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The structures and kinematics of planetary nebulae with close-binary central stars

Deborah L. Mitchell[1], **Don Pollacco**[2], **T. J. O'Brien**[1], **M. Bryce**[1], **J. A. López**[3] **and J. Meaburn**[1]

[1]Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL, UK
email: dlm@jb.man.ac.uk

[2]APS Division, Department of Pure and Applied Physics, Queen's University Belfast, Belfast BT7 1NN

[3]Instituto de Astronomía, Universidad Nacional Autnoma de México, Apartado Postal 877, 22800 Ensenada, B.C., México

Abstract. A programme is currently underway to study the structures and kinematics of planetary nebulae known to contain close-binary central stars. Images and high-resolution spectroscopy are presented of the collimated nebula Abell 63 and the ring-like nebula Sp 1. A spatio-kinematical model shows that Abell 63 has a tube-like structure, which has the same inclination as the orbital plane of the central binary system. Kinematic data reveal that Sp 1 is not a hollow sphere, but a tube-like nebula viewed pole-on.

Keywords. (ISM:) planetary nebulae: general, (ISM:) planetary nebulae: individual (Abell 63, Sp 1), (stars:) binary: eclipsing, stars: kinematics, stars: mass loss

1. Introduction

The role played by close-binary central stars in shaping planetary nebulae (PNe) has been widely debated over the past 20 years. It has been argued that the presence of a low-mass companion star is necessary to produce the complex, bipolar morphologies observed in many PNe (Morris 1987). We have instigated a programme to study the structures and kinematics of all planetary nebulae with confirmed close-binary central stars. The data will reveal any trends in the morphologies and kinematics that can be attributed to the presence of the companion star. Three of the targets are important test cases because their central stars are eclipsing systems: Abell 63, Abell 46 and SuWt 2. These objects are especially important as their physical parameters can be determined, at least in principle, in a model independant way. Consequently, the properties of these objects can be used as tests of stellar evolution theory.

2. Observations and data reduction

Spatially resolved, longslit line profiles were obtained of northern sky targets in June 2004 using the Manchester echelle spectrometer combined with the 2.1-m San Pedro Martir telescope (MES-SPM). A narrow-band 90 Å filter was used to isolate the Hα + [N II] λ6584 Å emission lines. After binning of 2×2 the spatial resolution was 4.79 km s^{-1} pixel^{-1}. The projected slit length on the sky was 5.3 arcmin and the slit was 150 μm wide ($\equiv 2.0''$ and 10 kms^{-1}).

Longslit observations were made in the southern sky using the University College London echelle spectrograph (UCLES) combined with the the 3.9-m Anglo-Australian Telescope in January 2005. Binning of 3×2 was adopted, giving a spectral resolution

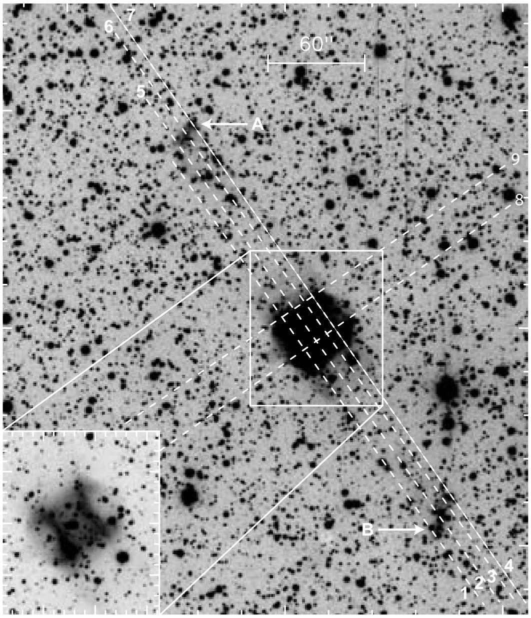

Figure 1. A narrow-band Hα + [N II] λ6584 Å image of Abell 63 taken from Pollacco & Bell (1997). The image shows the full extent of the nebula at low-contrast. Faint, collimated lobes can be seen extending from the bright central nebula. Two end-caps are visible at the tips of the lobes, labelled A and B. The insert shows the bright central nebula at high contrast. Slit positions are drawn on the image.

of 0.48$''$ pixel^{-1}. The projected slit length was 56.13$''$ and the slit was 1.97$''$ wide. Complementary southern sky observations were made using the ESO Multi-Mode Instrument (EMMI) in red-arm configuration combined with the 3.58-m New Technology Telescope in March 2005. Binning of 2 × 2 was used, giving a spatial and spectral resolution of 0.33 arcsec pixel^{-1} and 5 km s^{-1} pixel^{-1}, respectively. The projected slit length was 330 arcsec and the slit width was 1 arcsec.

