A&A 379, 551–556 (2001)
DOI: 10.1051/0004-6361:20011321

Astronomy & Astrophysics

Vela, its X-ray nebula, and the polarization of pulsar radiation

V. Radhakrishnan and A. A. Deshpande

Raman Research Institute, C. V. Raman Avenue, Bangalore – 560 080, India
e-mail: `rad@rri.res.in`, `desh@rri.res.in`

Received 31 July 2001 / Accepted 17 September 2001

Abstract. The recent identification of the perpendicular mode of radio polarization as the primary one in the Vela pulsar by Lai et al. (2001) is interpreted in terms of the maser mechanism proposed by Luo & Melrose (1995). We suggest that such a mechanism may also be operative for the parallel mode which opens up the possibility of accounting for all types of polarization observed in pulsars. We propose an alternative interpretation of the arcs in the nebular X-radiation observed by Pavlov et al. (2000) and Helfand et al. (2001) with the Chandra Observatory, and interpreted by the latter as an equatorial wind. We interpret the arcs as traces of the particle beams from the two magnetic poles at the shock front. We also propose that the alignment with the rotation axis of the jet-like feature bisecting the arcs is an effect of projection on the sky plane and that there is no physical jet along the axis of rotation.

Key words. X-ray: stars – stars: neutron, winds, outflows – pulsars: general – individual: Vela – supernovae: general – polarization – radiation mechanisms: non-thermal

1. Introduction

Unlike in the case of most other non-thermal radio sources, the polarization of the radiation from pulsars played an early and fundamental role in attempts to understand and model the operative emission mechanism. The high percentage of linear polarization, well over the maximum theoretical limit for synchrotron radiation, together with a special type of systematic sweep of the PA observed in the Vela Pulsar led to the "magnetic pole model" (Radhakrishnan & Cooke 1969). The sweep of the PA across the pulse was interpreted in terms of the line of sight tangentially encountering different field lines close to the magnetic pole as the pulsar rotated; and the parameters of the so called "S" curve of the PA sweep have ever since been interpreted in terms of α and β, the angles made by the magnetic axis to the rotational axis and to the line of sight (at minimum impact angle) respectively. An important point is that while the geometry of the "S" curve is intimately related, through α and β, to the locus of the sight line, the actual angle between the plane of polarization and the operative magnetic field line can have any value, as long as it remains fixed. In the case of synchrotron radiation, the most widespread emission mechanism invoked for non-thermal sources before the discovery of pulsars, the electric vector of the radiation would be perpendicular to the projected magnetic field, as the acceleration of the charged particles was due to their gyration around the field lines.

In the case of pulsars, the systematics of the polarization sweep, and its independence of observing frequency, indicated clearly that the radiation emanated from close to the polar cap in a region that had no internal Faraday rotation. The strength of the fields associated with these regions was so high that any transverse momentum and energy would be radiated away "instantly", and the charged particles would be in their lowest Landau levels and constrained to move along the magnetic field lines, like beads on a string. An appreciation of this constraint led to the suggestion (Radhakrishnan 1969) that the radiation could be due to the acceleration in the plane of the curved field lines, and has been known since then as "curvature radiation". As the motion of the particles, whether electrons or positrons, could be only along the field lines, the polarization of the emitted radiation should have the electric vector parallel to the projected field lines. A consequence of this was the identification of the intrinsic plane of polarization at the centre of the pulse (or more correctly the inflexion point of the S curve), with the projection of the rotation axis of the pulsar on the sky. This has had important implications for a variety of studies over the years relating to the space velocities of pulsars.

