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FURTHER EVIDENCE FOR COLLIMATED PARTICLE BEAMS FROM PULSARS AND PRECESSION

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ABSTRACT

We follow up on our (Radhakrishnan & Deshpande) radically different interpretation of the observed structures and morphologies in the X-ray observations of the nebulae around young pulsars (PWNe). In our general model for PWNe (Radhakrishnan & Deshpande), originally motivated by the *Chandra* observations of the Vela X-ray nebula, the bright arcs, the jetlike feature, and the diffuse components in such nebulae can be explained together in detail, wherein the arcs are understood as traces of the particle beams from the two magnetic poles at the shock front. We consider this as important evidence for collimated particle beams from pulsars' magnetic poles. In this paper we discuss the variability in the features in the Vela X-ray nebula observed by Pavlov and coworkers and assess the relevance and implication of our model to the observations on the Crab and other remnants. Our basic picture after incorporating the signatures of free precession of the central compact object can readily account for the variability and significant asymmetries, including the bent jetlike features, in the observed morphologies. The implications of these findings are discussed.

Subject headings: pulsars: general — stars: kinematics — stars: neutron — stars: rotation — supernovae: general

1. INTRODUCTION

The superb capabilities of the *Chandra* telescope have over the last 6 years revealed several spectacular images in X-rays of the nebulae surrounding pulsars, highlighting and resolving the various spatial structures richly loaded with information about many aspects. While most, if not all, of these images bear a remarkable commonality that is emphasized by their overall symmetric morphology about what is readily identified as the direction of the projected rotation axis, the forms and proportions of the components appear to differ significantly.

An overwhelming majority of the observers and theorists interpreting these observations seem to suggest and endorse the following basic picture. The jetlike features nearly along the symmetry axis, bisecting the arcs and the diffuse glow spread about them, are identified with collimated outflows of relativistic particles along the spin axis of the central compact remnant, a pulsar. The two arclike 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 the incompleteness of the rings is attributed to preferential Doppler boosting of the emission in the forward direction. The two rings, if apparent, straddle the equator symmetrically, and 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.

However, Radhakrishnan & Deshpande (2001, hereafter RD01) have suggested an alternative interpretation that differs from this mainstream model *in practically every aspect*, particularly those regarding the arcs and the jetlike features. The bright arcs, the jetlike feature, and the diffuse components (for example, in the Vela X-ray nebula) are explained together in detail by our "rotating vector model" in which the arcs are understood as traces of the particle beams from the two magnetic poles at the shock front. We consider this as important evidence for collimated particle beams from pulsars, a point that we find necessary to reemphasize.

In this paper we follow up on the RD01 model to address the new clues provided by the variability of various features, such as those in the Vela X-ray nebula observed by Pavlov et al. (2001, 2003), and assess the relevance and implication of our model to the observations on other remnants, such as the Crab. In the next section we begin with a brief summary of our model (RD01) for the X-ray nebulae around pulsars. In § 3 we revisit the Vela nebula story, now incorporating signatures of free precession of the central compact object, to explain the observed variability. We try to model, in § 4, the observed morphology of the X-ray nebula surrounding the Crab pulsar and the significant asymmetries, including the bent jetlike features. The implications of these findings are discussed in the last section.

2. THE ROTATING VECTOR MODEL: ORIGIN OF THE ARCS, APPARENT JETS, AND THE DIFFUSE GLOW

We begin with a brief summary of our general model (RD01) for the X-ray nebulae around pulsars, motivated initially by the *Chandra* observation of the Vela nebula in X-rays showing a well-defined pair of bright arcs and the jetlike feature(s) surrounded by a diffuse glow of X-radiation that is roughly symmetrical over its bright regions. Noting the clear separation of the Vela X-ray nebular emission into two elliptic arcs symmetrically located with respect to the inferred rotation axis, they are interpreted as the traces of the two particle beams from the magnetic poles on the walls of the cavity—the shocked region—created by the pulsar. The visible extent of the arcs arises simply from the spread of the pitch angles at the shock front.

