Disk evaporation in a planetary nebula

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ABSTRACT

Aims. Binary interactions are believed to be important contributors to the structures seen in planetary nebulae (PN), and the sole cause of the newly discovered compact dust disks. The evolution of such disks is not clear, nor are the binary parameters required for their creation.

Methods. We study the Galactic bulge planetary nebula M 2-29 (for which a 3-year eclipse event of the central star has been attributed to a dust disk) using HST imaging and VLT spectroscopy, both long-slit and integral field.

Results. The central PN cavity of M 2-29 is filled with a decreasing, slow wind. An inner high density core is detected, with radius less than 250 AU, interpreted as a rotating gas/dust disk with a bipolar disk wind. The evaporating disk is argued to be the source of the slow wind. The central star is a source of a very fast wind (∼10³ km s⁻¹). An outer, partial ring is seen in the equatorial plane, expanding at 12 km s⁻¹. The azimuthal asymmetry is attributed to mass-loss modulation by an eccentric binary. M 2-29 presents a crucial point in disk evolution, where ionization causes the gas to be lost, leaving a low-mass dust disk behind.

Key words. ISM: planetary nebulae: individual: M 2-29 (PN G 004.0-03.0) – Stars: AGB and post-AGB – planetary nebulae: general

1. Introduction

Disks are a recent addition to the range of structures seen in planetary nebulae. The outer nebulae show a large variety of morphological characteristics, including tori, bipolar flows, and ellipsoidal shapes (e.g. Ramos-Larios et al. 2008), with typical sizes of 10³–10⁴ AU. But embedded in these nebulae, in a number of cases a central dust disk has been discovered with sizes of order 10² AU, which can be resolved with the VLT interferometer (e.g. Chesneau et al. 2007). The disks appear well aligned with the outer nebulae but are too low mass to directly have affected their formation. More likely they are a byproduct of the original shaping process.

Other evidence exists for the presence of material very close to some central stars, including unresolved emission-line cores (Rodriguez et al. 2001) and eclipses from dust disks (Hajduk et al. 2008). The disks are believed to require binary systems for their formation but the details of the required system parameters are unclear. An interesting review on binary systems and their shaping of PNe was recently published by de Marco (2009).

Here we present a study of a planetary nebula with such an unresolved emission-line core, known to harbour a dust disk: M 2-29 (PN G 004.0–03.0). Deep echelle spectra and integral-field spectra, together with HST imaging, allow us to disentangle the various components of this complex nebula, and to determine the velocity fields. We find the central core to be the source of an on-going, but decreasing wind, which we attribute to a disk wind. Although direct evidence for the binary companion remains elusive, the outer structure suggests an interaction with a star on a non-circular orbit. From comparison with other objects with dust disks, we find evidence that such disks strongly decrease in mass during the planetary nebula evolution. However, they remain sufficiently massive that residual disks can survive long into the white dwarf phase.

2. Observations

2.1. The HST images

SNAPshot HST/WFPC2 images of M 2-29 were obtained in 2003, in three different filters: F656N, F547M and F502N. The pixel scale of the camera is 0.0455 arcsec. The Hα image (Hajduk et al. 2008) is shown in Fig. 1. The main nebular components are the central source, a wing-like structure, and the extended, fainter nebula.

2.2. VLT/UVES long-slit spectra

A 600-second VLT/UVES (Dekker et al. 2000) echelle spectrum was obtained in 2005, with the slit 0.5 arcsec wide and 11 arcsec long. The slit was put through the centre of the nebula, aligned with the jet-like structure. The pipeline calibration was applied, including wavelength calibration and merging of the separate orders of the spectrum. The observations cover a spectral region approximately from 3300 to 6600 Å. The long-slit spectra of M 2-29 are spatially resolved although they have much worse
Fig. 1. Hα HST image of M 2-29 obtained in 2003. Left shows a linear intensity scale, right shows a logarithmic intensity scale to bring out the fainter emission. North is on top, east to the left. The length of the bar is 2 arcsec. Taken from Hajduk et al. (2008)

resolution than HST images and the seeing during the observations was nearly 1.5 arcsec.

2.3. VLT/ARGUS-IFU spatially resolved spectroscopy

We also retrieved publicly available data from the ARGUS Integral Field Unit (IFU), a mode of the FLAMES instrument at the VLT (Pasquini et al. 2002). These observations of M 2-29 were performed in visitor mode as a part of program 077.D-0652 (PI. D. Schönberner). Two spectral ranges are available, HR8 and HR14B covering range 4911–5158 and 6383–6626 Å with resolution R \(\sim\) 32000 and R \(\sim\) 46000 respectively. Because we aimed for small scale structure, we selected only those frames which had seeing better than 1 arcsec; this constraint yielded one frame in HR14 (700s) and six frames in HR8 (6x110s). The large-area (12x7 arcsec\(^2\)) IFU was used, where each single resolving element (spaxel) covers 0.52x0.52 arcsec\(^2\).

The data were analyzed with the girBLDRS pipeline (a.k.a. Geneva pipeline). Correction of bias level flat fielding and the wavelength calibration were prepared in a standard way. Spectra were extracted with the sum-extraction method, because the default optimum extraction is not well suited to emission-like object. The airmass was lower than 1.06 for all frames alleviating the need to correct for differential atmospheric refraction. The data were not flux calibrated.

