Kinematics of the Pencil Nebula (RCW 37) and its association with the young Vela supernova remnant RX J0852.0-4622

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ABSTRACT
The association between the Pencil nebula (RCW 37, NGC 2736), the Vela X-ray fragment D/D’ and the recently discovered new X-ray supernova remnant (RX J0852.0-4622) in Vela is investigated. Recently published Chandra images of D/D’ are compared with optical images of RCW 37 and confirm the close association of the two objects. New optical line profiles of RCW 37 from an extended slit position passing through this unusual optical nebula are presented. They reveal a partial velocity ellipse with expansion velocities of around 120 km s⁻¹. Various scenarios for the origin of the nebula are considered and the evidence of a link with RX J0852.0-4622 is reviewed. A funnel of gas similar to those in the Crab and DEM34a SNRs is not ruled out but a more plausible explanation may be that a ‘wavy sheet’ is responsible. We suggest that RX J0852.0-4622 is located within the older larger Vela SNR and that some of the X-ray gas from RX J0852.0-4622 has collided with the dense H i wall of the older remnant. This gives rise to the morphology and velocity structure of the optical emission and explains the unusual X-ray emission from this portion of the supernova remnant. If our hypothesis is correct, a distance prediction of 250 ± 30 pc can be made, based on recent measurements of the distance to the old Vela SNR. This is at the lower end of the range of distances quoted in the literature would confirm unusual nature of this young nearby supernova remnant.

Key words: supernova remnants - ISM: individual: RX J0852.0-4622 - ISM: individual: RCW 37 - X-rays: ISM

1 INTRODUCTION
RX J0852.0-4622 is a young nearby supernova remnant (SNR) recently discovered (Aschenbach 1998; Iyudin et al. 1998) near the southeastern perimeter of the well known old Vela SNR. RX J0852.0-4622 has generated much interest since the distance and age could be as low as 200 pc and 700 yr respectively and thus it could have been generated by the nearest supernova explosion in recent human history.

The SNR was discovered in Rosat hard X-ray data (shown as contours in Fig. 1) and at these energies has a shell-like morphology. There is no obvious optical counterpart to the main body of the SNR but Redman et al. (2000) showed that a fragment of X-ray emission (labelled D/D’ by Aschenbach et al. 1995) coincides closely with a bright optical nebula, RCW 37. The X-ray fragment is located just beyond the main circular body of the remnant and is clearly visible in hard X-ray images. The main X-ray shell is not complete and there is a break in the emission in a direction coincident with that of the X-ray fragment and with RCW 37 (see Fig. 1). Redman et al. (2000) suggested that RCW 37 is physically associated with RX J0852.0-4622 and represents a venting of hot gas from the interior of the remnant to beyond the roughly circular shell as delimited in the X-ray.

RCW 37 (NGC 2736) was discovered in the 1840s by Sir John Herschel and is a bright optical nebula known to amateur astronomers as the Pencil Nebula (Fig. 2). The unusual, intricate morphology of the nebula and its large size and brightness make it surprising that there have been few studies of this object. Its apparent location at the dust-obscured eastern side of the six degree diameter old Vela SNR, away from the photogenic western filaments may be one reason. Blair et al. (1995) used the Ultraviolet Spectrometer on the Voyager 2 spacecraft to investigate O vi emission from RCW 37 and inferred that shock speeds of 160 - 300 km s⁻¹ are present. This is consistent with the limited line profiles obtained by Redman et al. (2000) at the edge of the nebula. The morphology of the nebula is striking and led Redman et al. (2000) to suggest that its funnel-like appearance could
be taken to indicate that there is indeed a collimated flow of hot gas taking place from the remnant interior. Alternatively, a pre-existing cloud could be being shocked by escaping hot gas. The kinematics were not sufficient to establish clearly the dynamics of the nebula.

In this paper, new optical forbidden line profiles from RCW 37 from an extended slit position across the filamentary bulk of RCW 37 are presented in order to determine the structure and dynamics of the nebula. The kinematics are discussed and used to describe a model for the origin of RCW 37 that places it in the context of RX J0852.0-4622 and the main Vela SNR. It is argued that RX J0852.0-4622 is embedded within the older larger Vela SNR.

