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Bow-shocks and possible jet-shell interaction in the planetary nebula M 2-48

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Abstract. Deep narrow band CCD images in the Hα, [O III] $\lambda 5007$ Å, [N II] $\lambda 6584$ Å, and [S II] $\lambda 6717 + 31$ Å emission lines have been obtained for the planetary nebula M 2-48. The discovery of a pair of symmetric low-excitation bow-shocks, separated by $4'$, and forming a highly collimated bipolar outflow, is presented. The bow-shocks are emitting in [O III] and present the ionization structure expected from working surfaces of collimated jets, pointing out that these structures are tracing regions with shocked gas at high velocities (> 100 km s^{-1}). In addition, an internal bipolar outflow ($60'' \times 30''$) and an apparent off-center semi-circular shell (size $\approx 110''$) are also detected. An enhancement of low-excitation line emission is observed in the shell along the outflow axis. This result can be interpreted in terms of a jet-shell interaction.

Key words: ISM: jets and outflows – ISM: planetary nebulae: individual: M 2-48

1. Introduction

In the last few years, observations of Planetary Nebulae (PNe) have shown new morphologies shaped by microstructures. These observations have modified our knowledge on the formation and evolution of the PNe (e.g. Miranda & Solf 1992; Balick et al. 1994; see López 1997 and Miranda 1999 for reviews). M 2-48 (PN G 062.4-00.2; α_{2000}=19:50:28, δ_{2000}=25:54:28) is a bipolar ($60'' \times 30''$) Planetary Nebula (PN), whose morphology seems to contain such microstructures. In fact, in the IAC Catalog of PNe (Manchado et al. 1996), we note the presence of a remarkable structure located at a distance of $\approx 60''$ from the central star and oriented almost along the major axis of the nebula (PA$\sim 70°$). Although this structure is faint, it looks like a bow-shock with the concave side facing the central star. This structure, which is clearly observed in [N II], is weaker in Hα, and apparently absent in [O III], suggests the existence of a collimated outflow in M 2-48. The possible presence of a bow-shock in M 2-48 presents great interest. Collimated outflow components in PNe appear as compact knots or elongated filamants (e.g., López et al. 1993; Miranda 1995; Corradi et al. 1996; Hajian et al. 1997; Guerrero et al. 1999), but bow-shocks are very rare, and only some cases have been recognized by means of spectroscopic observations (e.g., Schwarz 1992; Solf 1994; López et al. 1997).

In this paper we show deep CCD narrow-band images in the light of Hα, [N II], [O III], and [S II], carried out in order to study in detail the nebular structure and, in particular that of the bow-shock. Our data reveal new aspects of M 2-48 among which the detection of an extended and highly collimated nebular structure, the presence of bow-shocks and the possible interaction of this collimated structure with a circular shell, are the most outstanding results.

2. Observations and results

A first set of deep narrow-band images of M 2-48, in the light of Hα (15 Å HPBW), [O III] $\lambda 5007$ Å (25 Å HPBW) and [N II] $\lambda 6584$ Å (19 Å HPBW) were obtained in 1998 July 9, with the 2.2-m telescope at Calar Alto Observatory[1], using the Calar Alto Faint Object Spectrograph (CAFOS). A Loral CCD with 2048×2048, 15 μm (0.33 arcsec) square pixels was the detector. Exposure times were 1800 s in each filter. 'Seeing' varied between 1.3 and 1.5 arcsec during the observations. Images were reduced in the standard manner using IRAF and they are shown in Fig. 1. The small boxes show contour plots of the internal structure as seen in each filter.

A second set of images in the light of Hα (20 Å HPBW), [O III] $\lambda 5007$ Å (10 Å HPBW), [N II] $\lambda 6584$ Å (10 Å HPBW) and [S II] $\lambda 6724$ Å (20 Å HPBW) were obtained in 1999 May 20 and 22, with the 2.1-m UNAM telescope at the San Pedro

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[1] The Calar Alto Observatory is operated by the Max-Planck-Institut für Astronomie (Heidelberg) and the Spanish Comisión Nacional de Astronomía.