2.4. VLT/VISIR images

M 2-29 is a known dust emitter, detected at 25 μm by IRAS (the 12-μm detection was rejected for the faint-source catalogue, perhaps because of confusion with a nearby star). N-band spectroscopy presented by Casassus et al. (2001) indicates a possible broad silicate emission band at 8-12 μm. We retrieved and reduced archival Spitzer IRS data, which confirms the presence of silicate emission, and also shows a weak PAH feature at 11.2 μm (Fig. 2).

To study the location of the dust, we obtained mid-infrared images of M 2-29 using VISIR on the VLT (Lagage et al. 2004). We used a 0.075 arcsec per pixel scale and the VISIR SiC filter (\(\lambda_c = 11.85\) μm, \(\Delta \lambda = 2.34\) μm). The observations were carried out in visitor mode with great weather conditions, leading to diffraction limited images during the whole run. The observations were done using the standard chopping and nodding technique to reduce the background emission in the mid-infrared. The data reduction was performed using self-developed IDL routines described by Lagadec et al. (2008). Images were corrected for bad pixels and then co-added to produce a single flat-field-corrected image, comprising the average of the chop and nod differences.

The resulting image at 11.85 μm shows an unresolved source (Fig. 2), indicating that the emitting source is smaller than \(\sim\) 0.3 arcsec. Thus, the emitting hot dust only comes from one compact component (the core), and not from the extended nebula or wing-like feature.

Fig. 2. Left: Spitzer low-resolution spectrum, showing a broad silicate band with superposed emission lines and a weak 11.2 μm PAH band. Right: the VISIR image showing a strong point source. The image is 3.8 × 3.8 arcsec in size. The transmission curve of the filter used is shown on the spectrum.
3. Morphology from HST images

The HST Hα image (Hajduk et al. 2008) shown in Fig. 1 presents the complexity of the nebula, including the main ring, the halo, the wing-like structure, and the unresolved central object. The main ring is actually composed of two arcs, which may not quite connect. The gaps between them are nearly perpendicular to the wing-like structure. There is a slight indication for elongation or brightening in the EW direction, beyond the gaps (best seen in the left panel, with a linear scale). The overall impression is that of a barrel-shaped nebula, with a beginning bipolar to the wing-like structure. There is a slight indication for a largely spherical component whose brightness smoothly decreases outward. This component we will call the “dense wind”. The spherical symmetry of this component points to a stellar origin. Its brightness at Hα image proves it is not hydrogen deficient. For the discussion below we use the Hα image.

3.1. The outer halo and dense wind

To inspect the outer regions, we overplot in Fig. 3 two scaled cross-sections: one extracted along the wing-like structure and the other perpendicularly to it. The outermost nebular regions decrease in brightness in the same way in all directions, indicative of spherical symmetry. There is no clear evidence for ISM interaction (Wareing et al. 2007).

Intriguingly, the emission profile extends smoothly and symmetrically inside the arcs, up to the central object. This is shown in (Fig. 3), where the small bump on the left hand side corresponds to the arcs. The arcs and jet appear to be superposed on a largely spherical component whose brightness smoothly decreases outward. This component we will call the “dense wind”. The spherical symmetry of this component points to a stellar origin. Its brightness at Hα image proves it is not hydrogen deficient.

The emission profile of the dense wind, including the halo, corresponds roughly to the surface brightness of a sphere filled with matter of a \( r^{-0.5} \) density distribution. This is unusual. The most widely assumed AGB wind density is \( r^{-2} \), as discussed by Villaver et al. (2002). The \( r^{-0.5} \) density implies a mass-loss rate decreasing as \( \dot{M} \propto r^{-1.5} \). The surface brightness with an expansion velocity of \( 10 \text{ km s}^{-1} \) gives a current mass loss rate of \( 10^{-8} M_\odot \text{yr}^{-1} \).

![Fig. 3. The cross-sections through the Hα HST image of M 2-29 taken along the wing-like structure and perpendicularly to it. The intensity scale is the same for both profiles.](image1)

![Fig. 4. The cross-sections through the Hr HST image of M 2-29 taken along the wing-like structure. The dashed line shows the observed intensity profile, the dotted lines show both spherical components - the arcs (photoionization model) and the dense wind, the continuous line presents the difference between the observed cross section and the two spherical components.](image2)

3.2. The central nebula

From the HST images, (Hajduk et al. 2008) showed that the unresolved source at the centre contains an ionized nebula which outshines the central star in the emission lines.

A number of artificial PSFs were created using the TinyTim v.6.3 (Krist & Hook 2004), and fitted to this central nebula. Series of sub-pixel images for different shifts relative to the nebular image were obtained. The PSFs were convolved with Gaussian kernels of different FWHMs, and re-sampled to the resolution of the Planetary Camera. After re-sampling, the charge diffusion kernel was applied. The PSF was then subtracted from the M 2-29 image. Minimum residuals were obtained for PSFs convolved with a Gaussian of FWHM \( 0.8 \) pixel. A similar result was obtained for a background star. The broadening of the PSF with respect to the theoretical one could be due to an imperfect focus. From the comparison with the field star, we constrain the deconvolved FWHM of the nebula as \( < 0.6 \) pixel. This corresponds, at the distance of 8 kpc, to a diameter of \( < 250 \) AU \( (3 \times 10^{15} \) cm).

3.3. The wing-like feature

To obtain the radial emission profile of the wing-like feature from the HST image, the other nebular components should be subtracted.

