a hole near the polar regions of EE. Finally, this model also explains the point-symmetric distribution of arcs observed in the slits at P.A. 98° and offsets 3° north and 4° south; at these locations, the detectability of the shell is optimized because the shell is seen tangentially and the optical path is thus larger than at other locations.

4. THE MULTIPOLAR STRUCTURE OF MZ 3

Previous spatio-kinematic studies of Mz 3 have revealed an increasing level of complexity in this nebula. López & Meaburn (1983) studied the inner bipolar lobes (BL1) and concluded that these lobes are hourglass-shaped with the symmetry axis close to the line of sight. In a later paper, Meaburn & Walsh (1985) determined with greater accuracy a spatio-kinematic model of the inner bipolar lobes. Moreover, they extended the spatio-kinematic study of Mz 3 to the outer regions, reporting the presence of different sets of bipolar lobes. The low spatial resolution of the narrowband images available by then, however, hampered Meaburn & Walsh’s study: the bipolar lobes BL2 and BL3 were not distinguished from each other; the equatorial ellipse was interpreted as an additional bipolar lobe; and the detection of a high-velocity component in the Na i line, correctly interpreted as related to a high-velocity outflow from Mz 3, was not associated to the equatorial ellipse EE. More recently, Redman et al. (2000) obtained high-dispersion spectroscopic observations along the major axis of Mz 3 that allowed them to describe the kinematics of the bipolar lobes BL2 and to find high-velocity (\( \sim 200 \text{ km s}^{-1} \)) components at the location of the blowout at the tips of the inner bipolar lobes BL1. Because of the limited spatial coverage of their study, the association between these high-velocity kinematic components and the equatorial ellipse EE was not as clearly seen as evidenced in our echelle observations obtained at different slit positions (Fig. 3). Finally, in a simultaneous study of Mz 3, Santander-García et al. (2004) have derived spatio-kinematic models and kinematic ages for the three pairs of bipolar lobes that are in complete agreement with those derived here.

The present study reconciles many of the previously reported kinematic features of Mz 3 into a more comprehensive view of its physical structure. Mz 3 consists of four distinct structures, an oblate ellipsoid-like shell and three pairs of bipolar lobes with almost coincident symmetry axes. The properties of these structures are especially singular among similar structures observed in bipolar PNe. Unlike the slowly expanding rings, or tori, observed in some bipolar PNe, the oblate ellipsoidal shell expands at high velocity along the equator of the bipolar lobes. Similarly, very few multipolar PNe have pairs of lobes exhibiting the notable differences in opening angle, morphologies, and detailed small-scale structures as the three pairs of bipolar lobes of Mz 3: BL1 has hourglass-shaped expanding bubbles filled with X-ray-emitting hot gas (Kastner et al. 2003), while BL2 and BL3 are composed of knots and filaments following a Hubble flow with cylindrical and conical shapes, respectively.

Multipolarity has become a common feature among bipolar nebulae. A growing number of bipolar nebulae have been noted to have multiple systems of bipolar lobes either sharing the
same symmetry axis or having different symmetry axes, e.g., M2-9, M2-46, NGC 2440, and Hen 2-104 (Hora & Latter 1994; Manchado et al. 1996; López et al. 1998; Solf 2000; Corradi et al. 2001). Among these multipolar nebulae, the case of Mz 3 is of special interest because the kinematic ages of the different systems of bipolar lobes in Mz 3 are small and of the order of the difference in kinematic ages among them. The inner bipolar lobes BL1 have a kinematic age $500\pm600$ (D/kpc) yr, the cylindrical lobes BL2 and the equatorial ellipsoid EE are $\sim1000(D/kpc)$ yr old, and the outer bipolar lobes BL3 have a somewhat more uncertain kinematic age of $\sim1800(D/kpc)$ yr. Mz 3 is thus a multipolar nebula in the making, where BL1 corresponds to the most recent ejection from Mz 3 central star, EE and BL2 are older and probably coeval, and BL3 is finally the oldest structure, although its kinematic age is the most uncertain and we cannot rule out a formation closer in time to that of BL2.

