The Vela pulsar ‘jet’:
a companion-punctured bubble of fallback material

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ABSTRACT
Markwardt and Ögelman (1995) used ROSAT to reveal a 12 by 45 arcmin structure in 1 keV X rays around the Vela pulsar, which they interpret as a jet emanating from the pulsar. We here present an alternative view of the nature of this feature, namely that it consists of material from very deep inside the exploding star, close to the mass cut between material that became part of the neutron star and ejected material. The initial radial velocity of the inner material was lower than the bulk of the ejecta, and formed a bubble of slow material that started expanding again due to heating by the young pulsar’s spindown energy. The expansion is mainly in one direction, and to explain this we speculate that the pre-supernova system was a binary. The explosion caused the binary to unbind, and the pulsar’s former companion carved a lower-density channel into the main ejecta. The resulting puncture of the bubble’s edge greatly facilitated expansion along its path relative to other directions. If this is the case, we can estimate the current speed of the former binary companion and from this reconstruct the presupernova binary orbit. It follows that the exploding star was a helium star, hence that the supernova was of type Ib. Since the most likely binary companion is another neutron star, the evolution of the Vela remnant and its surroundings has been rather more complicated than the simple expansion of one supernova blast wave into unperturbed interstellar material.

Key words: nucleosynthesis — binaries: close — stars: neutron — pulsars: individual: PSR B0833−45 — supernovae: individual: Vela — supernova remnants

1 INTRODUCTION
1.1 Basic properties of Vela
The Vela supernova remnant is a large radio supernova remnant (see Green 1988 and references therein) associated with a nearly circular X-ray shell with a radius of 4 degrees (Aschenbach et al 1995). It is centred on and physically associated with the Vela pulsar (PSR B0833−45). The traditional value of its distance is 500 pc (Green 1988), but recent evidence both from optical observations (Wallenstein et al. 1995) and X-ray data (Aschenbach et al. 1995; Fig. 1) are more consistent with half that distance. Since various quantities relevant to our work do depend on distance, we will quote their distance scaling where appropriate in terms of

\[ d \equiv \frac{d}{250 \text{ pc}}, \]

thereby implicitly adopting the closer distance as our standard value.

The pulsar has a spindown age \( \tau_{\text{sd}} \) of 11 000 yr and a spin period of 89 ms, which implies a surface magnetic field of \( 3.4 \times 10^{12} \text{ G} \) and a total spin-down energy loss rate, \( L_{\text{sd}} \), of \( 7 \times 10^{36} \text{ erg s}^{-1} \) for canonical values of neutron star parameters (\( I = 10^{45} \text{ g cm}^2 \), \( R = 10 \text{ km} \), \( M = 1.4 \text{ M}_\odot \)). Most of the spindown energy loss is not accounted for in any hitherto known emission or other sink of energy. The pulsar is moving towards the northwest (position angle \(-54^\circ\)) with a proper motion of 59 mas yr\(^{-1}\) (Bailes et al. 1990), which implies a transverse speed of 70 \( \hat{d} \text{ km s}^{-1} \). If we extrapolate back the pulsar position to 11 000 yr ago, we find that it was then near a few dots of enhanced emission near the east edge of the bubble, suggestive of this being indeed the birth location of the pulsar. Then the pulsar has a true age close to the spindown age, hence its field has been approximately constant over most of its past life and that the initial spin period was significantly shorter than the current one.

1.2 The pulsar ‘jet’
Markwardt and Ögelman (1995) found a 12 by 45 arcmin emission region in the ROSAT 0.9–2.0 keV band extending from the pulsar to the south-southwest (Fig. 1). From
bremstrahlung fits to its spectrum, they derived a temperature of 1.3 keV/k and a density, $n_b$, of $0.57 \, d^{-1/2} \, \text{cm}^{-3}$. Frail et al. (1996) report that both ASCA data at higher energies and lower-energy ROSAT data support the thermal nature of the emission.