According to the above picture, the PA of the polarization can have one and only one value at any pulse longitude since the angle of the projected field line is fixed. But as early as 1975 (Manchester et al. 1975; Backer et al. 1976) it was discovered that the PA could have more than one value at a given longitude! Closer investigation revealed that the PA switched between two modes, taking any one of two values which were orthogonal to each other

---

Send offprint requests to: V. Radhakrishnan,
e-mail: `rad@rri.res.in`

(Backer & Rankin 1980). The polarization sweep pattern in any one mode appeared identical to that in the other, barring the 90° shift in PA. There has been no shortage of attempted models for the radiation mechanism, but in the absence of any other that could be meaningfully compared with observations, the simple picture of the magnetic pole model, with its rules for deriving α and β, has survived for over three decades, despite the blatant sweeping under the rug of the observed freedom of the polarization vector to take one of two orthogonal values, neither of which was ever shown to have a definite orientation with respect to the field direction!!

2. The X-ray Vela story

We turn now to a discussion of some observations which appear to offer for the first time the possibility of establishing a clear relationship between the directions of polarization and the magnetic field of the pulsar.

Recent observations of the Vela pulsar, and its immediate surroundings, with the Chandra X-ray Observatory show a two-sided jet at a position angle coinciding with that of the proper motion of the pulsar (Pavlov et al. 2000; Helfand et al. 2001). Lai et al. (2001) have argued that the symmetric morphology of the X-ray emission about the jet direction suggests strongly that the jet is along the spin axis of the pulsar. As corroborating this interpretation, they cite polarization observations using data from Deshpande et al. (1999) which have been corrected for Faraday rotation both in the interstellar medium and in the ionosphere. As the radio PA is at right angles to the direction of the X-ray jet, Lai et al. (2001) conclude that the polarization mode dominant in the Vela pulsar is one where the electric field in radio emission is orthogonal to the magnetospheric field.

Further support for this picture comes from recent radio observations of the region that have revealed a double lobe structure, with well separated lobes of comparable intensity (Dodson et al. 2001; private communication). These radio lobes are symmetrically placed on either side of the X-ray jet with their diffuse inner edges very close to the boundaries of the X-ray nebula, and independently suggest that the projection of the star's spin axis must match the observed direction of the jet in the sky plane.

From what has been discussed above, it must be concluded that the electric vector of the Vela pulsar's radiation is perpendicular to the plane containing the magnetic field-line, and not parallel to it as one has generally assumed. This was also noted by Helfand et al. (2001) although their major concern was with the morphology of the X-ray nebula and its interpretation. We shall also discuss the X-ray nebula shortly, but first the implications of the polarization PA.

3. Implications for the emission/amplification mechanism

There is no question that the charged particles in the polar cap regions of any pulsar will be constrained to move essentially along the field lines as already mentioned earlier. There is also no question that there will be radiation from these relativistic particles due to the acceleration associated with the curvature of the field lines, and that the polarization of this radiation will be linear and parallel to the projection of the field lines, assumed planar for the moment. But the brightness temperature of such radiation cannot exceed the kinetic temperature of the electrons (and positrons), which for even extreme values of the magnetic field and spin period are unlikely to be within orders of magnitude of the inferred brightness temperatures, as has been well known since the earliest observations. The absolute need for maser-like amplification, whatever the mechanism of the input radiation, has thus always been recognised, and has motivated numerous attempts over the decades to propose models for the radiation mechanism of pulsars.

As noted at the beginning, one of the striking characteristics of pulsar radiation, which must be accounted for in any theoretical model, is its polarization behaviour. Another, as just seen, is the extremely high brightness temperature. We find it remarkable that both these characteristics seem to be well accounted for in the model put forward by Luo & Melrose (1995). They assume that the input signal is curvature radiation, which as discussed in detail above, seems eminently reasonable to us. The amplification process requires a certain non-planarity of the field lines, for which there has long been evidence from many different lines of investigation on pulsars (Radhakrishnan 1992). The surprising aspect is that while the spontaneous curvature radiation is polarized parallel to the field lines, the amplified output is perpendicular to it, in agreement with the observations discussed in the last section. It would appear therefore that the "normal" polarization mode is really "orthogonal" (to the field lines) for reasons associated with the physics of the amplification process, without which pulsars would not be detectable.

