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Kinematics of the ring-like nebula SuWt 2*

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ABSTRACT

We present the first detailed spatio-kinematical analysis and modelling of the Southern planetary nebula SuWt 2. This object presents a problem for current theories of planetary nebula formation and evolution, as it is not known to contain a central post-main sequence star.

Deep narrowband [N II]6584 Å images reveal the presence of faint bipolar lobes emanating from the edges of the nebular ring. Longslit observations of the Hα and [N II]6584 Å emission lines were obtained using EMMI on the 3.6-m ESO-NTT. The spectra reveal the nebular morphology as a bright torus encircling the waist of an extended bipolar structure. By deprojection, the inclination of the ring is found to be 68° ± 2° (c.f. ∼90° for the double A-type binary believed to lie at the centre of the nebula), and the ring expansion velocity is found to be 28 km s^{-1}.

Our findings are discussed with relation to possible formation scenarios for SuWt 2. Through comparison of the nebular heliocentric systemic velocity, found here to be -25 ± 5 km s^{-1}, and the heliocentric systemic velocity of the double A-type binary, we conclude that neither component of the binary could have been the nebular progenitor. However, we are unable to rule out the presence of a third component to the system, which would have been the nebula progenitor.

Key words: planetary nebulae: individual: SuWt 2, PN G311.0+02.4 – stars: kinematics – stars: mass-loss – stars: winds, outflows – circumstellar matter

1 INTRODUCTION

Planetary nebulae (PNe) represent a late stage in the evolution of intermediate mass stars, the production of which has long been thought to be the result of a dense stellar wind, originating from the progenitor Asymptotic Giant Branch (AGB) star, being swept up into a fine rim by a faster wind from the emerging White Dwarf (WD) (Kwok et al. 1978). This model was later extended to become the Generalised Interacting Stellar Winds (GISW) theory, stating that enhanced equatorial mass-loss in the slow, dense wind phase can lead to a bipolar shape in the resulting nebula (see e.g., review by Balick & Frank 2002). The mechanism behind this highly non-isotropic mass-loss represents a particularly hot topic in the field of PN research. One favourable mechanism is for the central star of the planetary nebula (CSPN) to undergo a common envelope (CE) evolution with a binary partner. For a CE to form, one component of a close-binary system must overflow its Roche lobe and begin to accrete on to its partner, and the timescale for mass transfer must be considerably shorter than the timescale on which the accretor can thermally adjust, thus causing the accretor to also fill its Roche lobe. Any further mass lost by the donor, will then go on to form a CE which surrounds both stars. The shedding of this CE, by angular-momentum transfer, α-ω dynamo or accretion-driven jets (Nordhaus & Blackman 2006), provides the mass anisotropy required to form bipolar nebulae. The hydrodynamic simulations of Rasio & Livio (1996) confirm that equatorial density enhancement is a natural consequence of a CE evolution.

SuWt 2 (PN G311.0+02.4, $\alpha = 13^h55^m43.23^s$, $\delta = -59°22'40.03''$ J2000) is described by Schuster & West (1976) as 'an elliptical, nebular ring upon which several starlike images are superposed'. West (1976) classified SuWt 2 as a PN based on of the presence of strong emission from forbidden lines typical of this class of object.

* Based on observations made with ESO telescopes at the La Silla or Paranal Observatories under programme IDs 74.D-0373 & 55.D-0550.