They interpreted this feature as a hydrodynamic jet directly pushed by the pulsar, based on the fact that it is roughly aligned with the pulsar spin axis and that the derived energy flux through the jet approximately equals the pulsar spindown luminosity. They also derive the properties of the medium exterior to the region in the same way: $kT_{\text{ext}} = 0.12 \, \text{keV}$, $n_{\text{ext}} = 0.16d^{-1/2} \, \text{cm}^{-3}$.

The difficulty with the jet interpretation is that there is a momentum problem in the jet: the pulsar spindown energy loss rate is entirely in the form of electromagnetic energy (Pointing flux) and relativistic particles. Given the energy loss rate, $L_{\text{sd}}$, this means we know the momentum loss rate to be simply $P_{\text{sd}} = L_{\text{sd}}/c$. Let us assume that we somehow solve the problem of converting this roughly spherically symmetric emission of momentum into a directional flow of momentum that then pushes the jet. Conservation of momentum then imposes the requirement that $P_{\text{jet}} < P_{\text{sd}}$. But the derived jet properties violate this limit, as we can see from the energy flow and velocity of the jet which Markwardt & Ögelman derived from their work surface calculation. They found that $L_{\text{jet}} \simeq L_{\text{sd}}$ and $v_{\text{jet}} \simeq 1000 \, \text{km \, s}^{-1}$. The momentum flow through the apparently very sub-relativistic jet would then be $P_{\text{jet}} = 2L_{\text{jet}}/v_{\text{jet}}$. It follows that $P_{\text{jet}}/P_{\text{sd}} \simeq 1$, i.e. the momentum available in the pulsar emission falls short by a factor 300 of supplying the required jet momentum. The bubble therefore cannot be a true jet powered directly by the pulsar.

Another problem with the parameters of the bubble and the main SNR just outside it derived by Markwardt & Ögelman is that they find the bubble to be both hotter and denser than its surroundings. This means that its expansion into its surroundings should be almost like expansion into vacuum, i.e. proceed at the internal sound speed of the bubble, which is about $500 \, \text{km \, s}^{-1}$. But we know from its size and age that the mean expansion velocity of the bubble has only been about $50d \, \text{km \, s}^{-1}$, so unless we live at a very special time where the bubble has just become hot, this cannot be. The resolution for this conundrum was suggested to us by R. McCray, who noted that at these densities and temperatures the cooling is dominated by a forest of emission lines around 1 keV, which create the impression of a thermal peak at that energy but are not resolvable by ROSAT. The true density can easily be 10–30 times less, i.e. well below that of the main SNR. Hence the total mass of is of order $0.003d^{1/2} \, \text{M}_\odot$, and the total thermal energy content $10^{40} \, d^{-1/2} \, \text{erg}$. The main SNR just outside the bubble is too cool for line emission to be significant and the density is probably close to the value inferred by Markwardt and Ögelman.

What we propose is that the X-ray bubble is material from near the core of the exploding star that was hit by the reverse shock and thus not accelerated away strongly from the newborn pulsar. The pulsar spindown energy is absorbed by it close to the pulsar itself, and conducted throughout the bubble, powering its expansion. We discuss the formation and evolution of this bubble in sect. 2 and propose a binary companion as the reason for its asymmetric expansion. In sect. 3 we discuss the constraints on the progenitor binary that follow from the model.

## 2 THE FALBACK BUBBLE

The bubble was formed when some gas in between the fallback material and the fast ejecta stalled (Fig. 1, panel a). It was then hit by the energy flux from the newborn pulsar and started pushing into the bulk of the ejecta (Fig. 1, panel b). At the same time, the former binary companion to the pulsar ploughed through the ejecta, carving a low-density channel into it. Initially, this channel may cave in behind it due to the high external pressure. At some point, the pulsar-powered bubble catches up with the open part of the trail and starts expanding into it rapidly (panel c). When it catches (almost) up with the companion it has to adjust its speed to not overtake the companion (panel d). The trail behind the pulsar now has a somewhat tapered shape, because the expansion of the trail due to the bubble pressure has acted longer at the base, making it wider there. We now discuss the various stages in this scenario in more detail.