It should be pointed out that the above is not a violation of the fundamental requirement that in any amplifier the stimulated emission should be indistinguishable from the stimulating input signal. Because of the torsion in the field geometry, the spontaneous emission has a small component in the direction perpendicular to the field in the amplifying region, and it is this component that, according to Luo & Melrose (1995), is preferentially amplified and dominates the output.

The pattern of switching to orthogonal modes of polarization varies from pulsar to pulsar and can happen in different parts of the pulse profile for different pulsars. For Vela, the existance of both modes was noticed as early as 1983 by Krishnamohan & Downs. Although the radiation in the other mode is on the average much weaker, it is important to appreciate that detectable radiation in any mode, in any pulsar, always corresponds to brightness temperatures that require enormous amplification. We are thus forced to conclude that there must be more than one mode of amplification if the input signal is the spontaneous "curvature radiation", as is manifest by the

"S" curve outputs of the amplifier, in whichever mode it is operating. This implies that there must be conditions when the parallel mode develops more negative absorption than the perpendicular one favoured by Luo & Melrose, and results in a polarization flip. The probability of this happening could be influenced by the particular field distortions present over the longitude range in question. But the fact that either mode can occur is very reminiscent of maser processes in general, where different allowable modes typically compete with each other resulting in one of them rapidly taking over all of the available power.

The observation in many pulsars, of elliptically polarized radiation of detectable strength, is further evidence of the existence of amplification in both modes, but now simultaneously with some phase difference and different gains. A major obstacle in the understanding of pulsar polarization until now has been the difficulty of seeing how electric fields could be generated perpendicular to the ultrastrong magnetic field lines, only along which the charges were constrained to move. The mechanism of Luo & Melrose (1995) – thanks to torsion – allows and predicts radiation perpendicular to the field lines, and now reduces the explanation of any type of polarization in pulsars to a matter of detail, as opposed to a difficulty of principle.

4. The X-ray arcs: tracers of the radiation beams?

We turn now to the spectacular X-ray image provided by Chandra with two remarkably symmetrical arcs bisected by the jet like feature mentioned earlier. Helfand et al. (2001) have put forward a detailed model where they "assume that the two arc-like features lie along circular rings highlighting shocks in which the energy of an outflowing equatorial wind is dissipated to become the source of synchrotron emission for the compact nebula" and attribute the incompleteness of the rings to preferential Doppler boosting of the emission in the forward direction. They also "assume that the two rings straddle the equator symmetrically and suppose that the deficit of emission exactly in the equatorial plane is related to the fact that this is where the direction of a toroidally wrapped magnetic field changes sign i.e. the field may vanish there". They go on to derive the half opening angle of the wind θ as $23\overset{\circ}{.}3$, and the radius of the shock $r_{\rm s}$ as $a/d\cos\theta \sim 1 \times 10^{17}$ cm for $d = 250$ pc.

We would like to propose a somewhat different model for the X-ray arcs, starting from the magnetic pole model for pulsar radiation discussed at length earlier, and that is invariably miscalled the "rotating vector model[1]". In that model, the radiation (and also its amplification as just seen) are produced by highly relativistic particles streaming out along the open field lines from both magnetic poles. We now examine the X-ray data for the possibility that the two arcs reflect the traces of these two particle beams as they encounter the "walls" surrounding the central cavity created by the pulsar. Such a cavity was elaborated in the classic paper by Rees & Gunn (1974) for the Crab, and has since formed a part of most, if not all, subsequent discussions and models of pulsar created nebulae.