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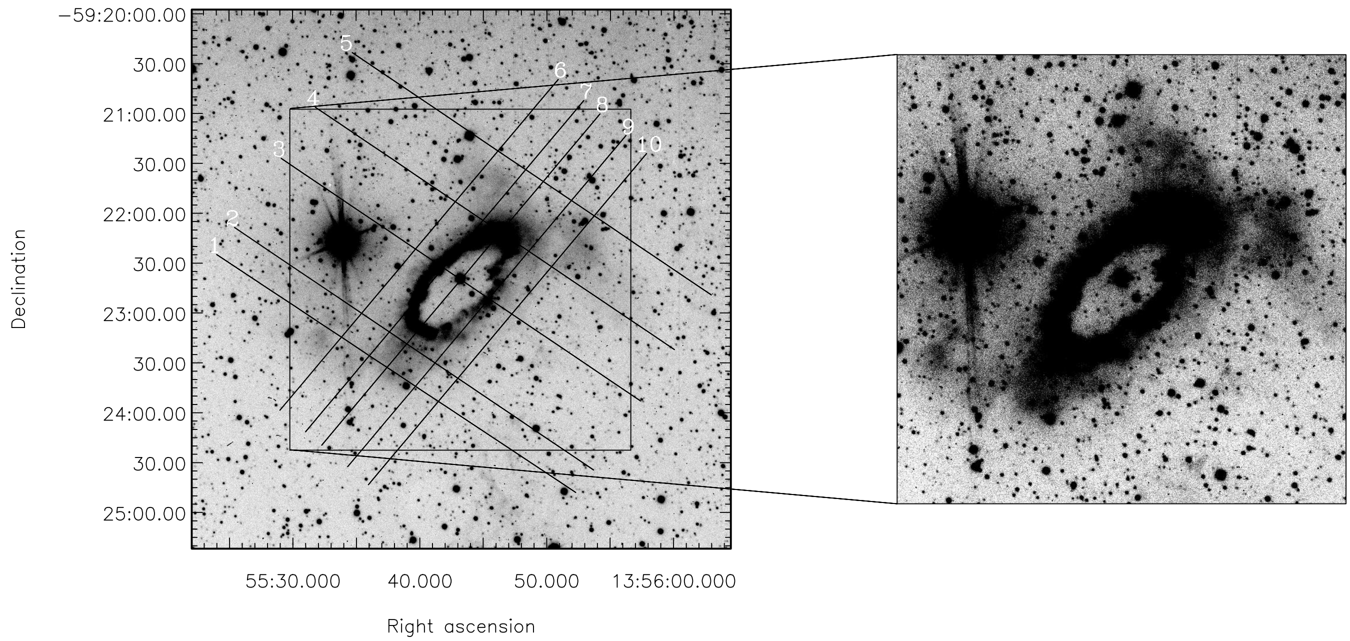


Figure 1. ESO-NTT exposure of SuWt 2 in the light of [N II]6584 Å showing the position and extent of slits used, the cut-out shows the same image at greater contrast in order to highlight the extent of the nebular ring and the presence of the bipolar lobes.

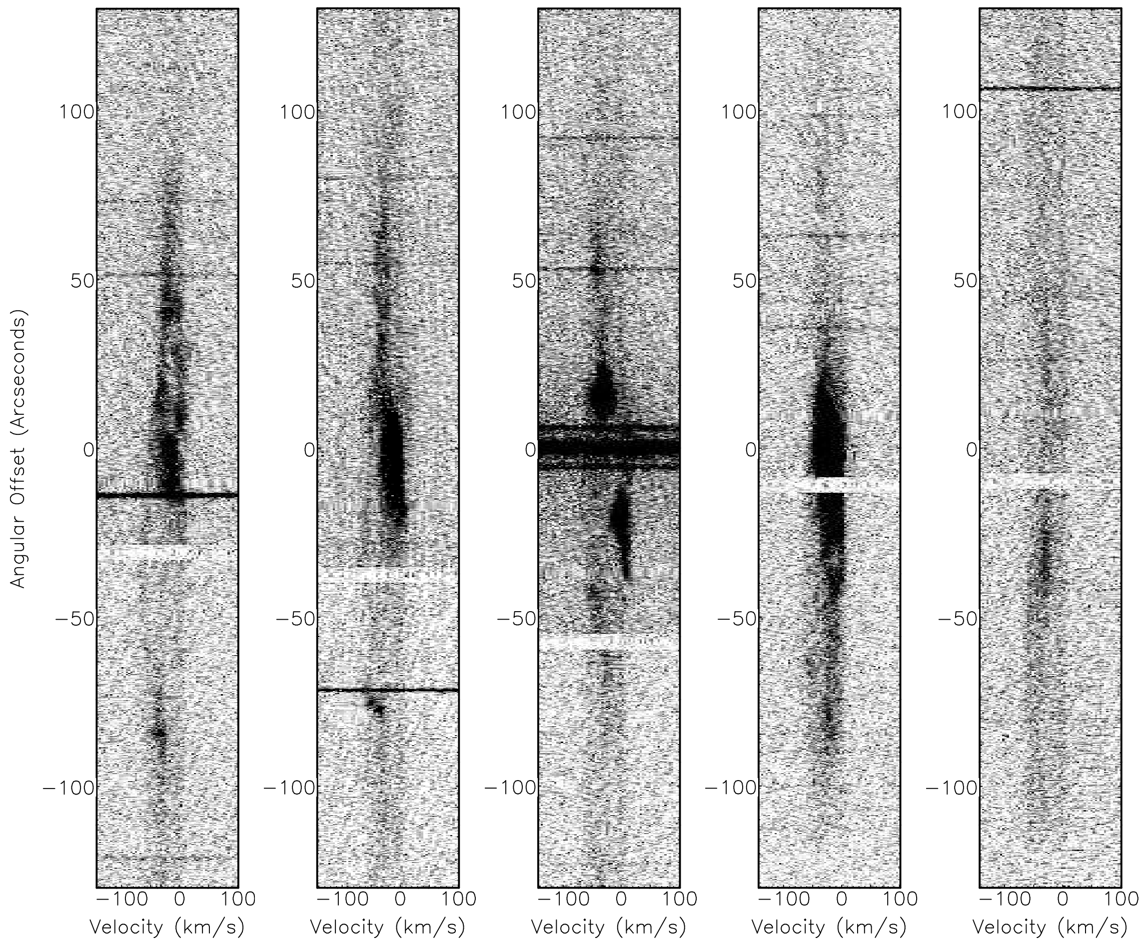
Smith et al. (2007) added further evidence through the comparison of line strengths between [N II]6584 Å and Hα, concluding that the nebula is nitrogen-rich and as such originates from a post-main sequence object. They also derive an electron temperature from the [N II] line ratio of $T_e = 11,400$ K, which is similarly consistent with those of other planetary nebulae (Kaler 1986).