### 2.1 Origin and composition

Current models of supernova explosions (Woosley et al. 1994) predict that about $0.03 - 0.1 \, \text{M}_\odot$ of material near the core boundary will be stalled by the reverse shock in the envelope and undergo r–processing before escaping in a neutrino–powered wind. The wind in turn stalls at speeds $\sim 100 \, \text{km \, s}^{-1}$, much less than the bulk of the envelope, if the initial main-sequence mass of the star is in the narrow range $20 - 25 \, \text{M}_\odot$ (Fig. 1a). The model predicts that the innermost few $\times 10^{-5} \, \text{M}_\odot$ of the original bubble are composed of about 80% He and 20% mixture of r–process isotopes of atomic number 100–200, and possibly a significant fraction of isotopes of atomic number near 80–90, like Sr, Y and Zr. The bubble material should contain about $10^{-5} \, \text{M}_\odot$ of isotopes ranging from germanium to lead, including platinum group metals, krypton, xenon and the rare earths, as well as molybdenum, tungsten and tin. The rest of the bubble material comes from near the remnant mass cut, and is probably chiefly nickel, copper, zinc, calcium, titanium and vanadium.
as well as helium. In this bubble we therefore observe almost directly the conditions inside an exploding star. Since the outer layers spend significant time at higher velocities at early times in the supernova, while the wind-driven r-process region nearly stalls at late times, we expect the material from the inner layers not to be well mixed into the bulk of the supernova remnant.

Since the elemental abundances are sensitive to the explosion models, spectroscopic detection of any of these isotopes, possibly feasible with the ASCA satellite or future proposed X-ray satellites, would provide a test of explosive nucleosynthesis in supernova models. An attempt has been made to detect r-process elements in absorption in the Vela remnant (Wallerstein et al. 1995) without success. The lines of sight probed were outside the bubble, constrained by the chance positioning of background B-type stars. If the hotter bubble is over-abundant in r-process elements, as conjectured here, intermediately ionised species might be observed in emission. Unfortunately line strengths, or even wavelengths, for highly ionised isotopes beyond nickel are not available in the literature. One exception is the recently identified Kr IV line at 534.6 nm (Péquignot & Baluteau 1994); it is also possible that L or M shell emission features of high-Z elements could be detected by ASCA.

2.2 Evolution

Once the bubble has formed, it will initially cool both due to adiabatic expansion and radiative cooling, until heating by the pulsar spindown energy becomes important. The total luminosity of the nebula is less than a percent of $L_{\text{sd}}$, so most of the energy goes into heating and expanding the bubble. Indeed, the cooling time of the bubble is now 100 Myr, much greater than its age; its thermal energy expanding the bubble. Indeed, the cooling time of the bubble close to the pulsar. Ordinary thermal conduction suffices to transport the pulsar spindown luminosity across the bubble. The total luminosity of the nebula is less than a percent of $L_{\text{sd}}$, so most of the energy goes into heating and expanding the bubble. Indeed, the cooling time of the bubble is now 100 Myr, much greater than its age; its thermal energy ($10^{46}$ erg) is much less than $L_{\text{sd}}\tau_{\text{sd}} \simeq 2 \times 10^{48}$ erg, so the bulk of the injected spindown energy is not in the bubble now. In the past, the cooling time was much shorter than the expansion time because the cooling time of a constant mass of material scales very steeply with radius. Then most of the absorbed spindown energy was immediately radiated, as is the case now in the ten times younger Crab Nebula.

The expansion of the bubble into the surrounding supernova remnant is akin to the supernova remnant’s expansion itself (Fig. 3), and self-similar solutions for it exist in various regimes (see review by Ostriker & McKee 1986). The problem is more complicated than that of the supernova explosion itself because the ambient medium is expanding so the bubble blast wave encounters a decreasing density with time and must asymptotically match onto a finite expansion velocity. The energy input is not all at the beginning as with a standard supernova explosion, but the pulsar’s dipole spindown luminosity decreases with time complicating the solution further.