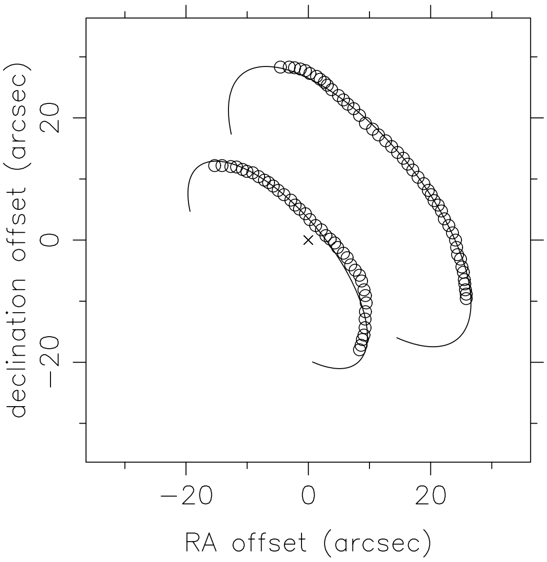

Fig. 1. Our best fit model for the pair of bright arcs seen in the Chandra Vela X-ray image. The pulsar location (at 0,0) is denoted by a cross; the circles denote the arcs seen in the X-ray image. The continuous lines show our best fit model where these arcs are the locii of the rotating magnetic-axis vectors (see text for further details).

We assume that the particles leave the weakening field lines at some point well before sweep-back effects set in close to the light cylinder, and proceed "ballistically" outwards. If this picture is valid, one of the two arcs should pass close to our sight line to the pulsar, as indeed it does. To assess this further, we have modelled the arcs as the near-side portions of two rings (seen in projection) traced by sweeps of the (magnetic) polar cones. The rotating magnetic-axis vector is as described in Deshpande et al. (1999). The model parameters are the pair of radial distances (r_1 & r_2 as measured from the star location and expressed in arcseconds) associated with the two ring traces, the inclination (α) of the magnetic axis of the star to its rotation axis, the angle of closest approach (the impact angle β) of the magnetic axis to our sight-line, and the position angle (PA_0) of the rotation axis projection on the sky-plane. The angle (ζ) between the rotation axis and our sight-line is simply ($\alpha + \beta$). Desired consistency with radio polarization observations would allow only certain combinations of the viewing geometry; that is $\sin\alpha/\sin\beta$ should be equal to the steepest sweep rate ($\mathrm{d}\chi/\mathrm{d}\phi$) of the polarization position angle with respect to the rotational longitude. When we constrain the α & β combinations using $(\mathrm{d}\chi/\mathrm{d}\phi)_{\max}$ of -9 degree/degree (as listed by Lyne & Manchester 1988), the best fit PA_0 is found to be

---

[1] This term was introduced by proponents of light cylinder emission models. A rotating vector is what is observed; the essence of the R.C. model was the location of the emission in the magnetic polar vicinity where the observed rotation would occur naturally. Ironically, the term would be perfectly appropriate for what we are proposing in this section and the next.

129 degrees (measured from North through East), the radial distances r_1 & r_2 are unequal (about 22 & 29 arcsec for the near and the opposite polar cones respectively) and $\alpha \sim 71$ degrees ($\beta \sim -6$ degrees correspondingly). Note that this implies a value of ζ of about 65 degrees, significantly larger than the 53 degrees estimated by Helfand et al. (2001) based on their model of an equatorial torus. The above model is illustrated in Fig. 1.

The changing direction of the magnetic axis viewed in projection on the sky plane as the star rotates is described in exactly the same way as that for the position angle of the radio polarization (Deshpande et al. 1999) whatever their relative difference. The proposed association of the arcs with the traces of the polar emission beams thus provides a new and independent means to probe the viewing geometry. They can sample (as they do in the present case) a much larger fraction of the rotation cycle and can provide additional constraints on the viewing geometry. One crucial such constraint becomes available via the trace of the polar emission from the other pole that is generally not available unless interpulses are observable. Also, interestingly, the "sign" of the impact angle β would become readily apparent from the beam traces even if they do not sample large fractions of the rotation cycle, and without needing to know the sense of rotation of the star.