\section{2 OBSERVATIONS AND RESULTS}

Contours of the smoothed hard ($E > 1.3$ keV) RASS discovery data of RX J0852.0-4622 are shown in Fig. 1 overlaid on an ESO archive IIaJ (green) image of the region. Fig. 2 is an ESO archive green image of RCW 37. Contours of smoothed Chandra ACIS data of D/D' obtained by Plucinsky et al. (2002) are shown in Fig. 3 overlaid on an ESO archive green image of RCW 37.

Spatially resolved, longslit echelle spectra of the [O III] 5007 Å and [S II] 6716 & 6731 Å emission lines were obtained with the Manchester echelle spectrometer (MES; Meaburn et al. 1984) combined with the f/7.9 Cassegrain focus of the Anglo-Australian telescope (AAT). The observations were made on 2001 February 13-14 during reasonable seeing. A 90 Å wide interference filter was used to isolate the echelle order containing the emission lines. A Tektronix CCD with $1024 \times 1024$ 24 µm square pixels was the detector. A slit width of 150 µm ($\approx 11$ km s$^{-1}$ and 1") was used. The CCD was binned by a factor of two in the spatial direction to give $512 \times 0''.32$ pixels along the slit length. Each integration was debiased and wavelength calibrated to better than 0.5 km s$^{-1}$ using Thorium–Argon spectra obtained between exposures. Data were obtained from five slightly overlapping east-west slit lengths to produce an effective slit length of about 700". The slit position is marked on Fig. 3. The data from each slit was reduced and the five were mosaiced together.
2.1 Kinematics

A negative gray-scale representation of a position-velocity (PV) array of [O III] 5007Å line profiles is displayed in Figs 4 and 5. Data from the full effective slit length is displayed in Fig. 4 while Fig. 5 is the section of the data from the eastern side of the effective slit. The bright vertical band is the spectrum of a star intersected by the slit which can be used as a reference point between the two figures. The following features can readily be seen. Throughout the data at zero heliocentric radial velocity there is faint background [O III] 5007Å emission. The bright eastern edge of the nebula begins at an offset of around 40″. The data here exhibit velocity knots and small velocity loops that correspond to the complex filaments readily seen in Fig. 4. With increasing offsets, the line profiles begin to split. At offsets of greater than about 300″ the profiles are no longer split and only a single faint component at positive velocities (up to ~ 120 km s$^{-1}$) is present. The positive velocity component then approaches the systemic with increasing offset and we identify the bright feature at around 700″ as being the western edge seen in Fig. 5. There is a negative velocity component from offsets of 550″ onwards that we attribute to the irregular diffuse emission present towards the western side of the nebula and not associated with RCW 37.

3 DISCUSSION

3.1 Dynamics of the nebula

The position-velocity arrays show a coherent velocity structure across the nebula. An almost complete classical velocity ellipse is clearly apparent. The morphology of the nebula is reminiscent of an incomplete funnel (or tube) but could also be simply a curved sheet of emission. This is discussed below but, broadly speaking, the velocity data indicate gas that is expanding radially at about 100 km s$^{-1}$. At the edge of the nebula, the motion is into the plane of the sky while towards the middle there is a velocity splitting between the near and far side of the emitting gas that increases towards the middle of the nebula. Eventually, the red-shifted emission disappears while that the blue-shifted emission returns to the systemic. At this point there is background emission (seen in Fig. 2) that contributes at negative velocities.

3.2 Funnel or Wavy sheet?

In the IIIaJ image in Fig. 2 RCW 37 exhibits a curved morphology but there is also a parallel line of emission to the west. This led Redman et al. (2000) to suggest that together with the eastern side, the structure may form a tube/funnel for hot gas to be vented from the remnant. Just such a structure is present in the Crab SNR (e.g. Fesen & Staker 1993), and also in the more evolved remnant DEM 34a (Meaburn 1987). The previous kinematic data were not sufficient to test this possibility. The new kinematic data across RCW 37 are nearly exactly those expected of a funnel of circular cross-section undergoing radial expansion. However, for a funnel, there should be a similar velocity splitting from the western edge towards the central of the putative funnel as for the eastern edge and so the ionization of the funnel would have to be incomplete. Another difficulty with this interpretation is that such a funnel would be pointing to the centre of the young SNR. Also the soft RASS X-ray maps reveal a more extensive bow shaped feature and it is only the hard RASS X-ray component of this that is adjacent to RCW 37 (Aschenbach 1998).