The slightly simpler problem of constant ambient density has been solved and we shall use it to get an idea of the solutions. For a constant rate of energy injection $L_{\text{in}}$ the flow enters a self-similar phase once the initial acceleration phase is over. The shape of $R(t)$ depends on whether radiative cooling is more important than $pdV$ work or not. Currently, radiative cooling is negligible: the cooling time scale of 100 Myr greatly exceeds the expansion time scale, which must be of order 10,000 yr, the bubble’s age. Since the (bremsstrahlung) cooling time of a constant mass of gas scales as $R^{-3}$, and the expansion time scale is a weak function of $R$, the cross-over from radiative to adiabatic expansion occurred when the bubble was 10 times smaller than it is now. Before that time the pulsar energy input was just radiated away and little power was applied to driving the expansion.

The expansion velocity of the bubble near the pulsar can be estimated from its size and the pulsar age to be about $50d\,\text{km}\,\text{s}^{-1}$. Since its internal pressure greatly exceeds that of the surrounding ejecta its expansion is best described by a self-similar power-law similar to the Sedov-Taylor solution for an adiabatically expanding blast wave, modified for continuous energy injection (Weaver et al. 1977).

The pressure in the main SNR decreases as $t^{-2}$, faster than the pressure inside the bubble at early times. Approximately $10^{4}$ years after the supernova explosion the pressure inside the bubble exceeds that of the main SNR and it starts expanding into the main SNR. The initial velocity profile depends on the exact ratio of the cooling time to the pulsar power injection at that time (which is uncertain); if the radiative cooling time is long at that point the bubble material accelerates until it reaches the self-similar expansion dictated by the balance of work done on the ambient medium and the instantaneous energy injection; if the initial expansion velocity is too large, the bubble decelerates to match the self-similar expansion profile.
The bubble is Rayleigh–Taylor unstable, with mixing time scale much shorter than the crossing time for the bubble, so material swept up by the expansion is well mixed through the bubble (Koo & McKee 1990). But given the small mass of the bubble, a substantial zone of material now still outside it should also have come from deep inside the nuclear cauldron and bear the signs of advanced nucleosynthesis, so the bubble composition will still be predominantly heavy elements and helium.

2.3 Asymmetric expansion

The expansion of the bubble should be roughly spherical if the density of the surrounding ejecta were uniform, but instead we see a very asymmetric expansion. Since the blast the density of the surrounding ejecta were uniform, but in-

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thesis, so the bubble composition will still be predominantly nuclear cauldron and bear the signs of advanced nucleosynthesis. In both cases, we have normalised to the highest likely values of the energy or mass loss rate (a very vigorous recycled pulsar or extremely active low-mass star), so one can see that the original channel is unlikely to be more than about 0.1 pc wide, rather less than the current width of 0.25$d$ pc at the narrowest point. Note that the standoff distance ahead of the Vela pulsar itself (0.25$d$ pc) is in good agreement with the value computed from Eq. (3), indicating that the value used for the external density is reasonable.

The speed of the flow down the channel can be self-regulated to the companion velocity (Fig. 4): obviously, if the bubble catches up with the companion it will run into unshocked ejecta and its expansion will slow down to that of the rest of the bubble. If it falls behind, the density it sees ahead of it becomes lower and it is heated more strongly via conduction from the rest of the bubble, causing its speed to increase again. As long as heat conduction is sufficient to keep powering the expansion and the companion speed is lower than the maximum expansion speed of the bubble (of order its sound speed), it will therefore keep up with the moving former companion. Both these requirements are fulfilled now, but as $L_{\text{opt}}$ decreases and the density and temperature of the bubble go down, the bubble expansion will start falling behind the companion motion. We therefore predict that a fast-moving former companion to the Vela pulsar should be found ahead of the bubble. Its distance to the Vela pulsar implies a projected velocity of $275d$ km s$^{-1}$ or a proper motion of 0.25 arcsec/yr.