In our picture, in stark contrast with prevailing faiths, the so-called jet is really an apparent one and is a manifestation of a physical flow of particles along the *magnetic* axis of the star, *not* along the rotation axis. The alignment with the rotational axis of the jetlike feature bisecting the arcs is simply a projection effect on the sky plane, as explained before (RD01) and discussed again below.

Depending on the spread in their energies, a small fraction of the particles from the relativistic particle beams leaving the magnetic poles and proceeding ballistically outward to the cavity walls may suffer repeated, small latitudinal deviations in their trajectory through the cavity due to the toroidal field (that they are carrying out, and) that would be perpendicular to their path, as well as, of course, the rotation axis. In addition to the original collimated flow ideally amounting to a pencil beam of particles along the rotating magnetic axis vector, a latitudinally and progressively elongated flow of particles will now develop on either side of it during their long passage to the cavity wall. Given that the particles in the flow components would continue to share the original longitudinal spread, their synchrotron radiation can be visible to us only during certain rotational longitudes. We see radiation when the projection of the magnetic axis coincides with that of the rotation axis *exactly as in the case of the radio pulse*, but now also over an apparently large range of angles in latitude. The jetlike appearance would thus be a result of radiation from particles across the entire latitudinal spread when our sight line happens to be tangential to their motion. The process that causes some particles to spread latitudinally from their original path is essentially that necessary to deflect them so that sometimes their radiation is directed toward us. 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, as well as the angles that the beams from the two poles make to the line of sight. Since this radiation will occur before the particles reach the cavity wall, the apparent extent of the jetlike feature is expected to be confined to the projected dimension of the cavity in the latitudinal direction but could exceed the extent of even the major axis of the ellipses of the arcs depending on the cavity shape. When these particles reach the cavity walls, they will create a diffuse glow around the arc regions but with a greater spread, *exactly as seen in the Chandra image of the Vela nebula*. The spread of this weak fan beam can be assessed from the size of the diffuse glow and from the poor visibility or nonvisibility of the corresponding radiation from the beam of the other magnetic pole.

A detailed discussion of our model and its application to the Vela X-ray nebula can be found in RD01. Here we focus on some of the key features that, we believe, need to be reemphasized. The so-called MHD plasma wind from pulsars, in our picture, is essentially in the form of a pair of collimated relativistic particle beams along the rotating magnetic axis vector. This is in no way different from that invoked universally to explain radio pulsar radiation, which corresponds to only a very tiny fraction of the high energy associated with the particle flow. Ironically, several major consequences of such a collimated energetic particle flow and its manifestations through unavoidable interaction with immediate and distant surroundings of a pulsar, which should have been anticipated, somehow remained largely unexplored. Also, what is not appreciated even after the seminal paper of Rees & Gunn (1974) is the *inevitability* of the creation of the cavity by the low-frequency radiation associated with the rotation of the pulsar at a frequency well below the plasma frequency of the surrounding medium. Our model merely recognizes and illustrates some of these direct consequences/manifestations of the collimated particle beams and the cavity to explain together the arcs, the "jet," and the diffuse components, as in the case of the Vela X-ray nebula. The gratifying agreement of our simulations based on this model (see Fig. 3 of RD01) with the *Chandra* observations[1] provides compelling evidence for collimated particle beams from pulsars and for the "apparent" nature of the jetlike feature, in contrast with any physical jet along the rotation axis of an *isolated* pulsar. The apparent jetlike feature, consistent with the underlying process, is expected to be linearly polarized parallel to itself and the rotation axis.