A plausible alternative interpretation is that the nebula gas is in the form of a thin ‘wavy sheet’ (Hester 1987) of emission which at the eastern side overlaps along the line of sight. At the western side the single thin sheet curves to become edge on, forming the western edge. Interestingly, whether the single sheet curves into or out of the plane of sky is ambiguous kinematically. The whole system appears to be undergoing a bulk expansion generating double-peaked line profiles at the eastern side where the sheet overlaps itself.

3.3 Association with RX J0852.0-4622

Redman et al. (2000) showed that RCW 37 and D/D’ are spatially coincident but the RASS data (see Fig. 3) were not of high enough resolution to allow further investigation and the unlikely possibility of a chance alignment could not be ruled out. The new Chandra data of D/D’ displayed in Fig. 3 show morphological similarities to the optical data (see Plucinsky et al. 2002 for an excellent image). There is an edge to the X-ray emission from D/D’ that runs parallel to the bright optical edge of RCW 37 and the X-ray peak is close to the peak of the optical emission. A chance alignment can be ruled out in the light of this new data. Plucinsky et al. (2002) argue that the morphology of D/D’ makes it unlikely that the object is a discrete ‘bullet’ of ejecta and favour a shock break-out model where a change in density ahead of the old Vela SNR boundary has led to a localised distortion in the shock-front. More controversial is whether, as suggested by Redman et al. (2000), RCW 37 and D/D’ are physically associated with RX J0852.0-4622. They argued that RCW 37 and D/D’ represent a venting of hot gas from the interior of the remnant to beyond the roughly circular shell as delimited in the X-ray. This view differs from that of Slane et al. (2001a) and Plucinsky et al. (2002) who argue that the X-ray spectrum of D/D’ shows enhanced abundances of O and Ne and is thermal in contrast to the spectrum of the main remnant body which is non-thermal. This led Slane et al. (2001a) to suggest that RCW 37 and D/D’ are not associated with RX J0852.0-4622. However, as Plucinsky et al. (2002) note, non-equilibrium ionisation models do not yield such enhanced abundances. Non-equilibrium models have to be used when the ionisation timescale is longer than the dynamical timescale as is likely to be the case for younger remnants. This is clearly important for RCW 37 and D/D’ since the dynamical timescale is either 12,000 years or 1000 years depending to which SNR it is attributing. Plucinsky et al. (2002) calculate an ionisation timescale range of $7.0 \times 10^{10} < n_{e} t < 7.0 \times 10^{11}$ cm$^{-3}$ s and find an upper limit of $4.0 \times 10^{11}$ cm$^{-3}$ s by assuming an ambient density of 1 cm$^{-3}$ and a timescale of 12,000 years. However, this density is likely to be an underestimate since Redman et al. (2000) used [S II] 6716 & 6731 Å line ratios to measure the local electron density within RCW 37, finding values of $n_{e} \sim 10^{3}$ cm$^{-3}$. The ambient density will have been up to a quarter of this value if there is little post-shock cooling but less if cooling and compression has occurred. Clearly, an
Figure 4. Position-velocity array of $\text{[O\textsc{iii}] 5007\AA}$ line profiles mosaiced from five consecutive slit positions. The dark vertical line is the spectrum of a star intersected by the slit. The vertical axis is heliocentric radial velocity.

Figure 5. Data from previous figure, cropped and rescaled to show the brightest velocity features at the eastern edge of RCW 37. The dark vertical line from the intersected star can be used as a reference point between the two figures. The vertical axis is heliocentric radial velocity.
ambient medium density of \( \sim 10 \, \text{cm}^{-3} \) and a timescale of \( \sim 1000 \, \text{yr} \) or less would also be consistent with the data. It seems reasonable to suggest therefore that the differing spectral properties between the main shell and D/D' are due to non-equilibrium ionisation effects. A reason for this, that D/D' has impacted the old wall of the Vela SNR is discussed below.