The profile of the dense wind was obtained from the dashed line in Fig. 3 by taking the average of this cross section with its mirror reflection. The arcs are more difficult, as they are not circular symmetric and cannot be taken from the perpendicular profiles. Instead we used a photo-ionization model (see Section 5), approximated by a spherical shell best fitted to the two arcs, and subtracted the profile calculated from this model. The unresolved core was not subtracted. At the decomposition weighting factors were applied. The result is shown in Fig. 4.

To the left (south) of the central object, a flat profile was obtained. The wing-like structure shows up only to the north (right) of the core.
No clear residual is seen at the cross-over point of the wing-like feature and the arcs. A superposition on the sky, rather than a physical connection, seems to be indicated.

3.4. The arcs

The successful decomposition of the image cross-section into the dense wind and the photo-ionization model, shown in Fig. 4, indicates that the southern arc can be interpreted as a fragment of a photoionized sphere showing emissivity enhancement at the edge. The same can be said about the northern arc. A very common interpretation of such a structure is that the arcs form the projection of a thin annulus, open to the two poles. The dense wind fills the inside and the outside of the barrel. This appears to suggest that the density enhancement of the barrel formed out of the dense wind.

4. The spectra

4.1. Velocity maps

In Fig. 5, we present spectroscopic observations in emission lines of [O III] 5007 Å and [N II] 6583 Å. These are strong forbidden lines, which probe the inner and outer nebular regions respectively. For both lines we extracted from the data cubes three representative slices corresponding to the systemic radial velocity (panels b and f) and those shifted by 12 km s\(^{-1}\) below (panels a and e) and above (panels c and g) this value. The grey scale represents the relative intensities normalized for each slice separately. The square pixels are of spatial size of 0.52 x 0.52 arcsec\(^2\).

The contours show the HST images: [O III] for the upper row, H\(\alpha\) for the bottom row. The right-most frames show the long-slit UVES spectra, where the slit was positioned along the wing-like structure i.e. 5° away from the N-S direction.

At the central star position, the [O III] velocity maps show strong emission at both the positive and negative velocities (panels a and c) but a minimum at the systemic velocity (panel b). This emission corresponds to the unresolved central component and can be interpreted in terms of a bipolar outflow. The wing-like structure can be traced in panels (a) and (b) with velocity decreasing outwards; this can also be seen in the long-slit spectral presentation of bright emission lines in the UVES spectra, where the slit was positioned along the wing-like structure i.e. 5° away from the N-S direction. The emission at the central star position is [O III] at the same velocity (panel a), and is seen at both sides of the central component. This emission corresponds to the unresolved central component and can be interpreted in terms of a bipolar outflow. The wing-like structure can be traced in panels (a) and (b) with velocity decreasing outwards; this can also be seen in the long-slit spectrum (panel d). The southern arc is best distinguished at the zero velocity panel (b).

More details can be derived from [N II] images. The wing-like structure at -12 km s\(^{-1}\) (panel e) is clearly more extended than in [O III] at the same velocity (panel a), and is seen at both sides of the central component. The systemic velocity image (panel f) shows the wing-like structure extending two arcseconds in the northern direction, far beyond what is seen in the H\(\alpha\) image. The long-slit UVES spectra (panel h) also show this significant extension. The southern arc can also be seen at the systemic velocity, and a very weak component is seen in panel (f) extending for a couple of pixels in S-W direction. Panel (g) shows that a component at the eastern end of the southern arc is moving away from us, in fact at a little more than +12 km s\(^{-1}\).

In Fig. 5, we present more examples of the 2-D (position-velocity) contours presentation of bright emission lines in the UVES spectrum. All plots are shown to the same scale, but in the blue spectral region the slit was shorter so the spatial extent of these lines is smaller. Many more emission lines are identified in the spectrum, but the three presented here best supplement those in Fig. 5, showing the variety of line profiles.

The emission of the wing-like feature is visible from the centre until about 2 arcsec up. It is very pronounced in the [O III] 5007 Å, [N II] (Fig. 5) and He \(\alpha\) lines, very weak in the [O I] line and completely absent in the highly excited [O III] 4363 Å line.

The velocities are relatively low (around 10 km s\(^{-1}\)) compared to typical expansion velocities of planetary nebulae.

4.2. Photoionization modelling of the outer nebula

To model the spectra and line profiles, we applied the Torun photo-ionization codes (Gesicki & Zijlstra 2003; Gesicki et al. 2006). The star is assumed to be a black body with a luminosity and effective temperature. The nebula is approximated as a spherical shell defined by the radial density distribution and the radial velocity field. The chemical composition ([O/H] = 7.44) and the observed line intensities were adopted from Exter et al. (2004). We have also measured the line intensities from the low resolution SAAO spectrum (Hajduk et al. 2008). Table I presents the observed data together with our best model. The model emissivities are shown in Fig. 7.

References. (1) Exter et al. (2004); (2) Howard et al. (1997).
The one-dimensional model by necessity assumes spherical symmetry. It solves for the observed line intensities and the radial surface brightness distribution. For the latter, we extracted the image cross-sections taken at 45 degrees left and right to the arcs. The two cross-sections are quite similar. The model assumes a central cavity: neither the central unresolved nebula, nor the inner part of the dense wind (i.e. inside the arcs) is included.