The key input parameters for our model are (1) the viewing geometry characterized by the inclinations of the rotation axis with respect to the sight line and the magnetic axis (i.e., ζ and α, respectively, where the impact angle β is given by $\zeta - \alpha$), (2) the pitch-angle distribution or the spread of radiation occurring at and beyond the cavity wall, (3) the latitudinal spread developed during the passage within the cavity, and (4) the shape of the cavity. The first of these can be known from radio polarization and/or can be estimated from the ellipses associated with the arcs, by fitting the rotating vector model (as illustrated in Fig. 1 of RD01, based on analytical description as in Deshpande et al. 1999). It follows that the ratio of the minor to the major axes will be equal to $\cos\zeta$, and the *signed* value of β would be apparent from the normalized separation of the nearest arc from the pulsar location. The pitch-angle distribution can be estimated from the angle between the rotating vector direction corresponding to the end points of the arc and the sight line. The third input, the latitudinal spread, may be assessed from the apparent jet extent in units of the projected latitudinal dimension of the cavity.

The shape and the dimension of the cavity created by pulsars are by far the most uncertain parameters. This is despite the fact that such a cavity was elaborated in the paper by Rees & Gunn (1974) for the Crab referred to earlier and has since formed a part of most, if not all, subsequent discussions and models of pulsar-created nebulae. The arcs do sample the shape, but only at certain latitudes. The diffuse component does potentially sample a much wider latitude range, but not fully in most cases. The relative intensities of the different components, such as the arc, jet, and the diffuse glow, as well as the width of the pencil beam of particles and the position angle (P.A.) of the rotation axis projection on the sky plane, are the other inputs to the model. A quantitative comparison with the observations would in principle provide best-fit estimates for most of the mentioned parameters, except for the shape of the cavity. It may not be always possible to assume symmetry in the cavity shape about the star's equatorial plane, or even about the rotation axis, since the large space velocity of a pulsar can significantly displace its location from the point of symmetry, if any, for the cavity. It is not clear how the cavity shape and size would evolve when a pulsar moves across a significant fraction of the cavity size during its lifetime. Fortunately, in our picture, the arcs provide us with important information including about the otherwise "unseen" pole. By allowing in the model for unequal values of α_1 and α_2 (the half-angles of the polar cones associated with the two poles) and similarly for the semimajor axes r_1 and r_2 of the two elliptical traces, assessment of the apparent asymmetry becomes possible at least to its first order.

3. REVISIT TO THE X-RAY VELA STORY: PRECESSION-INDUCED VARIABILITY?

Now let us take a look at the subsequent observations, reported by Pavlov et al. (2001, 2003), that show significant variability in the locations and the intensities of the arcs and the jetlike feature in the Vela X-ray nebula. The first indication of such variability was noted in the two epoch observations by Helfand et al. (2001),

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[1] Image available at http://chandra.harvard.edu/photo/2000/vela/index.html.

who found a 5% brightening of the outer arc within a month and suggested a connection with the large glitch (Dodson et al. 2000) that had occurred a few days prior to their first observation.

Initial follow-up by Pavlov et al. (2001), with further *Chandra* observations separated by 7 months, showed changes up to 30% in the brightness of various features of the nebula. Shifts up to a few arcseconds and/or spectral changes in the various *elements* of the nebula were also noticed. The several subsequent *Chandra* observations, providing together a set of 13 epochs spread over about two and a half years, also display similar or stronger variability (as apparent from the impressive animation[2] available at the *Chandra* Web site). Pavlov et al. (2001, 2003), who reported these observations, also find a dim, curved, $100''$ long extension of the jet beyond the outer arc, referred to by them as an "outer jet." They report that this extension shows particularly strong variability, changing its shape and brightness. From their analysis of the image sequence highlighting the so-called cosmic firehose, they "observed bright blobs in the outer jet moving away from the pulsar with apparent speeds $(0.3\text{–}0.6)c$ and fading on timescales of days to weeks." Based on their merged smoothed image, they detect a faint, strongly bent extension of the outer jet, in addition to a relatively fainter "outer counterjet" that is not apparent in individual images. Pavlov et al. (2003) consider the combined action of the wind within the supernova remnant, with a velocity of a few times 10 km s^{-1}, along with the ram pressure due to the pulsar's proper motion as a likely cause for this bend. In addition, they associate the more extreme bends closer to the pulsar, as well as the apparent side motions of the outer jet, with kink instabilities of a magnetically confined, pinched jet flow. Their basic picture, however, is that "most likely, these jets are associated with collimated outflows of relativistic particles *along the pulsar's rotation axes*." It is not surprising then that they liken these features to the jets observed in active galactic nuclei and Galactic microquasars and hope that studying pulsar jets may shed light on the mechanism of jet formation in these as well.