A simple calculation shows that the visible extent of the arcs is consistent with an X-radiation spread confined to about 70 degrees around the respective directions to which the magnetic axis points as the star rotates. We consider this as explained simply in terms of the initial dispersion of the motions as the particle beam ploughs into the region of compressed toroidal field – the shocked region as usually described – and the consequent spread of the pitch angle distribution. By just assuming that we will see radiation as long as there is some component of the motion towards our line of sight (i.e. $\leq 90°$) our simulation reproduces remarkably well the Chandra observations of the arcs.

5. The "axial" jet!

We now turn to the jet like feature whose symmetric bisection of the arcs discussed above has prompted immediate identification with its rotation axis. The fact that the projection on the sky-plane of the rotational axis as derived from the polarization data (with a 90° shift) is also in agreement has been interpreted as further and strong evidence of the above supposition. In fact, Lai et al. (2001) go so far as to say "... If the jet originates from the pulsar magnetosphere, as seems likely, it is most natural to associate the jet axis with the pulsar spin axis". The alignment of the jet with the observed proper motion for Vela seems also to have prompted an association with, and raised hopes of an explanation for the space velocity of the neutron star. The fact that a similar jet was already seen in the Crab, also aligned with the derived PA of the spin axis, and its proper motion, heralds an incipient industry as more X-ray images of radio pulsar nebulae become available.

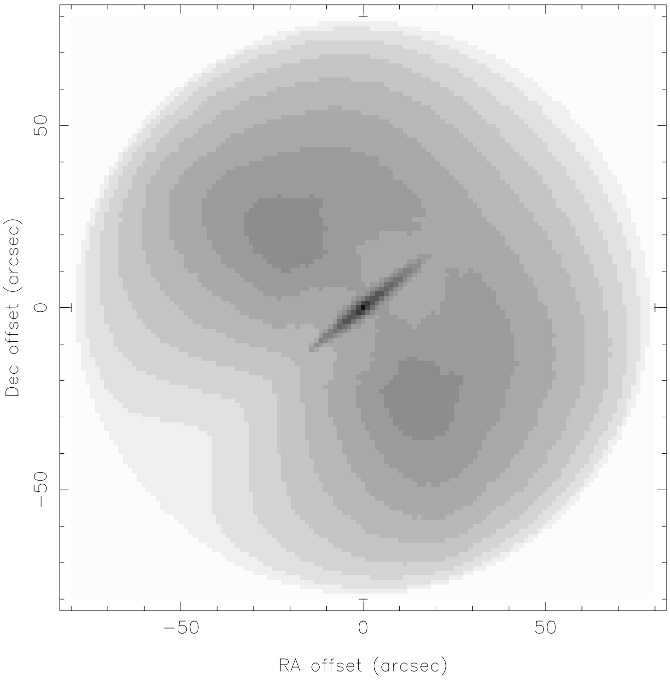

Fig. 2. Gray-scale plot showing the distribution of the expected X-radiation corresponding to the "jet" and diffuse components around the pulsar. The RA & Dec offsets are with respect to the pulsar position. The particle flow causing these components of the X-radiation is assumed to be in the form of an elongated fan beam (with angular spreads of ±5° and ±70° in the longitudinal & latitudinal directions respectively) centred around the rotating magnetic axis vectors associated with both the poles. The particles are allowed to suffer angular deviations only in the latitudinal direction and are assumed to be confined to the ±70° spread of the fan beam for consistency. All the values of relevant angles associated with our viewing geometry are as estimated from the best fit solution described in the earlier section.

A radio pulsar is not an accreting object like an X-ray pulsar, a black hole binary, or an AGN. In our view, it is not only unlikely, but unphysical to expect an actual jet along the rotation axis of a radio pulsar. There is an immense amount we don't know about the magnetospheres of radio pulsars, but one thing we have known for over three decades is that the particle emission is along the magnetic axis (Goldreich & Julian 1969), that is often at large angles to the rotation axis. The only connection that there can possibly be between the X-ray jet and the rotation axis is one of projection on the sky-plane as we shall argue below.