The satisfactory solution is summarized in Table 2. Although the comparison of the Hα and [OⅢ] HST images indicates a density bounded PN, the line intensities (integrated over the whole nebula) are in fact significantly better fitted when the PN is ionization bounded. We solved this problem by adopting the whole nebula) are in fact significantly better fitted when the PN density bounded PN, the line intensities (integrated over the dense wind (i.e. inside the arcs) is included. The model as-

The ionized mass of the nebula is rather high, in view of the conclusion of [Torres-Peimbert et al. (1977)] concerning old age (and therefore low initial mass) of the object. The age may have been underestimated, or mass transfer can be proposed. However, caution should be applied when deriving a mass from a spherical model for a non-spherical nebula.

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Table 2. M 2-29 photoionization and kinematic model parameters.

| Parameter                        | Value          |
|----------------------------------|----------------|
| distance                         | 8 kpc          |
| $T_{\text{e}}$                   | 70 000 K       |
| Luminosity                       | $1200 L_{\odot}$ |
| Ionized Mass                     | 0.38 $M_{\odot}$ |
| log He / H + 12                  | 10.99          |
| log N / H + 12                   | 7.14           |
| log O / H + 12                   | 7.44$^*$       |
| log Ne / H + 12                  | 6.84           |
| log S / H + 12                   | 5.64           |
| Nebula Expansion Velocity        | 12 km s$^{-1}$ |
| Turbulent Velocity Component    | 7 km s$^{-1}$  |
| Kinematic Age                    | 5 000 yr       |

$^*$ this adopted value might be too low (see the text)

4.3. Extended wings of H$\alpha$

The H$\alpha$ emission line reveals very wide wings, seen at the location of the central unresolved source only. In the UVES position-velocity diagram (Fig. 8), the vertical structure shows the emission from the wing-like structure, and the horizontal extent shows the high velocity wings, located at the same position as the stellar continuum.

Averaging the slit spectra over the central 1.5 arcsec, the emission wings can be traced over 1000 km s$^{-1}$ (Fig. 9). The ARGUS-IFU data cube confirms that at wavelengths beyond $\pm 4$ Å ($\pm 200$ km s$^{-1}$) from the line centre the emission originates solely from the unresolved source.

Extended wings can also be seen in [O III] 5007 Å shown in Fig. 5(f), and in H$\beta$ (not shown here). For weaker lines it is not clear whether the wings are present or absent (see e.g. N II 6583 Å line in Fig. 5(i)). However, the O III 5007 Å line shows wings one order of magnitude narrower than H$\alpha$. This should be considered when interpreting this emission component.

The fact that the large broadening is only seen in some lines argues against electron scattering. The presence of a high velocity component in the central object is indicated.

4.4. The permitted emission lines

The UVES spectrum shows a number of permitted emission lines. The recombination lines of C II at 4267.26 and 6578.05 Å are present (e.g. Fig. 8). Also the recombination lines of O III at 4638.85, 4641.81, 4649.14 and 4650.84 Å can be identified. These lines are useful in abundance analysis, e.g. Garcia-Rojas et al. (2005).

For the well exposed C II 6578 Å line, an ARGUS-IFU image was obtained by integrating over its line width. This line originates in an extended region as can be seen in Fig. 10 where it is compared with He I 5016 Å line. Concerning the other permitted lines the situation is not so clear since they are weaker and more noisy. The well-known group around 4650 Å falls at an echelle order merging where distortions may occur; it is also not covered by the ARGUS-IFU spectral range. The UVES data suggests that it may also form in an extended region but this requires confirmation.

We also identified a number of permitted N II lines (4097.33, 4103.43, 4364.14, 4640.64, 4641.85 Å). They are often interpreted in terms of the Bowen mechanism (see e.g. Selvelli et al.).
The UVES spectra of M 2-29 show interstellar absorption lines of Na\textsc{i} and Ca\textsc{ii} K in the spectrum of M 2-29. The profiles are shown in the heliocentric reference frame.

\[ V_{\text{red}} \]

\[ -100 \quad 0 \quad 100 \]

\[ \text{heliocentric velocity [km/s]} \]

**Fig. 11.** The interstellar absorption line profiles of ions Na\textsc{i} and Ca\textsc{ii} K in the spectrum of M 2-29. The profiles are shown in the heliocentric reference frame.

\[ \text{Na}\textsc{i} 5895 \quad \text{Ca}\textsc{ii} 3933 \]

\[ \begin{align*}
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\text{\[ V_{\text{red}} \]} & \quad \text{\[ -100 \quad 0 \quad 100 \]} \\
\text{\[ \text{heliocentric velocity [km/s]} \]} & \\
\text{\[ \text{Na}\textsc{i} 5895 \quad \text{Ca}\textsc{ii} 3933 \]} \end{align*} \]

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\text{\[ \text{Na}\textsc{i} 5895 \quad \text{Ca}\textsc{ii} 3933 \]} \end{align*} \]

The emission at this velocity seems to extend over some distance. The distance to this cloud or complex is not known, but as M 2-29 is clearly located behind it, we suggest it is situated relatively close to the Galactic centre. Small Ca\textsc{ii} and Na\textsc{i} absorption clouds with similar high velocities appear to be common in the Galactic halo (Ben Bekhti et al. 2008), with a variety of origins.

It is remarkable that the non-rotational interstellar absorption component near \(-100 \text{ km s}^{-1}\) is very close to the systemic radial velocity of M 2-29. As a PN, or related object, M 2-29 is expected to be old and evolved, and any association with the interstellar component is deemed accidental.