Photometric analysis of the CSPN reveals a 4.9 day period, eclipsing binary (Bond et al. 2002). Later spectroscopic analysis confirmed this period and also revealed the two stars to both be A-type with masses of about 3 $M_\odot$; there is no indication of a hotter component in the observed spectra (Exter et al. 2003). It is unclear what mechanism could lead to the formation of a planetary nebula associated with this system. It is also impossible for either star to account for the ionising flux required to illuminate the nebula, leading Bond et al. (2002) to put forward the possibility that the system is actually a triple with a distant, and as yet undetected, third WD component which would account for both the origin and illumination of the nebular shell. However, Smith et al. (2007) speculate that the source of the ionising radiation could be the bright B2 star approximately 1′ Northeast of SuWt 2. This hypothesis could also account for the observed brightness enhancement in the Northeastern edge of the nebular ring and would require the star to be at a similar distance to SuWt 2. They conclude that further investigation is required to assess the validity of this hypothesis. It is also possible that the nebula is actually seen in recombination (Exter et al. 2003), meaning no current source of ionising radiation is required.

In this paper we present longslit spectroscopy of SuWt 2, from which, combined with deep narrow-band images (see Figure 1), we derive a spatio-kinematical model of the nebula, with the aim of probing the nature of the relationship between the nebula and the double A-type system apparently at its centre.

2 OBSERVATIONS AND DATA REDUCTION

The narrow band [N II]6584 Å image of SuWt 2 shown in Figure 1 was obtained using the ESO Multi-Mode Instrument (EMMI, Dekker et al. 1986) on the 3.6-m ESO New Technology Telescope (NTT) on 1995 April 20 with an exposure time of 1000 s and seeing of 1″ (the pixel scale of EMMI in this mode is 0.27″ per pixel). The image shows the bright, nebular ring and much fainter lobes extending to the Northeast and Southwest of the ring, which were first alluded to by Exter et al. (2003) but have never before been presented in such a deep image. The ring is almost elliptical, but somewhat irregular and slightly wider to the Northwest. It can be seen, by comparing the two panels in Figure 1, that the bright nebular ring appears much thicker and more regular when shown at high contrast, as noted by Smith et al. (2007). The lobes seen to be protruding to the Northeast and Southwest of the ring appear to show the bipolar morphology typical of many ring-PNe (for example; IC 2149: Vázquez et al. 2002, Me 1-1: Pereira et al. 2008 & WeBo 1: Bond et al. 2003). The nebula can be seen to exhibit brightness variations across not only the ring, as noted by Smith et al. (2007), but also in the bipolar lobes; both lobes appear brighter along their Northwestern edges and the lobe protruding to the Northeast appears brighter than its Southwestern partner. West (1976) suggested that the observed Balmer decrement indicated some obscuration, particularly in the Western part of the ring. Furthermore, the bright star appearing inside the nebular ring, the double A-type binary, can clearly be seen to be offset by approximately 4″ North and 2″ East from the ring's centre as found by ellipse fitting.