3 THE BINARY COMPANION AND THE PRE-EXPLOSION ORBIT

The pulsar velocity is known from its proper motion to be 700 km s$^{-1}$ (Bailes et al, 1990) and in our model the velocity of its former companion is also known from its position just ahead of the bubble. This tightly constrains the initial mass of the Vela pulsar progenitor and the size of the binary orbit (fig. 1). First, while the pulsar may receive a velocity kick at birth, this is not true for the companion. Therefore, energy conservation implies that its orbital velocity in the progenitor binary must have exceeded $275d$ km s$^{-1}$. This excludes a red giant as the progenitor to the supernova, because such a speed cannot be obtained in an orbit wide enough to accommodate a red giant. The solid and dashed curves from lower left to upper right are the orbital separation for which a companion of 1.4 and 0.5$M_\odot$, respectively, have an orbital velocity of $275d$ km s$^{-1}$. These are firm upper limits to the allowed orbital separation, both because the companion will use up some of its velocity in escaping the attraction of the Vela pulsar after the explosion and because the $275d$ km s$^{-1}$ only represents the companion speed in the plane of the sky; its true speed must be greater.

The only likely candidate progenitors of the Vela pulsar that fit into the required orbits of a few solar radii are helium stars or even more evolved stellar cores. Hence the explosion...
Figure 3. Constraints on the progenitor binary. \( M_{\text{He}} \) is the mass of progenitor of the Vela pulsar, and \( a \) the binary orbital separation. The solid curves apply to a 1.4\( M_\odot \) neutron star companion, and the dashed ones to an 0.5 \( M_\odot \) main-sequence companion. Diagonal lines to upper right represent the maximum orbital separation consistent with a companion velocity of 250\( d \) km s\(^{-1} \). The lower curves represent the minimum separation for which neither star in the progenitor binary fills its Roche lobe. The left panel is for the nearby distance to Vela of 250 pc, the right one for the classical 500 pc distance.

that formed the Vela supernova remnant must have been a type Ib or Ic supernova, and any material that can be identified as purely ejecta should not contain significant amounts of hydrogen. The remnant does contain many filaments that emit \( \text{H}\alpha \) (Elliot, Goudis, & Meaburn 1976), but that could well be swept-up material, the total mass of which is by now expected to exceed the original ejecta mass considerably. It would be quite difficult, therefore, to determine the supernova type from the ejecta composition in a remnant as old as Vela. Especially distinguishing types II and Ib/c, as we would want, is very difficult in any case because the amounts of heavy elements ejected in both would be almost the same.

Close binary stars with pure helium star companions form when a red giant in a wide binary engulfs its low-mass companion star, which then plunges into the giant’s envelope; this causes the envelope to be ejected and the orbit to tighten (Bhattacharya & Van den Heuvel 1991). The now close binary consists of the low-mass companion and the core of the red giant, i.e., a naked helium star. The two likely companion types are another neutron star, in which case the pre-explosion binary was probably a strong X-ray source like Cygnus X-3 (Van Kerkwijk et al. 1992, Van den Heuvel & De Loore 1973); or a low-mass main-sequence star, in which case the binary would have evolved into a low-mass X-ray binary had it not been disrupted in the supernova explosion.

In both cases, the Vela pulsar binary forms an important link in our understanding of binary stellar evolution, so we shall investigate them further. A lower limit to the size of the orbit follows from the requirement that neither star overfill its Roche lobe prior to the explosion (for the radius of the helium star, we took values at core Carbon ignition from Habets 1986). This limit is shown as the lower curve in fig. 3 for both cases.

If the pulsar received no velocity kick at birth, the mass of the helium star, \( M_{\text{He}} \), and orbital radius, \( a \), follow from the current velocities of the pulsar and the companion, given their current masses: as shown elegantly by Radhakrishnan and Shukre (1985), the velocities at infinity of the binary components after the explosion can be expressed in terms of the pre-explosion masses \( M_{\text{He}} \) and \( M_{\text{comp}} \), the mass \( \Delta M \) lost in the explosion, and the initial semi-major axis \( a \). If we now choose \( M_{\text{comp}} \) and fix the pulsar mass \( M_{\text{He}} - \Delta M \) at 1.4\( M_\odot \), we are left with two unknowns, \( M_{\text{He}} \) and \( a \), expressed in terms of the measured \( v_{\text{PSR}} \) and \( v_{\text{comp}} \). The only uncertainty we have is that the measured proper-motion velocities depend on the uncertain distance to the Vela pulsar and that we do not know how much larger the true velocities of the two objects are than their projections on the plane of the sky; typically, the ratio of the true to projected velocity would be \( \sqrt{3/2} \). To account for this, we adopt velocity ranges of \( v_{\text{PSR}} = 70-100 \) km s\(^{-1} \) for the pulsar and \( v_{\text{comp}} = 275-400 \) km s\(^{-1} \) for the companion.