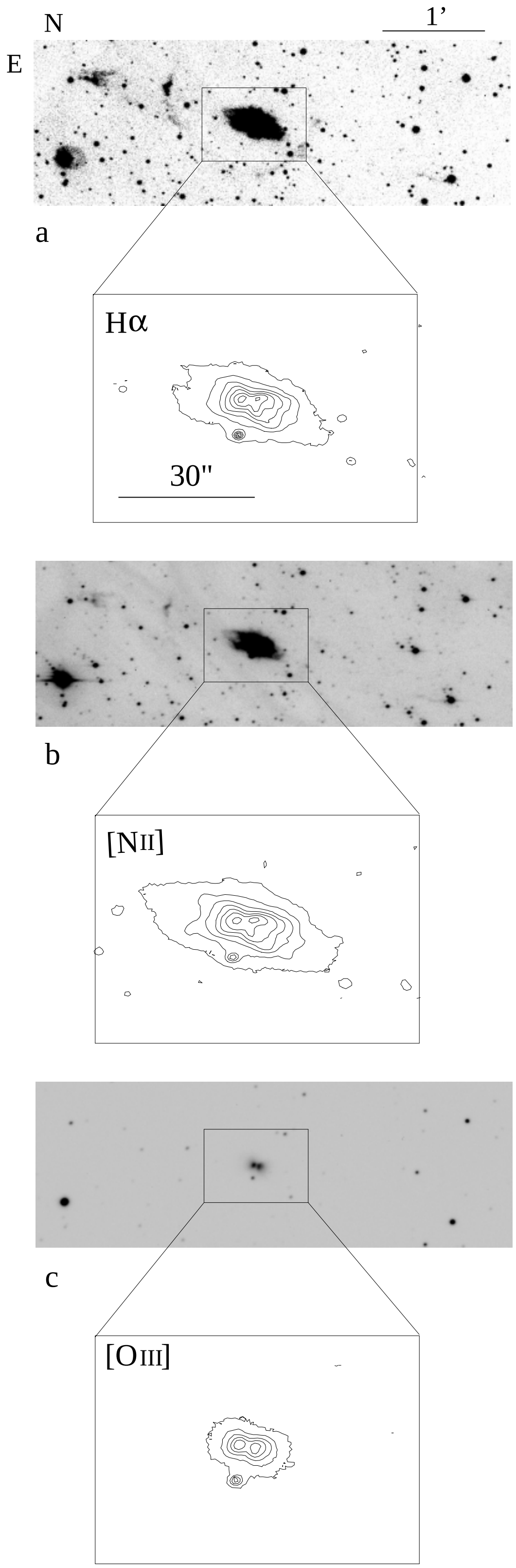

Fig. 1a–c. CCD images taken in the Calar Alto Observatory and contour plots from the central region in the light of: Hα **a**, [N II] $\lambda6584$ Å **b**, and [O III] $\lambda5007$ Å **c**. Levels in contour plots correspond to differences of $\log\sqrt{2}$ in the relative intensity. North is up, and East is to the left.

Mártir Observatory[2], using the UNAM Scanning Fabry-Pérot Interferometer (PUMA; Rosado et al. 1995) in its direct image mode. Exposure times ranged from 600 to 1500 s. A Tektronix CCD with 1024×1024, $24\,\mu$m (0.6 arcsec) square pixels, was used in the binning modes 1, 2, and 4. In this case, 'seeing' varied from 1 to 1.5 arcsec during the observations. Combinations of images in all these modes, giving a 4-binned final image for each filter (2.4 arcsec per pixel), are presented in the image mosaic of Fig. 2. In these images, the field was partially star-cleaned, in order to better show the nebular structures. Stars were not removed if they were inmersed in, or close to, nebular emission regions. A contour map of the [N II] image is shown in Fig. 3 in which some of the most important morphological features are labeled.

The images in Figs. 1 and 2 reveal two bow-shock-like structures, labeled B1 and s1 (Fig. 3), towards the northeastern side of the main nebula (central region). s1 corresponds to the feature observed in the IAC Catalog (see below), whereas B1 has been detected in these images for the first time. B1 is located near the major axis of the main nebula at an angular distance of $\approx 2'$ from the central star. Remarkably, it is detected not only in Hα and [N II], but also in [O III] and [S II]. In all filters, the two "wings" of the bow-shock B1 can clearly be distinguished as well as an enhancement of the emission at the apex. Towards the shoutheastern side, a counterpart of B1, labeled B2, can be recognized in the Hα, [N II] and marginally in [O III] by the presence of faint emission "wings". Unfortunately, a bright star at the position of the expected apex of B2 prevents a complete view of this feature. The images also show that B1 and B2 are not isolated features but they are connected to the main nebula by faint emission detected in Hα, [S II] and [N II]. In fact, this faint emission and B1–B2 trace two narrow and extended lobes, each with a collimation degree of $120''/30'' = 4$.