(a) Slit 1 (b) Slit 2 (c) Slit 3 (d) Slit 4 (e) Slit 5

Figure 2. The observed [N II]6584 Å PV arrays from slits 1 to 5 (see Figure 1). Note that the gap between the two CCD chips appears as a white band at negative angular offsets.

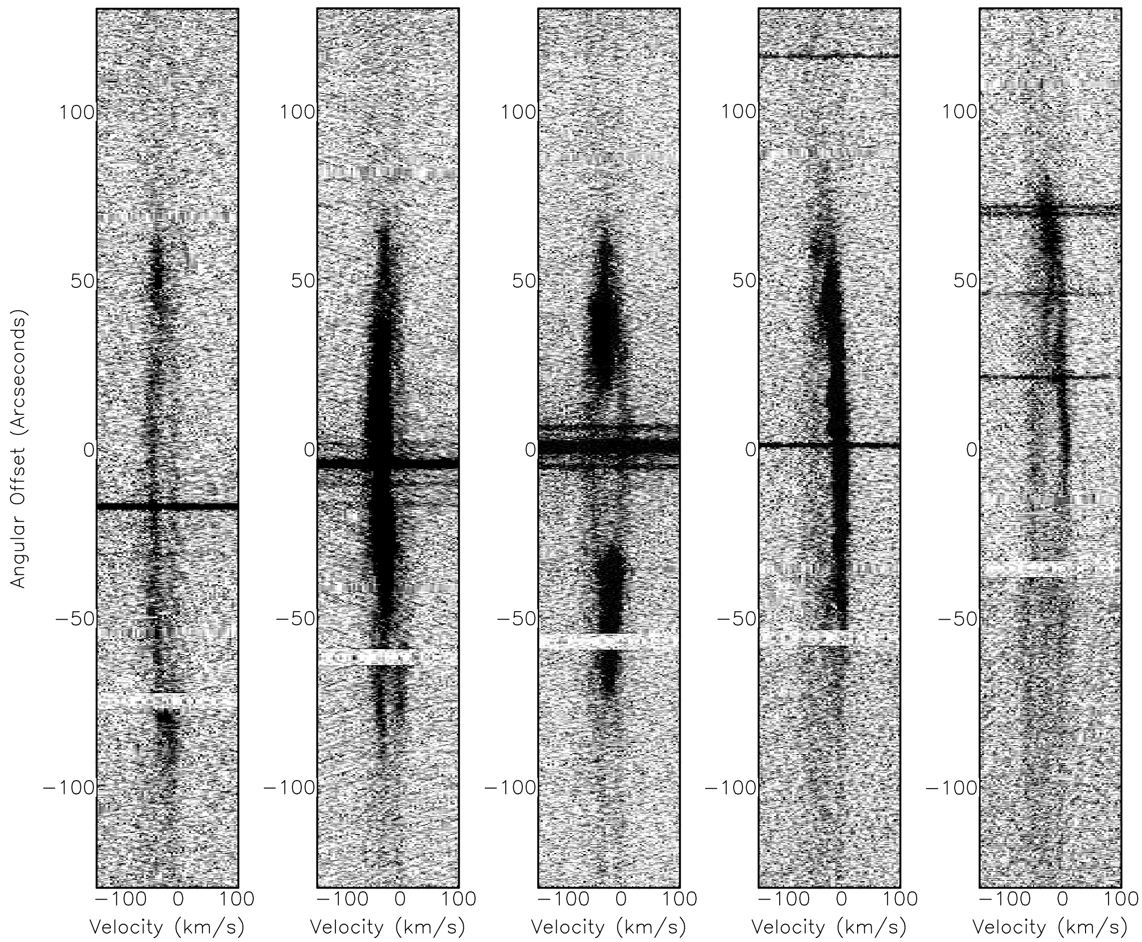
Spatially resolved, longslit emission-line spectra of SuWt 2 have been obtained with EMMI on the NTT. Observations took place in 2005 March 2-4 using the red arm of the spectrograph which employs two MIT/LL CCDs, each of 2048×4096 15 μm pixels ($\equiv 0.166''$ per pixel), in a mosaic. There is a gap of 47 pixels ($\equiv 7.82''$) between the two CCD chips which can be seen in the observed spectra.