In our picture of the relativistic particle beams leaving the magnetic poles and proceeding ballistically outwards to the cavity walls, we can ask what if any deviations they are likely to suffer. The only field along their trajectory through the cavity is the toroidal field (that they are carrying out) and that later gets compressed and strengthened at the wall. This toroidal field will, over most or all of the trajectory, be perpendicular to the path of the particles, and, of course, the rotation axis. Depending on the spread of their energies, it should not be surprising if a small fraction of the particles acquired a spread of velocities in the latitudinal direction making their synchrotron radiation visible to an observer when their motion is tangential to the sight line.

One should, as a consequence, expect to receive radiation from these particles when the projection of the magnetic axis coincides with that of the rotation axis, precisely as in the case of the radio pulse, but now over a larger range of angles in latitude. Wherever the observer, the apparent jet will appear along the minor axis of the projected ellipses of the arcs but the extent over which it is visible will depend on the spread of particle velocities, and the angles the beams from the two poles make to the line of sight. These particles must also reach the cavity walls and will then create a diffuse glow around the arc regions but with a greater spread, exactly as seen in the Chandra image. We have assessed the spread of this weak fan beam from the size of the diffuse glow, and from the poor or non-visibility of the corresponding radiation from the beam of the other magnetic pole. We estimate a spread of about $\pm 70^{\mathrm{o}}$ from the observed extent of the jet and have used this value in our simulation (Fig. 2) of the jet and the associated diffuse components.

If this interpretation of the "jet" is correct, it has a major implication for the picture of particle flow from the pulsar to the nebula. In Sect. 4 when attempting to explain the formation of the X-ray arcs, we made the assumption that the particle beam separated from the polar field lines well within the light cylinder and before the effect of any sweep-back. The justification for this assumption is now seen as the absence of any misalignment between the apparent jet (defined by the trajectory of particles radiating towards us) and the projected rotation axis, the very observation that prompted the physical misinterpretation of the jet referred to earlier.

The total picture that emerges is as follows. There is a cavity of radius of order 10^{17} cms, which we can presume was created by the dipole radiation originally of much higher frequency than the present 11 Hz. Inside is a double cone of half angle $\alpha \sim 70^{\mathrm{o}}$, along which there is a relativistic particle flow in straight lines with a drift time of $\sim$0.1 year before they encounter the "shock". In addition, there is a low density of particles separating from the cones but whose trajectories are in planes containing the rotation axis. Any observer will see radiation only from those particles in the plane containing the observer and the rotation axis and we predict that this radiation should be highly linearly polarized with the electric vector parallel to the rotation axis.

6. Discussion

In the long march towards the elucidation of the mysterious ways of pulsars, now numbering around a thousand, a few special ones have taught us more than most of the rest put together. The Vela Pulsar is one such, and played an important role in several ways within months of its discovery in 1968. The superb capabilities of the Chandra telescope have put this pulsar in the limelight again by providing a spectacular image in X-rays of the surrounding nebula. Its form and proportions, reminiscent of pre-Columbian pectoral ornaments are loaded richly with information about many aspects. To begin with, the symmetry of the nebula has provided compelling evidence for the identification of the PA of the rotational axis of the pulsar. The near precise orthogonality of this PA to that inferred with certain assumptions from polarization measurements, has had important implications. We support the finding of Lai et al. (2001) and Helfand et al. (2001) that the dominant polarization mode in the Vela Pulsar has the electric field orthogonal to the magnetospheric field. We find this is in accordance with the mechanism of Luo & Melrose (1995) that appears to explain three important characteristics of the radio radiation. They are the high brightness temperatures, the dominant polarization mode, and the observed sweep of the PA across the pulse, the last clearly identifying the input signal to the maser as curvature radiation from the field lines in the polar neighbourhood. Since the first and third characteristics also apply to the parallel polarization mode to which the radiation occasionally flips, as seen in many pulsars, we propose that the same amplification mechanism must also be operative at times in the other mode. If the Luo & Melrose mechanism can in fact operate in both modes, the explanation of any type of elliptic polarization becomes a matter of detail, a topic which we shall address later.