\section{5. Disentangling the nebula}

The nebula of M 2-29 shows four distinct components: the inner unresolved nebula, the dense wind extending outwards, the arcs, and the wing-like structure. The arcs appear to be an enhancement within the dense wind rather than an independent structure. Here we attempt to obtain an understanding of the other two structures.

\subsection{5.1. An outer partial ring: the wing-like structure}

The 'wing-like' feature is a low-velocity structure. Based on the observed location and the lack of interaction with the arc, we locate it outside of the main nebula. We identify it as a partial, expanding ring, surrounding the main nebula, and whose plane is almost coincident with the line of sight. The ring has an inner radius of about 2 arcsec.

The velocity structure along this ring is depicted in Figs. \ref{F:1} and \ref{F:2}. In the \([\text{O}\text{iii}]\) line, only the top (north) of the ring is seen, but the \([\text{Na}\text{i}]\) line shows the more complete structure. In the southern part, the \([\text{N}\text{ii}]\) is displaced to the left (see Fig. \ref{F:5}). The displacement suggests that the plane of the ring is seen at an inclination of approximately 20 degrees with respect to the line of sight. Because the displacement is seen in the rear part of the ring it is not unlikely that the structure is warped.

The line splitting shows that it is expanding: an expansion velocity (with a minor correction for the inclination) of about \(12 \pm 2 \text{ km s}^{-1}\) is indicated.

The UVES slit was aligned with the brightest part of this structure, however because of the inclination the southern extension fell outside the slit. This is made clear by the ARGUS image. The position-velocity diagrams from the UVES data therefore have an incomplete coverage. Still, the brightness distribution of the ring is strongly asymmetric, while the velocities appear symmetric. The peak \([\text{O}\text{iii}]\) emission occurs at a velocity of \(-10 \text{ km s}^{-1}\), offset by about 1 arcsec from the star. This corresponds to a location on the ring about 30 degrees from the line of sight to the centre. The bright \([\text{O}\text{iii}]\) emission occurs over an arc of roughly 90 degrees, on the forward side of the ring. Some faint emission originates from the backside, seen towards the southwest at positive velocities, in Fig. \ref{F:5}.

The bright \([\text{N}\text{ii}]\) emission covers a much wider arc, extending for some 120 degrees. At a much fainter level the ring may be almost closed. The \([\text{N}\text{ii}]\) emission is spatially also much more extended than \([\text{O}\text{iii}]\), with a fainter outer region with a radius of at least 4 arcsec. This is seen in Fig. \ref{F:5} as the northern extension. This region only contributes at near-systemic velocity, suggesting that the expansion velocity decreases sharply from 2 to 4 arcsec radius. The radial extension is not seen towards the south, showing that at its outermost radius the ring is not closed, perhaps limited to some 180 degrees.

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\vspace{1em}
\textsuperscript{2} The mean rotation of the Galactic bulge at the longitude of M 2-29 is around \(+50 \text{ km s}^{-1}\) (Minniti & Zoccali 2008).

\vspace{1em}
\textsuperscript{3} The very weak He\textsc{ii} line is confused with H\textsc{ii} of the full Ca\textsc{ii} line complex near 4650 Å. (The \([\text{Ca}\text{ii}]\) H and K lines (i.e. adding together all Doppler components) shows an approximate linear recombination for explaining the \([\text{N}\text{ii}]\) line complex near 4650 Å. This component cannot be explained with Galactic rotation, nor Bulge rotation.\textsuperscript{2}

\vspace{1em}
\textsuperscript{4} The interstellar absorption line profiles show components from different interstellar clouds. The three main components are at (heliocentric) velocities of \(-50 \text{ km s}^{-1}\), at \(-60 \text{ km s}^{-1}\), and at \(-80 \text{ km s}^{-1}\). The absorption at positive velocities can be associated with the Molecular Ring around the inner Galaxy, while the intermediate negative velocity component is consistent with the 3 kpc expanding ring as seen in CO (Dame et al. 2001). However, the Galactic CO maps show no counterpart to the most negative velocity component in M 2-29. This component cannot be explained with Galactic rotation, nor Bulge rotation.\textsuperscript{4}

\vspace{1em}
\textsuperscript{5} The UVES spectra in this region do show a H\textsc{i} emission feature corresponding to this negative velocity component. It may be related to a nearby catalogued high velocity cloud, HVC 002.9-06.2-088 (Putman et al. 2002), with the same velocity, as...
The ring is also seen in He I, C II, and [O I], at the location of the brightest [O II] and [N II] emission. Thus, there is sufficient column density in this direction to cause ionization stratification and an ionization boundary, as also indicated by the photoionization model. The lack of [O II] beyond 2 arcsec is consistent with the photoionization model of Fig. 7.

Finally, this ring system is located close to the equatorial plane of the main nebular barrel defined by the northern and southern arc (see Sect. 3). A slight misalignment is explained by the inclination.

Thus, we arrive at a model of an expanding equatorial, partial ring, 2–4 arcsec in radius, with a strong azimuthal density gradient, a radial density gradient, and an expansion velocity of \(12 \pm 2 \text{ km s}^{-1}\) at 2 arcsec, decreasing with increasing radius.