EMMI was used in single order echelle mode, with grating #10 and the narrowband Hα filter (#596) to isolate the 87$^{\rm th}$ echelle order containing the Hα and [N II]6584 Å emission lines. Binning of 2×2 was used giving spatial and spectral scales of $0.33''$ per pixel and 3.8 km s^{-1} per pixel, respectively. The slit had a length of $330''$ and width $1''$ ($\equiv 10$ km s^{-1}). All integrations were of 1800 s duration and the seeing never exceeded $1''$.

Data reduction was performed using STARLINK software. The spectra were bias-corrected and cleaned of cosmic rays. The spectra were then wavelength calibrated against a long exposure ThAr emission lamp, taken at the start of each night. The calibration was confirmed using short Ne emission lamp exposures throughout the night, and by checking the wavelengths of skylines visible in the exposure. Finally the data were rescaled to a linear velocity scale (relative to the rest wavelength of [N II]6584 Å taken to be 6583.45 Å) and corrected for Heliocentric velocity.

In total, ten integrations were obtained, five inclined at 9° to the minor axis of the nebular ring at a PA = 56° (numbered 1 to 5) and five inclined at 87° to the minor axis of the nebular ring at a PA = −40° (numbered 6 to 10). The slit positions are shown on the deep image of SuWt 2 in Figure 1. The fully reduced position-velocity (PV) arrays for [N II]6584 Å emission are shown in Figures 2 and 3.

The y-axis zeroes (spatial dimension) of the PV arrays are set to the point at which the slit crosses either the major (slits 1 to 5) or the minor (slits 6 to 10) axis of the nebular ring. Here both the major and minor axes are taken to be through the bright double A-type binary star. Note that the spectrum of the double A-type binary is not spatially centred between the bright regions of emission from either side of the nebular ring [Figure 3(c)], confirming that the binary does not lie at the geometric centre of the nebula. Although slits 7 and 9 [Figures 3(b) and (d)] show stellar continuum at approximately $0''$, these are merely coincidental field stars and only slits 3 and 8 [Figures 2(c) and 3(c)] actually cross the double A-type binary. Similarly both slits 3 and 8 appear to show three stellar continua around zero arcseconds,



(a) Slit 6 (b) Slit 7 (c) Slit 8 (d) Slit 9 (e) Slit 10

Figure 3. The observed [N II]6584 Å PV arrays from slits 6 to 10 (see Figure 1). Note that the gap between the two CCD chips appears as a white band at negative angular offsets.

this is actually an artefact of the system resulting from the comparative brightness of the double A-type binary relative to the nebular emission.

It can be seen from the PV array of slit 3 [Figure 2(c)] that the nebular ring is tilted such that its Northeastern side is towards the observer (assuming that it is expanding radially outwards). The PV array from slit 8 [Figure 3(c) appears to show a 'velocity ellipse' with very bright end components where the slit crosses the bright ring, and much fainter red and blue components connecting the bright ends. The bright emission in slits 7 and 9 [Figures 3(b) and (d)], which cross the Northeast and Southwest limbs of the ring, again show that the Northeastern part of the ring is blue-shifted and the Southwestern part is red-shifted.

The PV array from slit 1 [Figure 2(a)] shows that emission from both the brighter Northeastern lobe and the fainter Southwestern lobe is split into two components out to at least $50''$. This splitting can also be seen in slits 2 to 5, [Figure 2], particularly in the Southwestern lobe. Slits 6 and 10 [Figure 3(a) and (e)], which do not cross the bright ring, show velocity ellipses in their PV arrays, indicating that the two lobes have a hollow-shell structure.