The feature s1 is located at $\approx 1'$ from the center and does not appear to have a counterpart towards the southwest. It corresponds to the isolated bow-shock-like structure observed in the images by Manchado et al. (1996). However, Figs. 1 and 2 show that s1 is a part of a group of small emission clumps (s2, s3, s4, and s5) and faint nebular arcs, whose spatial distribution apparently traces an off-center semi-circular shell of $\approx 110''$ in diameter. This feature is observed in Hα and [N II] and could be present in [S II], though very faint. In Fig. 3 we show an eye-fitting of this shell.

Finally, the main, internal structure of M 2-48 is a bipolar shell, $60'' \times 30''$ in size, consisting of two lobes separated by a faint region. The lobes appear to be open and connected with the extended and highly collimated lobes defined by B1–B2.

3. Discussion

Our deep images of M 2-48 have revealed the existence of three main structural components in this nebula: a pair of symmetric bow-shocks located at the apex of two highly collimated bipolar

[2] The Observatorio Astronómico Nacional (OAN) is operated at the Sierra de San Pedro Mártir (México), by the Instituto de Astronomía, UNAM.

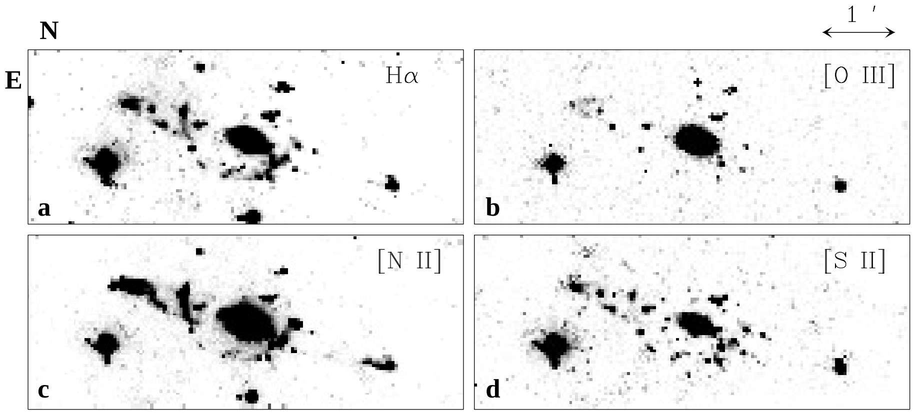

Fig. 2a–d. 4-binned images of M 2-48 in: Hα **a**, [O III] λ5007 **b**, [N II] λ6584 **c**, and [S II] $\lambda 6717+31$ **d**. North is up, and East is to the left.

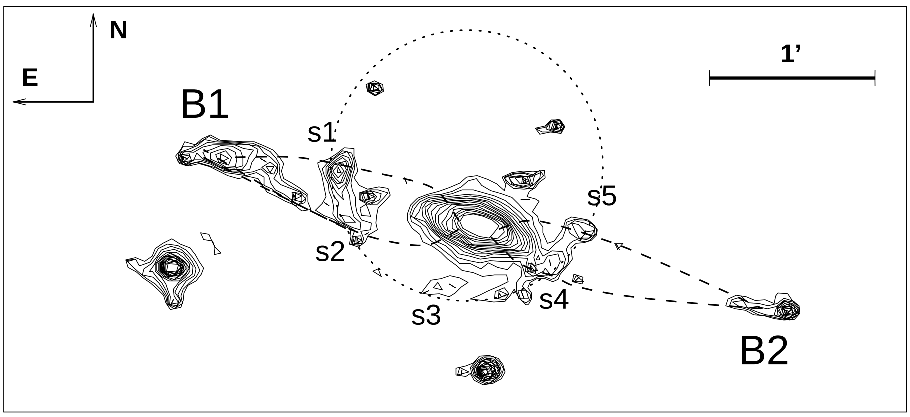

Fig. 3. Contour plot of the [N II] emission of M 2-48. The main morphological features are labeled, and the structures are marked with dashed lines (the two lobes and the off-center semi-circular shell). The map has logarithmic levels separated each one by $\log 2$. North is up, and East is to the left.

lobes, an off-center semi-circular shell, and an internal bipolar structure.