Noting the clear separation of the X-ray nebular emission into two elliptic arcs symmetrically located with respect to the inferred rotation axis, we propose that they are the traces of the two particle-beams from the magnetic poles on the walls of the cavity − the shocked region. We explain the visible extent of the arcs as arising simply from the spread of the pitch angles at the shock front. We also explain the alignment with the rotational axis of the jet like feature bisecting the arcs as simply a projection effect on the sky plane. We attribute its visibility to a latitudinal spread of the velocities of a small fraction of the particles in the beam, an explanation strongly supported by the presence of diffuse emission around the arcs. We present a simulation of the expected X-radiation around the pulsar based on the above model for the arcs, the jet, and the diffuse glow around both (see Fig. 3), and find gratifying agreement with the Chandra observations[2]. We predict that the polarization of the jet feature will be linear and parallel to it, and claim that there can be no physical jet along the rotational axis of the pulsar.

Note that the "jet" is really an apparent one. There are at least $3{\times}10^7$ input bunches of particles along any line from the pulsar to the cavity wall, and even the slightest dispersion in velocity would smooth this out to a uniform

---

[2] Image available at
`http://chandra.harvard.edu/photo/cycle1/vela`

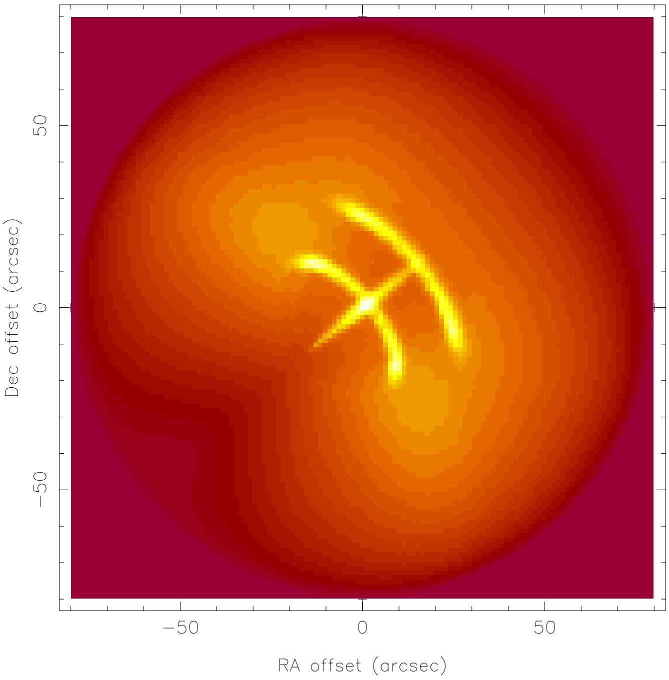

Fig. 3. A result of our simulations as in Fig. 2, but now including also the arc components. The colour code used here is roughly similar to that in the Chandra image referred to in the text.

flow at a very short distance from the pulsar. Even in the absence of velocity dispersion, the finite gamma of the bunch combined with the distance over which it is radiating will result in smearing. The radiation will thus appear continuous and be a part of the unpulsed fraction in X-rays, the fraction depending on the extent of the jet/nebula from which radiation is collected.