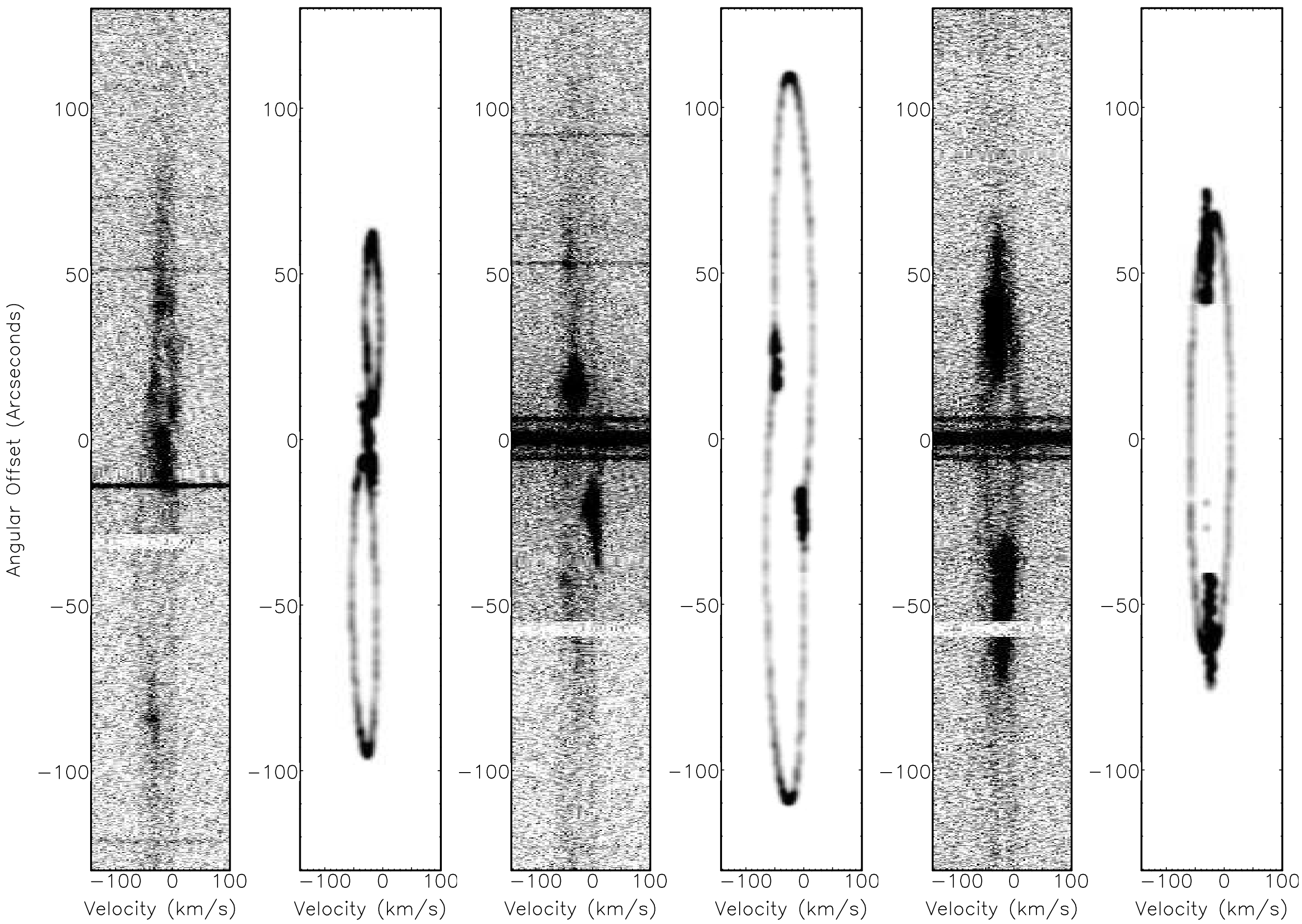
Other noticable features include a compact bright component in slits 1 at $-80''$ and 2 at $-70''$ (Figure 2(a) and (b)), and a double component in the emission from the region just beyond the Southeastern edge of the ring which is most apparent in Slit 7 [Figure 3(b)]. Faint emission can be seen extending out beyond $\pm 100''$ along all the slits.

3 ANALYSIS

A spatio-kinematic model of the [N II]6584 Å emission from SuWt 2 has been derived in order to confirm that its structure is indeed bipolar and to constrain the derived systemic velocity so that this can be compared to the systemic velocity of the double A-type binary.

The model was developed using SHAPE (Steffen & Lopez 2006) and compared to the observed [N II]6584 Å emission, which has a significantly greater intensity and less thermal broadening than the Hα emission. The observed Hα profiles are also contaminated by background galactic emission.

As a starting point, it was assumed that the visible ring of SuWt 2 is, in fact, circular, and by deprojection an inclination of $68^\circ \pm 2^\circ$ was derived. This value is in reasonable



(a) Slit 1 (b) Synthetic slit 1 (c) Slit 3 (d) Synthetic slit 3 (e) Slit 8 (f) Synthetic slit 8

Figure 4. A selection of the synthetic PV arrays derived from the closed bipolar model, shown with the corresponding observed [N II]6584 Å arrays.