3. Abell 63

Fig. 1 shows a narrow-band Hα + [N II] λ6584 Å image of Abell 63 with the 9 slit positions drawn on. Abell 63 is a low surface brightness nebula with faint, well confined extensions that lead to “end caps” (labelled A and B on Fig. 1) giving the overall impression of tube with a waist. The faint material visible surrounding the central nebula may be the relic of an earlier mass-loss episode from the binary system.

An Hα + [N II] λ6584 Å longslit spectrum showing the full spatial extent of the major axis of Abell 63 is shown in the left-hand panel of Fig. 2. The corresponding plot showing the variation of heliocentric radial velocity, $V_{\rm hel}$, along the slit is shown in the right-hand panel. The end-caps have a $V_{\rm hel}$ of $\sim$5.5 km s^{-1} once the systemic velocity of $\sim$41.5 km s^{-1} has been accounted for. At a distance of 2.4 kpc (Bell *et al.* 1994), this gives a kinematic age of 13000 years, which is consistent with the expansion age of the central nebula shell. Longslit spectra from the bright central region of the nebula are shown in Fig. 3 (top).

The present kinematical observations support our hypothesis that Abell 63 has a tube-like structure: the Hα line-splitting observed along the major axis of the central nebula [Fig. 3 (top)] is consistent with observing a hollow tube along its major axis.

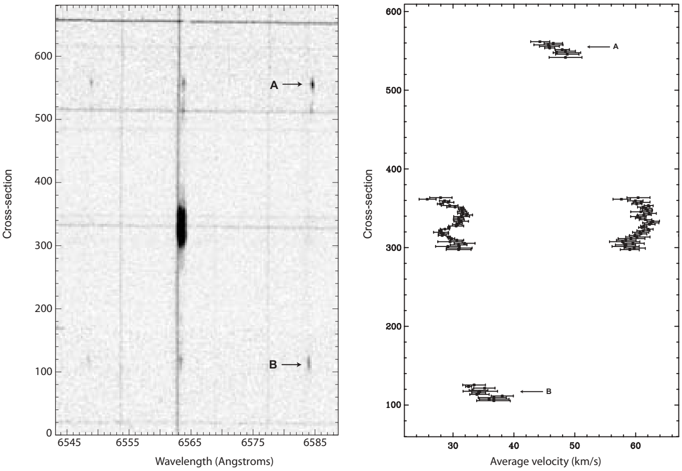

Figure 2. Left: An Hα + [N II] λ6584 Å longslit spectrum showing the full spatial extent of Abell 63, including both end-caps (labelled A and B). Right: Corresponding centroids of best-fit Gaussians to observed Hα + [N II] λ6584 Å profiles.

We have constructed the most simple three-dimensional morphological-kinematical model that is consistent with the observed large-scale velocity features of Abell 63. This model does not contain any dynamical explanation for the structure or dynamics of the nebula, it simply explains the three-dimensional structure and radial velocities observed.

The model was created using the code described in Gill & O'Brien (1999), which produces a grid consisting of two spatial dimensions in the plane of the sky and one dimension corresponding to velocity along a line-of-slight. It is assumed that the expansion velocity increases uniformly with distance from the centre of the nebula. We use a maximum expansion velocity of 20 km s^{-1}. The model assumes axisymmetry and allows for arbitrary inclination to the line-of-sight. We assumed the nebula has the same inclination as the orbital plane of the central binary system, 87.5°. The model is shown in the bottom left panel of Fig. 3.