The images suggest that B1 and B2 are of low-excitation. This is confirmed by the [N II] λ6583/Hα line intensity ratio of $\simeq 3$ obtained by Acker et al. (1992) for the bipolar shell and the relative intensity of the nebular components. In particular, a very strong [N II] emission in B1 and B2, compared with Hα, can be inferred from the images. In this respect, B1 and B2 present the low-excitation typically observed in collimated components in PNe (see references above). However, [O III] emission is also detected, indicating that B1 and B2 correspond to high-velocity shocked regions ($V_{\rm s} > 100\,{\rm km\,s^{-1}}$; Hartigan et al. 1987). Moreover, B1 is noticeably wider (perpendicular to the flow axis) in [O III] than in [S II] and even in Hα. In addition, the "wings" of B1 are shorter (along the outflow axis) in [O III] than in the other low-excitation emission (e.g. [S II]). These results agree with the ionization structure in a bow-shock in which one expects a high-excitation region around the apex surrounding a low-excitation region and a decrease of the excitation at large distances from the apex. From these comments we suggest that B1 and probably also B2 trace the working surfaces of highly collimated, high velocity bipolar jets.

The morphology of M 2-48 closely resembles that in other bipolar PNe such as M 1-16 (Schwarz 1992), He 3-1475 (Bobrowsky et al. 1995; Riera et al. 1995), or the features A1–A2 in KjPn 8 (López et al. 1995; López et al. 1997). In all these cases, high-dispersion spectroscopy indicate the presence of highly collimated outflows involving high-velocity shocks ($V_{\rm s} > 200\,{\rm km\,s^{-1}}$). In particular, the bow-shocks A1–A2 in KjPn 8 also present enhanced [O III] emission (López et al. 1995).

With regard to the apparent semi-circular shell, the images show that it is also a low-excitation feature. Moreover, enhancement of low-excitation emission is observed in the shell mainly along the major nebular axis and in regions apparently coinciding with the highly collimated lobes (Fig. 3). This result suggests an interaction between the jet and the shell with s1, s2, s4, and s5 representing the contact zones and gives further support to the possibility that this apparent shell is a real structure. Evidence for interaction between collimated outflows and shells has also been reported towards other PNe, such as NGC 6572 (Miranda et al. 1999), NGC 4361 (Vázquez et al. 1999) and NGC 6891 (Guerrero et al. 2000).

We propose a scenario in which the formation of the jets in M 2-48 was produced in a subsequent event, after the shell was expelled. In fact, the large radius of the shell, as compared to the size of the main nebula, suggests that it is probably related with mass loss through a slow wind in the AGB stage of the progenitor. Rough estimates for the kinematic age of the semi-circular shell and B1–B2 can be obtained. In the case of the shell, we assume an expansion velocity of $v_{\rm shell} \sim 10\,{\rm km\,s^{-1}}$ which is typical of an AGB wind. The resulting kinematic age, $\tau_{\rm shell} \simeq 3\left[\frac{d}{\rm kpc}\right] \times 10^4\,{\rm yr}$ (where d is the distance in kpc) is the one expected for the remnant envelope of a AGB progenitor. This is a consequence of having set the velocity wind to a typical value for AGB stars ($v_{\rm shell} \leq 30\,{\rm km\,s^{-1}}$). In the case of the jets, we assume that the ejection axis is perpendicular to the line-of-sight with a velocity $v_{\rm jet} \geq 100\,{\rm km\,s^{-1}}$. Thus, the corresponding kinematic age is $\tau_{\rm jet} \leq 5.7 \left[\frac{d}{\rm kpc}\right] \times 10^3\,{\rm yr}$. A comparison between both kinematic ages suggests that the ejection of the highly collimated outflow is a much more recent event than the mass ejection from the AGB progenitor of M 2-48. In these circumstances, a jet-shell interaction appears plausible. For the inner bipolar shell no estimates of kinematic ages can be done. The possible relationships between the bipolar shell and the other nebular components, as well as their kinematics (specially for the apparent semi-circular shell), should be investigated by means of high resolution, spatially resolved spectroscopy.

4. Conclusions

Narrow band CCD images towards the PN M 2-48 were obtained, which reveal a pair of symmetric bow-shocks separated by $4'$ and probably related to a bipolar jet ejection. The bow-shocks exhibit the ionization structure expected if they trace the working surface of highly collimated jets. An apparent off-center semi-circular shell (size $\approx 110''$) is also detected surrounding the internal bipolar shell of the object. There is an enhancement of low-excitation emissions in this structure along the major nebular axis. This result can be interpreted in terms of a jet-shell interaction.

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