agreement with the value of $64^\circ \pm 2^\circ$ found by Smith et al. (2007) who used the same method but a different image. The model nebula consists of a bright torus (giving rise to the observed ring) and fainter, symmetric, bipolar lobes. A Hubble-type flow was assumed, with the same scale velocity for each nebular component (torus and bipolar lobes). The model parameters (size, shape, expansion scale velocity, etc.) were manually varied, and the results compared by eye to the observations, both spectral and imaging, until a best-fit was found. The best-fit model has a scale velocity equivalent to a 28 km s^{-1} expansion velocity (from the nebular centre) for the torus and a systemic velocity of -25 ± 5 km s^{-1}. Both open and closed bipolar lobe models were tested, the observed spectra from the lobes are too faint and irregular to conclusively distinguish between these two alternatives. It seems that the Northeastern lobe is better matched by a closed model whereas the Southwestern lobe is better matched by an open model. It is not unheard of to find nebulae with components inclined with respect to each other (for example; Menzel 3 - Santander-García et al. 2004), however there is no evidence that the lobes are inclined at a significantly different angle to the ring.

A selection of synthetic PV arrays extracted from the closed lobe model are shown in Figure 4, together with the corresponding observed data. The synthetic arrays have been convolved in both spatial and spectral dimensions to reflect the observed spatial and spectral resolutions.

3.1 Comparison of model to data

The bright emission from the ring is generally well reproduced by the synthetic data (Figure 4), although the model torus appears at first sight to be larger than the observed bright ring. This is because the model torus has dimensions matching the full extent of the ring, but does not include the significant brightness variations observed across the ring. The spectra confirm that the emission from the faint, outer part of the ring is kinematically consistent with the emission from the bright, inner part. The model PV array from slit 8, [Figure 4(f)], which lies close to the major axis of the ring, reveals that the bright, end components of the 'velocity ellipse' are from the bright ring, whereas the connecting faint components are in fact from the much fainter bipolar lobes. The faint emission from the lobes can also be seen on slits 7 and 9 [figure 3(b) and (d)], where slit 7 shows the blue-shifted edge of the bright ring, and a faint red-shifted component from the red-shifted lobe behind it, and slit 9 shows the red-shifted edge of the bright ring and the faint blue component from the near-side lobe which lies in front of it. The identification of the observed ring as a flattened equatorial ring structure rather than a limb-brightened ellipsoid is consistent with the findings of Smith et al. (2007), based on their intensity profile analysis of the image.

The bright emission around $0''$ offset from slit 1 [Figure 4(a)] is seen to originate in the outer edge of the torus and would not be matched by a model with a smaller torus. On the irregular Northwestern part of the ring, some emission appears from within the region that would be occupied by the model torus. However if the torus were to be offset to the Southeast to accommodate this irregularity, the model would then fail to reproduce the observed velocity structure of slits 6 to 10.

The faint emission from beyond the extent of the bright ring is generally consistent with a bipolar structure, although the brightness asymmetry between the Northeast and Southwest of the nebula is not included in the model. Neither the relatively bright, double velocity component observed at around $-70''$ in slits 7 and 8 [Figure 3(c) and (d)] nor the compact, bright structure appearing on slits 1 and 2 [Figures 2(a) and (b)] between $-70''$ and $-90''$ are reproduced by the model, although these features are almost certainly associated with the nebula, due to their similar velocities. One possibility is that the compact bright feature marks the nebular rim or opening. This is, however, unlikely, because the faint emission seen at more negative angular offsets indicates that the bipolar lobe continues beyond this point. It is more likely to be as a result of some filamentary structure in the nebular shell. It is of note that this feature cannot be seen on the deep image of SuWt 2 (Figure 1), however it is unclear whether this is as a result of transmission wavelength variations (of the filter) with angle of incidence (and therefore field position, see Ruffle 2006) or that it is simply too faint.

All the PV arrays show what appears to be a very faint component at 0 km s^{-1} along the full extent of the slit. This may indicate the presence of a large halo surrounding the nebula, similar to those shown in Corradi et al. (2003), or simply be faint galactic emission.

3.2 Distance estimate and kinematical age

There is, as yet, no published distance for SuWt 2, but an estimate of the distance to the double A-type binary can be made by taking $m_v = 11.99$ (and assuming both stars of of equal magnitude), $E_{b-v} = 0.4$ (Exter, priv. comm.) and the spectral type as A3V ($M_v \sim 1.5$, Cox 2000). This gives a value of approximately 1 kpc.

If it is assumed that the nebula is at the same distance as the double A-type binary, then the size of the nebular ring is ~ 0.44pc and the lobes even larger. With the same assumption, the expansion velocity of the torus can be converted into a kinematical age of 7600 ± 1500 years (or more generally, 7600 ± 1500 years kpc^{-1}).