5.2. The unresolved disk

The central source is detected in emission lines of H\(\beta\), [O III] 4363 and 5007 Å, He II, the Bowen N II lines, and [O I]. Other lines are present but are confused by the spatial and velocity overlap with the extended emission. The very high velocity wings, and the [O III] 4363 Å line are only seen in this core. The size of the core is \(< 0.03\) arcsec, or \(< 250\text{AU}\) at the distance of the Galactic Bulge.

The [O III] 4363/5007 line ratio is much higher in the core than in the extended nebula. This indicates high density and temperature, in agreement with Torres-Peimbert et al. (1997) who first showed the presence of a high density and high electron temperature component close to the star. We ran some test models to estimate the parameters of the inner nebula, using the central star parameters derived above. In these models, the ratio 4363/5007 [O III] lines can be reproduced with \(T_e \approx 1 \times 10^5 \text{K}\) and \(n_e \approx 6 \times 10^3 \text{cm}^{-3}\). These values are a little lower than the estimates of Torres-Peimbert et al. (1997). At these densities, the mass of the compact nebula needed to reproduce the observed H\(\beta\) flux is \(10^{-4} M_\odot\). This value is not very accurate, as the core is unlikely to show constant density and spherical symmetry, but provides a believable order of magnitude. Other lines often used as the electron density indicators, e.g. lower ionized/excited [O II] or [S II], predominantly originate in the wing-like structure. This makes an extraction of the central component much more unreliable, in no case as clear as the [O III] 4363 Å line.

All lines show velocity broadening of \(\sim 10\text{ km s}^{-1}\). For this velocity, the kinematical age of the core is less than 100 years, requiring a continuing mass-loss rate of \(\sim 10^{-6} M_\odot \text{ yr}^{-1}\). The lower limit to the mass-loss rate is 1 to 2 orders of magnitude lower than that required for the extended nebula (assuming a kinematic age of 5000 yr), and the surface brightness distribution of the extended wind indeed implies a linearly decreasing mass loss rate with time. It raises the question, however, why the mass-losing star is not seen. Such mass-loss rates and velocities are found in red giants. (The wind from the hot central star will be very much faster). Neither the spectrum nor the photometry shows evidence for a contribution from any other star than the PN central star. The 2MASS photometry excludes the presence of a red giant more luminous than \(100 L_\odot\). Although a mass-losing star has clearly been present in the recent past, it does not appear to be present at the moment.

The alternative to on-going stellar mass loss is a stable, rotating structure. This has some evidence in favour: the line widths decrease with decreasing excitation, from \(\pm 18 \text{ km s}^{-1}\) HWHM for [O III] line to close to a few \(\text{ km s}^{-1}\) or less for the [O I] line consistent with rotation velocities decreasing outward. Hajduk et al. (2008) derive a putative orbital period for the wide binary of \(\sim 17\) yr, implying an orbital velocity of approximately \(10-15 \text{ km s}^{-1}\). They also show that a circumbinary dust disk in such a system can explain the long-duration eclipse. A rotating, circumbinary disk would show an innermost velocity a little less than the binary orbital velocity, at some 10 AU, in agreement with [O III]. The [O I] velocity corresponds to radii of a few hundred AU.

The extreme H\(\alpha\) wings show the presence of a fast outflow, which in the presence of a stable disk will have a bipolar flow pattern. The dense wind shows the presence of outflow: we interpret this as a disk wind, caused by evaporation of the photoionized gas. The limit of stability of the gas disk is set when the thermal velocities exceed the rotational velocity. (Beyond about 100 AU, only neutral gas or dust can be stable.) Evaporating gas can be accelerated by the fast H\(\alpha\) wind, as a mass-loaded wind (Borkowski et al. 1995). The [O III] core emission shows a double peak, and this may indicate it forms in part in such a bipolar wind.

A likely interpretation of the inner nebula is, therefore, in terms of an opaque disk seen edge-on (Hajduk et al. 2008) with ionized bipolar outflows. The infrared dust emission and neutral [O I] line originate at the outer static boundary. The dense wind originates in the evaporating disk. At larger distances such an evaporating-disk wind is expected to be essentially spherically symmetric (Alexander 2008). The disk can be located in the same plane as the outer partial ring, at an inclination of 20 degrees from the line of sight, with the bipolar flow directed towards the openings between the two arcs.

6. Discussion

6.1. The nebula

The one-side structure of the wing in M 2-29 is unusual but not unique. It is duplicated in He 2-428, and in A 79 (Rodríguez et al. 2001), and possibly also in the symbiotic star V417 Cen (Van Winckel et al. 1994). In all four cases, the structure is essentially identical, allowing for the difference in viewing angle. But no further object with a similar morphology could be identified in the IAC morphological catalog (Manchado et al. 1996), confirming the rarity of this structure.

Outer asymmetries can be formed by interaction with the interstellar medium, and these are a very common phenomenon (Wareing et al. 2007). In M 2-29, there is indeed a possible association with interstellar gas at a similar velocity, and a possible ISM sweep-up should be explored. However, the good alignment of the outer ring with the equatorial plane of the nebula, the presence of expansion, and the existence of a few very similar objects, all suggest that the partial ring was part of the planetary nebula ejection.

The arcs show the presence of a more (if not entirely) spherically symmetric component in the nebula, located within the outer ring. This suggests a scenario where the mass ejection was initially highly asymmetric, but became less so over time. The arcs could trace a temporary mass-loss enhancement, or they could be caused by the pressure enhancement from the onset of ionization. The compact core is evidence that a fraction of the ejected mass was retained close to the star.