The smaller group of dots in each panel of Fig. 3 represents the domain of pre-explosion orbits consistent with those velocity ranges for the case of a 0.5\( M_\odot \) main-sequence companion. It lies entirely below the Roche limit (lower dashed curve) for either distance to Vela and can be ruled out, unless the Vela pulsar received a kick velocity at birth of at least 50 km s\(^{-1} \).

Possible orbital solutions for the case of a neutron star companion are indicated by the larger dotted area in Fig. 3. These all fall above the Roche limit, so a neutron star is a viable companion candidate. One would expect it to be a recycled pulsar, like the Hulse-Taylor relativistic binary pulsar, with a magnetic field of perhaps \( 10^{15} \) G and a period of several tens of milliseconds. It may be a challenge to detect
it as a radio pulsar, given that it is in such a radio bright region and may even be beamed away from us. But since it was accreting material until 10,000 years ago, it may still be hot enough to be detectable with some effort in soft X rays or optical radiation, like the Vela pulsar itself.

Note also that the presence of significant fallback material to form the bubble constrained the initial mass of the exploding star to be around 6–8\(M_\odot\). Such a star would leave a naked Helium star of 6–8\(M_\odot\). This overlaps nicely with the range of allowed pre-explosion He star masses for the case of a neutron star companion.

4 DISCUSSION AND CONCLUSION

If our model is correct, then the evolution of the Vela remnant and its surroundings could be rather more complicated than that of a simple supernova remnant expansion, especially if the companion star is a neutron star, for then a prior supernova exploded at the location of the Vela remnant 3–10 Myr ago, and the Vela SNR is now expanding into this old remnant. In fact, there is a region of about 20\(r\) radius around the Vela SNR called the Gum Nebula, which is tenuous and ionised and could well be either an old wind bubble or SNR. Somewhere along its way, the Vela SNR would overtake the envelope of the red giant that was ejected during the spiral-in of the first-born neutron star. Since the Gum Nebula as a whole is rather tenuous, this might well change the expansion rate significantly. The speed of the ejected envelope is probably about 100 km s\(^{-1}\), and the He star would live for another few hundred thousand years after the spiral-in, so it would be a few tens of pc away when the Vela pulsar was formed. Since the radius of the Vela SNR is 15\(d\) pc, the shell could be ploughing into this material now. This could seriously confuse estimates of the age of the remnant based on the current size and X-ray brightness (Aschenbach et al. 1995).

We have shown that the newly discovered asymmetric X-ray feature near the Vela pulsar can be interpreted as a pulsar-powered bubble of fallback material that originated very near the collapsing core in the supernova explosion that formed the Vela pulsar. The asymmetry of the expansion can be explained by the hypothesis that the Vela pulsar had a close binary companion before the explosion which is now ploughing a channel through the Vela remnant into which the bubble can expand much more rapidly than in other directions.

The derived orbital radius and mass of the progenitor binary imply that Vela is the remnant of a type I\(b\) supernova, and that either the companion is a neutron star or that the Vela pulsar received a velocity kick at birth. Our model is easily falsifiable because it makes a number of very specific predictions: the bubble should contain large amounts of heavy \(r\)-process elements, and at or near the end of the elongated X-ray bubble there should be a former binary companion to the Vela pulsar, most likely a neutron star or a late-type main-sequence star. It can easily be recognised as the former binary companion because of the direction and magnitude of its proper motion (0\(^{\circ}\).25/yr towards the south-southwest). If such observations confirm our model, the chemical composition of the bubble will provide an rare and highly valuable test of explosive nucleosynthesis in supernovae.

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