Combi et al. (1999), using the data of Lucas et al. (1999), mapped radio emission from RX J0852.0-4622 and have shown that a patch of non-thermal radio emission from the remnant beyond the X-ray shell also coincides with D/D' and RCW 37 (see their figure 1). Interestingly, they identify a further three patches of radio emission beyond the main X-ray remnant boundary. This could indicate that the X-ray shell is fragmented and interior gas is escaping through several points. This would strengthen the case that RCW 37 and the emitting gas giving rise to the X-ray source D/D' are indeed associated with RX J0852.0-4622. However, the region is very confused and Duncan & Green (2000) argue that two of the features that Combi et al. (1999) identify are part of an (unrelated) extended structure and that the third (feature C, in the Combi et al. 1999 nomenclature) is isolated and unconnected to RX J0852.0-4622. Duncan & Green (2000) suggest that none of the Combi et al. (1999) features are associated with RX J0852.0-4622. Follow-up observations will likely clarify this important issue.

### 3.4 RCW 37, RX J0852.0-4622 and the old Vela SNR

The velocity structure and X-ray properties described above may be explained in the following simple way. We suggest that RX J0852.0-4622 exploded within the main Vela SNR. The Vela SNR is approximately 11,000 yrs old and by this stage it will have swept up the interstellar medium into a cold dense shell at its boundary. The unusual optical morphology, and X-ray properties of RCW 37 and D/D' are simply due to a localised venting of hot gas from RX J0852.0-4622 impacting the old wall of the Vela SNR. This creates an X-ray 'hot spot' and a curved sheet of optical emission tracing the inside edge of the old shell wall. Dubner et al. (1998) have mapped the whole Vela SNR in H I and find it to be a located in a thin shell closely correlated with the X-ray emission of Aschenbach et al. (1999). This is the wall with which we conjecture the blast wave is interacting. The hot gas may even have caused localised expansion of the wall at this point - the eastern boundary of the Vela SNR as mapped in soft X-rays by Aschenbach et al. (1999) is distorted at the position of RCW 37 and D/D' from the interior of the RX J0852.0-4622 led Slane et al. (2001a) to conclude that the two objects are unrelated to each other (see above). However, in the context of the above scenario, differing X-ray properties are expected since the X-ray gas in fragment D/D' has only recently impacted the dense neutral wall of the older Vela SNR resulting in non-equilibrium ionisation. The new Chandra data are indicative of a shock break-out (Plucinsky et al. 2002) which in our model would be caused by the impact of the X-ray emitting gas with the neutral wall. Interestingly, to the north of the main body of RX J0852.0-4622 there is another much fainter X-ray fragment than D/D'. It coincides with a knot of non-thermal radio emission (feature C in Combi et al. 1999) but there is no obvious optical emission associated with it. We would expect that the X-ray spectra of this gas is more akin to that of RX J0852.0-4622 than to D/D' since it is probably not interacting with a pre-existing obstacle.

Duncan & Green (2000) plot radio surface brightness of known galactic supernovae against diameter and find that unless RX J0852.0-4622 is located at around 1 kpc, it is extremely faint. Duncan & Green (2000) note the unusual radio properties of RX J0852.0-4622 and, as concluded by others, suggest that the remnant must be expanding into a hot low density medium. If, as argued above, RX J0852.0-4622 is located within Vela SNR then the hot interior of the older remnant can provide just such an environment. The radio faintness of RX J0852.0-4622 could have important implications in the investigation of supernova remnants in extreme environments (such as the radio SNR in the starburst galaxy M 82 by Pedlar and co-workers, see e.g. McDonald et al. 2001; Pedlar et al. 1993; Wills et al. 1997).