3.3 Systemic velocity of the nebula

The Heliocentric systemic velocity of the PN was found to be -25 ± 5 km s^{-1}. This is somewhat lower than the value of -40 ± 9 km s^{-1} found by West (1976). However, if one considers that their value is derived from lower spectral-resolution observations and that the nebula is much brighter on the blue-shifted side, it is far from unreasonable to conclude that their value was taken as the velocity at the brightness peak of the nebula (using this method for our own slits 3 and 8 we determine velocities of -38 ± 3 and -37 ± 4 km s^{-1}). Our preferred value of -25 ± 5 km s^{-1}, however, is determined through comparison of model spectra to observations (and as such is not biased by the brightness variations across the nebula).

4 DISCUSSION AND CONCLUSIONS

High spatial and spectral resolution longslit [N II]6584 Å spectra have been obtained from the ring-like PN SuWt 2. These spectra, together with a deep [N II]6584 Å image, have been used to derive a spatio-kinematic model comprising a bright torus encircling the waist of a fainter bipolar nebular shell. The symmetry axis of the model nebula is inclined at $\sim 68°$ to the line-of-sight. A Hubble flow is assumed with an expansion velocity for the torus of 28 km s^{-1}, which is consistent with typical PNe expansion velocities, further confirming the nature of SuWt 2. The heliocentric systemic velocity of the PN was found to be -25 ± 5 km s^{-1}.

The bright double A-type binary is slightly offset from the geometric centre of the nebula (Smith et al. 2007 and this paper), which may indicate that it is not actually the central star, although it is not uncommon to find CSPN offset from their nebular centres, particularly in ring nebulae like SuWt 2 (Pereira et al. 2008). The eclipsing nature of the binary (Exter et al. 2003) implies that the inclination of the binary plane is $\sim 90°$, which is substantially different from the inclination angle of the nebula. This would seem to rule out either star as the nebular progenitor, if it is believed that the orientation of the nebula follows that of the central binary system (e.g. Mitchell et al. 2007). Moreover, the binary is a double A-type system meaning neither component can be the nebular progenitor without invoking a born-again scenario (considered unlikely due to the determined parameters of the stars, Bond et al. 2002).

However, it is possible that the nebula was formed from the third component of a triple system (Bond et al. 2002). In this case, the plane in which the A-type binary orbits the progenitor CSPN would be expected to be similar to the nebular inclination. One would also expect to see a periodic variation in the systemic velocity of the A-type system (as it orbits the third star). Exter (paper in prep.) finds that this systemic velocity does show some variation (priv. comm.), with a maximum observed deviation of ~ 21 km s^{-1} (corresponding to a systemic velocity of -4 km s^{-1}) from the nebular recession velocity of -25 km s^{-1} reported in this paper. This indicates that an association between the nebula and the AA binary (with possible progenitor companion) cannot be ruled out on purely kinematic grounds. A triple-progenitor scenario is also supported by the unusually slow rotation period seen in the A-type binary, which could have resulted from an interaction with a third star (Bond et al. 2008). However, as yet there is no direct observational evidence for such a third component.

It has previously been noted that a double A-type system would not provide sufficient ionisation to illuminate the nebula. Smith et al. (2007) speculate that the bright star to the Northeast of the nebula could be the ionising source. However, if the double A-type binary has a wide companion white dwarf, which would have been the nebula progenitor (Bond et al. 2002), this would obviously provide the ionising source for the nebula. Alternatively the CSPN may have faded such that the nebula is seen in recombination (Exter et al. 2003). This would imply that the nebula is very old. It is difficult to estimate the age of SuWt 2 as its distance is unknown, however, based on the distance of 1 kpc to the double A-type binary derived in Section 3.2, the kinematical age of the ring, assuming it is radially expanding at 28 km s^{-1}, is $\sim$ 7600 years which is not particularly old for a PN. Therefore if the central star has faded to the extent that it can no longer ionise the surrounding nebula, this would imply that SuWt 2 is considerably older and hence lies much further away. Although this could offer a possible explanation as to why the central star has yet to be directly observed, it is, however, very unlikely as at such a distance the physical size of the nebula would be extremely large.

A connection between the double A-type binary and SuWt 2 cannot be ruled out and a detailed radial velocity study of the binary system would hopefully shed more light on the nature of the relationship between the two.

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