The ejection of the partial ring can be related to an interaction with a companion with an elliptical orbit. Such an interac-

\footnote{In the photoionization model of the outer nebula the [O III] 4363 Å line is underestimated by an order of magnitude which is another argument that it does not belong to the outer main ring.}
tion is discussed by Soker & Rappaport (2001), their scenario 4. If the orbit is such that interaction occurs at periastron only, amplifying or initiating the mass loss at this point, the mass loss will occur preferentially in the direction of the velocity vector of the mass-losing star at periastron, and not at the systemic velocity. As the stellar radius increases, the binary orbit may circularize or the stellar mass loss may become self-sustaining: the mass loss will now occur everywhere along the orbit, centred on the systemic velocity.

The interaction between these two winds offset in velocity provides a natural explanation why an identical structure is seen in several objects, and seems the most plausible explanation for the outer wing, and the fact that the asymmetry occurred only during early mass loss. There is some evidence that V417 Cen, which shows a similar morphology, has an elliptical orbit (Van Winckel et al. 1994).

### 6.2. Classifying the star

M 2-29 is one of only three PNe known to show dust eclipses (the others are: NGC 2346 and CPD--56°8032 (Hajduk et al. 2008; Cohen et al. 2002; De Marco et al. 2002), and one of two with a binary period of order 1 month (NGC 2346 has period of 16 days (Hajduk et al. 2008; de Marco 2009)). It is also one of few showing a dense, unresolved nebular core inside an extended PN. Other cores include EGB 6, a very faint and nearly circular PN around a binary composed of a very hot white dwarf and a visual point-like companion with dense emission-line nebula (Bond et al. 1993; Rodriguez et al. 2001) finds a similar core in He 2-428. B[e] stars, a mixed class which includes some young PNe (Lamers et al. 1998), also show compact cores and Hβ line wings similar to M 2-29 (Zickgraf 2003). But M 2-29 lacks the low-ionization iron lines found in B[e] stars. A very late thermal pulse leads to the ejection of a new core (van Hoof et al. 2007), but this core is hydrogen-poor and different from what is seen in M 2-29.

A relation to the dusty symbiotic stars has been proposed (Hajduk et al. 2008; Miszalski et al. 2009), based on the orbital period of M 2-29. Symbiotic systems contain a mass-losing giant, and a hot white dwarf which irradiates the wind: the ionized gas shows dense cores (e.g. M 2-9, OH 231.8 Ant, and a hot white dwarf which irradiates the wind: the ionization period of M 2-29. Symbiotic systems contain a mass-losing giant (van Hoof et al. 2007), but this core is hydrogen-poor and different from what is seen in M 2-29.

### 6.3. Evolution of the disk

Compact dust disks are common around post-AGB stars (de Ruyter et al. 2006), and are increasingly being identified around the central stars of planetary nebulae: examples are the ant nebula (Chesneau et al. 2007), the helix nebula (Su et al. 2007), CPD--56°8032 (Cohen et al. 2002), M 2-48 (Phillips & Ramos-Larios 2008) and NGC 2346 (Costero et al. 1984).

| Table 3. Ages and dust masses of the disks in planetary nebulae |
|---------------------------------------------------------------|
| **Nebula** | **Nebular Age** | **Dust Mass** | **Reference** |
|---|---|---|---|
| CPD--56°8032 | 10² | 3 x 10⁻⁴ | (2), (3) |
| Ant nebula (Mz 3) | 10¹ | 1 x 10⁻⁵ | (1), (4) |
| M 2-29 | 5 x 10¹ | 10⁻⁶ | This paper |
| Helix nebula | 1.1 x 10⁴ | 4 x 10⁻⁷ | (5), (6) |

References. (1) Chesneau et al. (2006); (2) Chesneau et al. (2007); (3) De Marco et al. (1997); (4) Guerrero et al. (2004); (5) Meaburn et al. (2008); (6) Su et al. (2007).

The origin and evolution of these disks is not yet understood. They are interpreted as circumbinary disks which formed during the mass loss phase, or as debris disks either left over from the main sequence phase or built recently from tidally disrupted smaller orbiting bodies as discussed in e.g. Su et al. (2007) or Brinkworth et al. (2009). The plethora of different classes of objects with such disks (B[e] stars, symbiotic stars, RV Tau stars) shows that they form relatively easily. Binary companions appear required in all cases, but the orbital periods range from 200 days (post-AGB binaries with disks) to 100 yr (such as M 2-9).

Interestingly, similar dust disks have not been discovered around the post-common-envelope binaries seen in about 15–20% of PNe (Miszalski et al. 2009), with periods of hours to days. Although models (Sandquist et al. 1998; Nordhaus & Blackman 2000) indicate that the common envelope is not necessarily completely ejected and there remains some gas around the system, there is no evidence that this residual leads to a dust disk. The known dust disks are seen around longer-period systems which avoided a common envelope phase. M 2-29 is argued to trace the phase where the gas disk is lost and the dust disk remains. Rotation velocities far exceed thermal velocities while the gas is molecular or neutral. The dust will settle towards the mid plane at this time (Dominik et al. 2003). But once ionization starts, the thermal velocities are comparable to the rotation velocities, and a disk wind initiates. In M 2-29, the disk wind began ~ 10³ yr ago, but has been decreasing over time, likely reflecting the decreasing gas reservoir. At the current time, some 10⁻⁴ M⊙ of gas remains. The current disk-wind mass-loss rate of 10⁻⁸ M⊙ yr⁻¹ gives a decay time of the disk similar to the age of the nebula.