Synthetic longslit spectra were generated by collapsing the datacube along a spatial direction orthogonal to the slit over 2 pixels and then extracting these slices. The observed long-slit spectra from slits 1, 3 and 9 are shown in Fig. 3 (top) and their synthetic counterparts are shown directly beneath. The synthetic spectra successfully reproduce the velocity trends observed in the longslit spectra from Abell 63. This supports our prediction that the nebula has the same inclination as the orbital plane of the binary system.

The most plausible explanation for the formation of the tube-like structure of the central nebula and the faint, highly collimated lobes is that they have been created by a jet-like outflow from the central binary system, UU Sge. As UU Sge has an orbital separation of just a few solar radii, it must have passed through the common envelope phase and this makes it a likely candidate for Roche lobe overflow. This will create an accretion disk around the primary AGB star and the rotational motion of the accretion disk may be converted into the axial motion of a jet.

4. Sp 1

Fig. 4 shows a deep [O III] λ5007 Å image of Sp1 with 4 slit positions drawn on. The corresponding uncalibrated longslit spectra for each slit position are also shown. The

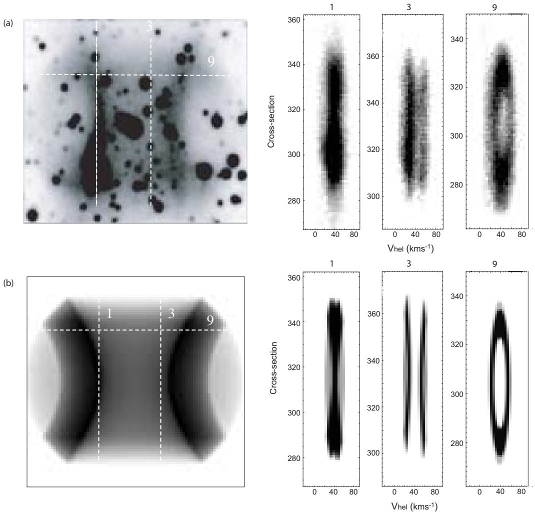

Figure 3. Top: observed longslit spectra from slits 1, 3 and 9 (from left to right). Bottom: convincing synthetic longslit spectra (right) from corresponding slit positions on model (left) with inclination 87.5°.

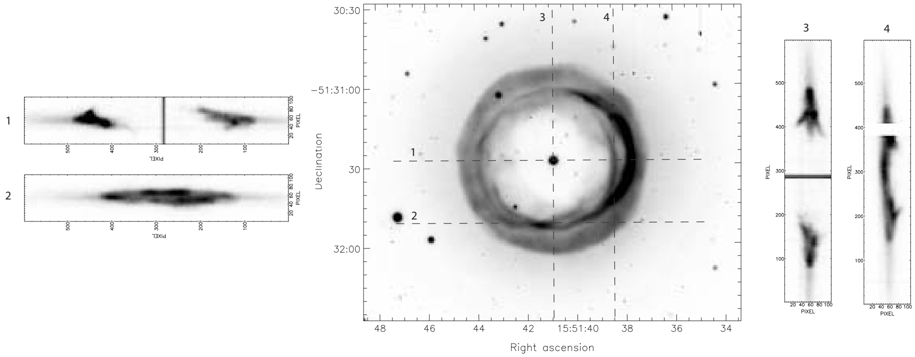

Figure 4. A λ5007 image of Sp 1 showing its nested ring-like structure. Four slit positions are drawn on the image and the corresponding uncalibrated longslit spectra are shown.

nebula appears unique amongst the known sample of PNe with close-binary nuclei as it has an almost perfectly circular structure. This is characteristic of viewing a hollow, spherical nebula in cross-section. Such a morphology is not expected among PNe with close-binary nuclei (Morris 1987). It is apparent from Fig. 4 that the shell of Sp1 has a nested ring structure. Such a structure would be expected if we are viewing a tube-like nebula pole-on. Kinematical data is required to distinguish between these possible morphologies. The longslit spectra (Fig. 4) exhibit three components corresponding to blue-shifted, red-shifted and zero-velocity emission. This supports the prediction that Sp 1 is a tube-like PN viewed pole-on.

References

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