### 3.5 The distance to RX J0852.0-4622

Estimates of the distance to RX J0852.0-4622 are very uncertain, if it is not assumed to be physically associated with the old Vela SNR. Duncan & Green (2000) have summarised some of the difficulties. Aschenbach (1998) estimate that the lack of absorption of the X-ray flux gives an upper limit of 1 kpc. Comparison with the surface brightness of SN 1006 gives a lower limit of 200 pc. Lyudin et al. (1998) date the remnant at 700 yr giving a distance of \( \sim 200 \, \text{pc} \) but this is based on rather uncertain \( ^{44}\text{Ti} \) yields and an estimated shock velocity. The calcium decay products of \( ^{44}\text{Ti} \) were detected by Tsunemi et al. 2000, giving an age of between 630 and 970 yr. Burgess & Zuber (2000) re-examined nitrate abundance data from Antarctic ice cores obtained by Rood et al. (1979) which had peaks that seemed to correspond to historical supernovae. They suggested that an unidentified peak at \( \approx 700 \) yr could have been caused by RX J0852.0-4622 though of course, there is no indication of the location in the sky of the event. Note however that the claim by Rood et al. (1979) that SN events can be detected in this way has been questioned in subsequent studies (e.g. Herron 1982, Risbo et al. 1981). H I studies cannot constrain the distance to RX J0852.0-4622 because of the highly confused nature of this region which is close to the galactic plane (Duncan & Green 2000).

Slane et al. (2001b) use the non-thermal spectrum of portions of RX J0852.0-4622 with a power-law model of the emission to compare derived H I column densities with other parts of the Vela SNR. Slane et al. (2001b) acknowledge the uncertainties in then scaling the differences in column density to obtain a distance but argue that the higher column density of RX J0852.0-4622 implies that it is located somewhat further to the back of the Vela SNR and the Vela molecular ridge at 1 – 2 Kpc.

The lack of an obvious compact central object within the remnant also seemed at first to indicate that RX J0852.0-4622 must be located at a large distance (Mereghetti 2001). However, an X-ray source (but with no associated optical counterpart) has recently been discovered (Pavlov et al. 2001). It appears that the central object might be rather similar to that of Cas A - a radio quiet young isolated neu-
tron star. However, it is worth noting that there is a 64 ms pulsar with coordinates within the supernova remnant boundary. Due to the uncertainties involved in the distance of RX J0852.0-4622 an association cannot be ruled out (Redman & Meaburn, in prep). The various distance estimates are not consistent with each other and follow-up work is clearly required to remove the uncertainties inherent in the different techniques.

Our optical study offers a clear distance constraint if RX J0852.0-4622 was generated within the Vela SNR. Cha et al. (1999) have used optical absorption lines towards a significant sample of OB stars in the direction of the Vela SNR to constrain the distance as 250 ± 30 pc with a conservative upper limit of 390 ± 100 pc. Clearly, if indeed RX J0852.0-4622 is located within the older Vela SNR then the distance is constrained to be ∼ 250 pc. We note that if subsequent studies firmly indicate that RX J0852.0-4622 lies well beyond the old Vela SNR, then our model can be ruled out.

4 CONCLUSIONS

New [O iii] 5007 Å line profiles of RCW 37 have been presented that show the kinematics of this nebula for the first time. A partial velocity ellipse is discovered in the pv array of line profiles. The kinematics and morphology could suggest that the structure of RCW 37 is that of a thin wavy sheet of optical emission that overlaps itself towards the eastern edge and is undergoing a systematic expansion. The western edge curves towards the line of sight but does not appear to form a complete tube or funnel of emission. We compared this feature with those found towards other SNRs. The evidence that the RCW 37 optical nebula and associated X-ray feature, D/D’ are in fact part of RX J0852.0-4622 has been discussed and we conclude that it is likely that this is the case. A simple explanation for the origin of the morphology of RCW 37 is that RX J0852.0-4622 has occurred within the older, larger Vela SNR and that a portion of the supernova ejecta from RX J0852.0-4622 has impacted the pre-existing cold dense wall of the Vela SNR. The thin sheet of optical emission then traces out the inside edge of this shocked wall while the X-ray emission marks shock-heated gas. This model predicts that the distance to RX J0852.0-4622 will be similar to that of the main Vela SNR which has been recently measured to lie at 250 ± 30 pc.

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