The future evolution is of interest to the disks seen around more evolved objects. The Spitzer spectrum with the strong silicate emission and PAH emission indicates that the dust is relatively hot. The dust will cool sharply once the star enters the white dwarf cooling track where it rapidly fades by a factor of 100. The central star of the helix is such a cooling track star. The cooler dust will emit mainly at longer wavelengths: the dust disk of the helix is detected mainly at 24 µm and 70 µm (Su et al. 2007). Such cool disks can have gone largely unnoticed.

Table 3 lists the ages and disk dust masses for four planetary nebulae where these have been measured. The ages are defined from the end of the AGB, i.e. the ejection of the main nebula. The dust masses are taken from the given references, where we assumed a gas-to-dust ratio of 100 for M 2-29. The age of CPD--56°8032 has likely been underestimated as the object has been known for longer than this (Gill 1900).

The Table indicates that the disk masses decrease sharply as the star ages. Although this should be taken with care because of the small sample and the possibly disparate origins of the ob-
jects, it appears possible that much of the dust mass is lost during the PN phase. Dust can be carried away in the wind from the evaporating gas disk, and unshiled dust may be destroyed by the intense UV radiation field. \textit{Chesneau et al.} (2006) suggests that an efficient dissipating process is occurring in the disk of CPD $-56^\circ 8032$.

The original masses of the disks are unknown. However, disks around post-AGB stars show dust masses similar to CPD $-56^\circ 8032$: RU Cen and AC Her show $5 \times 10^{-4}$ and $2 \times 10^{-3} M_\odot$ respectively (\textit{Giesicki et al.} 2007). These objects have stars which are still too cool to cause ionization, and have avoided ionization-driven dissipation.

Thus, we suggest that the disk of the helix nebula may be the remnant of a post-AGB dust disk, rather than a debris disk as preferred by \textit{Su et al.} (2007). Once the star is on the cooling track, the disk becomes largely stable and the further dissipation time is set by Poynton-Robertson drag, with a time scale of order $10^7$ yr. Thus, the disks may remain detectable for the order of $10^5$ yr, long after any sign of the planetary nebula has disappeared.

Several disks have been discovered around white dwarfs (e.g. \textit{Gänsicke et al.} 2006). Surveys for such disks around the oldest white dwarfs have been unsuccessful (\textit{Kilic et al.} 2009), but around 15% of local white dwarfs show metal-rich material in their photosphere, indicative of accretion from a residual dust reservoir (\textit{Sion et al.} 2009). Although these may have a variety of origins, they may include the progeny of the M 2-29-type disks.

7. Conclusions

We have presented a detailed study of one Bulge planetary nebula, with the aim to find evidence for disk evolution. Our main findings are:

1. M 2-29 has a likely distance consistent with membership of the Galactic Bulge. It shows absorption features of a cloud with high velocity, which we tentatively identify with the nearby HVC 002-9-06-2-088.

2. The nebula is surrounded by a partial ring, slowly expanding at 12 km s$^{-1}$. Such a structure may be derived from interaction with the interstellar medium, but based on the expansion, and the alignment with the inner and outer nebula, we associate it with an early mass-loss phase from the central star. A model where mass loss is triggered initially only during periastron of a companion in an elliptical orbit can explain the structure: in this model, the ring was ejected with a preferential velocity in the orbital plane, reflecting orbital motion of the central star.

3. We find evidence for on-going mass loss from the central source, decreasing with time, with a slow expansion velocity of 10 km s$^{-1}$, and with a current rate of $\sim 10^{-8} M_\odot$ yr$^{-1}$. There is however no evidence for any mass-losing star which could be the source of this material.

4. There is evidence for a very fast wind ($\sim 10^3$ km s$^{-1}$) from the central star, based on the He line wings. The [O[\textit{i}] also shows wings, but a factor of ten narrower.

5. The unresolved core with diameter < 250 AU shows strong forbidden and permitted emission lines with a range of ionization states, down to [O[\textit{i}]. The velocity HWQH of the 4363[O[\textit{i}]] line is 18 km s$^{-1}$; [O[\textit{i}]] is much narrower. Because of the very short dynamical time scale, and the velocity gradient with excitation, we interpret this as a stable, rotating system. The mass of the core is estimated as $M_\ast \sim 10^{-4} M_\odot$. The dust emission is located within this core.

6. We interpret the on-going mass loss as a disk wind, driven by the ionization and heating of the gas. The thermal gas velocities are similar to the rotation velocity, making the disk susceptible to evaporation. The fast wind from the star may be accelerating gas shed from the disk, as seen in the [O[\textit{iii}]] line wings. The mass and current mass-loss rate of the disk indicate an decay time similar to the age of the nebula.

7. By comparing masses of dust disks in planetary nebulae of different ages, we show that the dust disks dramatically reduce in mass as the nebula evolves, reflecting the disk evaporation. The dust mass decrease from $\sim 5 \times 10^{-4} M_\odot$ at the start of the PN phase, to $\sim 4 \times 10^{-5} M_\odot$ for the helix nebula on the white dwarf cooling track where the luminosity of the star quickly drops by a factor of 100, reducing the rate at which the dust disk would be lost.

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