The different kinematic properties of the three pairs of bipolar lobes suggest distinct formation scenarios. The ballistic motion of the two outermost bipolar lobes of Mz 3, BL2 and BL3, indicates that the gas within these lobes expands freely under its own inertia. Most likely, these lobes are the result of two episodes of explosive mass ejection or outbursts that occurred $\sim1800(D/kpc)$ and $\sim1000(D/kpc)$ yr ago. The last episode of mass ejection responsible for BL2 also resulted in high-velocity ejecta along the equatorial plane that formed EE, the equatorial ellipse. On the other hand, the morphology and hot gas content of the innermost pair of lobes, BL1, indicate that they resulted from the interaction of highly pressurized hot gas with the surrounding material. This hot gas may be produced by the onset of a fast stellar wind. An alternative origin has been proposed by Kastner et al. (2003), who attribute the X-ray emission to the action of an X-ray jet along the symmetry axis of Mz 3. Our observations indeed reveal bipolar collimated outflows along the symmetry axis of Mz 3 (the knots further away the leading edges of the BL1 lobes as seen in Fig. 4) but not with the high velocities required to produce the observed X-ray emission. Note, however, that the outflow detected in our observations may trace high-density material accelerated by a much higher velocity jet that, being responsible for the X-ray emission, would elude optical detection because of its low density.
The oblate shell forming the equatorial ellipse EE of Mz 3 is a very singular structural component. Many bipolar PNe show equatorial disks or tori, but all of them have modest expansion velocities, ~30 km s$^{-1}$. Bipolar nebulae around symbiotic stars also show equatorial disks or tori, but their expansion velocities are modest too. The only exception among symbiotic stars is the remarkable elliptical shell or ring around H$\text{en}$ 2-147 with an expansion velocity ~100 km s$^{-1}$ (Corradi et al. 1999). Thus, the $\simeq$200 km s$^{-1}$ equatorial outflow in Mz 3 is the most extraordinary among bipolar PNe and nebulae around symbiotic stars.

The equatorial outflow of Mz3 rivals that of the massive star $\eta$ Car. The equatorial outflow around $\eta$ Car shares many similarities with that found in Mz 3: the nebula around $\eta$ Car has several systems of bipolar lobes (Ishibashi et al. 2003), and the formation of the equatorial outflow has been timed during or around the moment when the main bipolar lobes in $\eta$ Car, the Homunculus Nebula, were formed. Despite these similarities, the equatorial outflows in both nebulae are notably different. The equatorial outflow in $\eta$ Car has been described as an extended equatorial disk expanding with velocity proportional to the angular distance to center (Davidson et al. 2001; Smith 2002), whereas the physical structure of the equatorial outflow in Mz 3 is best described by an oblate shell. Furthermore, their detailed morphologies are different and very likely indicate different origins: in $\eta$ Car, the equatorial outflow seems to be composed of multiple jetlike features located along the equatorial plane, whereas in Mz 3 the equatorial outflow shows the limb-brightened morphology characteristic of a thin shell.

The formation of multipolar nebulae can be explained as the result of recurrent outbursts as those observed in massive stars in binary systems during the luminous blue variable (LBV) phase, e.g., $\eta$ Car. In low-mass stars, recurrent outbursts can be related to nova-like eruptions on the accreting hot component of a symbiotic star or to structural instabilities in the late evolution of the central star of a PN (e.g., thermal pulses). In symbiotic novae, the timescales of successive outbursts are determined by the mass of the accreting white dwarf, the mass-loss rate of the red giant, and the accretion efficiency of the wind capture, which is related to the binary interaction (e.g., Prialnik & Kovetz 1995). Recurrence periods of a few hundred years are typical of symbiotic novae (Prialnik & Kovetz 1995; Corradi et al. 1999). The formation of multipolar PNe is far more difficult to explain, as it requires the alternation between a dense, slow wind and a fast, tenuous wind. The evolution of the central star of the PN in a binary system provides a natural scenario for recurrent outbursts during the evolution through a common envelope phase or as the result of accretion and nova-like outbursts on the white dwarf component of a symbiotic star. This raises the similarities between Mz 3 and other symbiotic stars like R Aqr and Hen 104, or other suspected symbiotic stars yet classified as PNe, e.g., M2-9, and casts doubts on the true nature of Mz 3 as a PN.

Even if we accept that Mz 3 has formed as the result of recurrent nova-like outbursts in a symbiotic star, the physical structure of this bipolar nebula is rather unique. The successive collimated ejections in Mz 3 are rather regular in time, but they have very different morphological and kinematic properties, which suggest very distinct conditions and formation mechanisms. In Mz 3, we are thus witnessing the formation of a multipolar nebula that evolves dramatically between periodic outburst episodes.

M. A. G. and L. F. M. acknowledge support from the grant AYA 2002-00376 of the Spanish MCyT (cofunded by FEDER funds). We thank Miguel Santander Garcia for providing us with the results on their spatio-kinematic modeling of Mz 3 before publication. We also thank the referee, Matt Redman, for his valuable comments.

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