In our modelling of the pair of arcs as traces of the two polar beams on a cavity wall (e.g. as illustrated in Fig. 1), we find that an assumption of equatorial symmetry does not fit the observations well. As already mentioned in an earlier section, the best fit r_1 is significantly different from r_2 (i.e. $(r_2/r_1) \approx 1.35$). Note that, in our model, r_1 & r_2 represent the implied distances to the "wall" from the star along the "rotating vectors" associated with the near and the opposite poles respectively. The arcs provide us important information including about the otherwise "unseen" pole. Significantly improved fits are obtained when unequal values of α_1 & α_2 (the half angles of the polar cones associated with the two poles) are allowed in the model. The corresponding r_1, r_2 are unequal again. Even better fits are obtained if β is not constrained by the radio observations. But interestingly, the implied value of $\zeta(= \alpha_1 + \beta)$, the angle between the rotation axis and our line of sight, is about the same as in the other cases. Further detailed modelling, than has been possible presently, may provide better estimates of the above parameters and clues about the size as well as the shape of the "cavity".

Inequality between α_1 & α_2 has implications, particularly for certain acceleration mechanisms for the origin of pulsar velocities. For example, the "rocket" mechanism of Harrison & Tademaru (1975) does necessarily require such an inequality amounting to a tilted and offset dipole.

Other possible/plausible implications are the following.

i) If the dominant radio polarization mode is indeed the "orthogonal" mode, then any analysis based on the assumption that the observed central polarization PA is the same as the PA of the rotation axis needs to be reviewed. This applies, for example, to the comparisons of the proper motion directions of pulsars with the orientations of their rotation axis. In the work of Deshpande et al. (1999), they allowed for mode ambiguity in cases where emission of both modes is observed, and have assessed the distribution of the proper motion direction (relative to the rotation axis PA) as shown in their Fig. 1b. We argue that the required revision will amount to simply replacing the relative angle by its complement. Since no particular preference was found for any relative angle value, the conclusions of Deshpande et al. remain unaltered.

ii) Given the similarities observed between the morphologies of the surrounding nebulae as well as other properties of the Vela & Crab pulsars, it would not surprise us if a similar arc structure is revealed around the Crab pulsar by observations with improved spatial resolution.

Acknowledgements. We would like to thank Don Melrose, Qinghuan Luo and Mark Walker for many useful discussions, and Richard Dodson for kindly providing information prior to publication.

References

Backer, D. C., Rankin, J. M., & Campbell, D. B. 1976, Nature, 263, 202
Backer, D. C., Rankin, J. M., 1980, ApJS, 42, 143
Deshpande, A. A., Ramachandran, R., & Radhakrishnan, V. 1999, A&A, 351, 195
Dodson, R., et al. 2001, private communication
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Harrison, E. R., & Tademaru, E. 1975, ApJ, 201, 447
Helfand, D. J., Gotthelf, E. V., & Halpern, J. P. 2001, ApJ, 556, 380
Krishnamohan, S., & Downs, G. S. 1983, ApJ, 265, 372
Lai, D., Chernoff, D. F., & Cordes, J. M. 2001, ApJ, 549, 1111
Luo, Q., & Melrose, D. B. 1995, MNRAS, 276, 372
Lyne, A. G., & Manchester, R. N. 1988, MNRAS, 234, 477
Manchester, R. N., Taylor, J. H., & Huguenin, G. R. 1975, ApJ, 196, 82
Pavlov, G. G., Sanwal, D., Garmire, G. P., et al. 2000, AAS Meeting, 196, 37.04
Radhakrishnan, V. 1969, Proc. of Astr. Soc. of Australia, 1, 254
Radhakrishnan, V. 1992, in Magnetospheric Structure and Emission Mechanics of Radio Pulsars, Proc. of IAU Colloq. 128, Poland, 1990, ed. T. H. Hankins, J. M. Rankin, & J. A. Gil (Pedagogical Univ. Press: 1992), 367
Radhakrishnan, V., & Cooke, D. J. 1969, Astrophys. Lett., 3, 225
Rees, M. J., & Gunn, J. E. 1974, MNRAS, 167, 1