Our picture of these apparent jets in X-rays around isolated pulsars excises the very basis for this hope, but the observed faint extensions of the jets are not at all surprising as long as their projected dimension fits within the projected latitudinal extent of the central cavity.

The most relevant question for us presently is what is the underlying process responsible for the observed dramatic variability. Although Pavlov et al. (2003) concentrate on the jet features in their discussion, we prefer to take a closer look at the overall variability across the nebula (as reported in Pavlov et al. [2001], and that illustrated by the animation showing the full set of images). We notice significant correlated or systematic variability within the extents of individual features, as well as across them. This variability is apparent in the orientation, location, and brightness of the features. Regardless of the exact quantitative measure of the temporal/spatial correlation between these apparently coherent variations, it would be far fetched to imagine that the emissions received from sites located several light-months apart from each other coordinate their variability, unless they have a common central origin. We consider two broad classes of central activity inducing distinguishable coherent variability of the nebula and its fine structures. The first one relates to any general variability in the collimated particle flows along the magnetic axis, including those in the particle density, strength of the magnetic fields they carry, and the distribution of particle energies. Here we would expect the resulting variability in the nebula features to be mainly in the form of intensity variations, although widths and extents of the narrow features may also appear to vary.

In the second class, we consider the rotational and kinematic history of the pulsar, including slow and fast changes in its angular velocity, and the effects of its space motion. The connection Helfand et al. (2001) suggest between glitch and the changes in the brightness would be one possible example. However, the persistent variability in X-ray intensities and locations of most features appears to suggest temporally continuous, and most likely periodic, changes in the angular velocity of the pulsar, particularly in its direction. In this context, we recall the findings of Deshpande & McCulloch (1996, hereafter DM96) based on their analysis of radio data from a long-term dual-frequency monitoring of the Vela pulsar.

The large fractional variations they observed in the pulse intensities at two frequencies (635 and 950 MHz) showed significant mutual correlation, and also with the pulse arrival time differences across the frequencies. The magnitude of such variations and the correlations could, in principle, be explained as due to interstellar refractive scintillations. However, based on their detection of a significant periodicity of 330 days (not confused with any annual cycle) characterizing these variations, and also noting that the sweep rate of the polarization position angle measured at several epochs shows intriguing and yet unexplained scatter, DM96 suggested an interesting possibility, namely, that the Vela pulsar is undergoing free precession.

Certain characteristics of the variability in the radio and in the X-rays appear to be too similar to be considered as having different origins. In view of this and other considerations discussed above, we interpret the complex variability observed in X-rays as a rather direct and natural manifestation of the free precession of the Vela pulsar. If true, the collimated particle beams would also precess, and the radiation that these particles subsequently produce at a given distance from the star will be in accordance with the phase of the precession cycle and with the implied viewing geometric in the past when they started from the central star. Hence, the time taken by the particles to reach the location of the respective emission, plus the light-travel time from this location to the observer, will determine the precession phase corresponding to the emission we sample. What we will observe is a combined picture of this differently delayed manifestation of an otherwise coherent central activity, leading to reduction in the apparent coherence of variability across the nebula.

To assess this interpretation, we simulate the effect of free precession in our model, and the result is shown in the form of an animation.[3] In Figure 1 we show one sample image taken from this image time series. In these images, the brightness of the jet feature is artificially enhanced so as to improve the visibility of the weak jetlike feature. We have currently assumed the cone angle and the period associated with the precession to be 5° and 330 days, respectively. We find the remarkable qualitative correspondence between the observations and our simulations encouraging. A more detailed quantitative modeling would need to await access to the observed data for comparison. The cavity size in the latitudinal direction is assumed to be somewhat larger than that in the orthogonal direction, in accordance with the extent of the outer jet feature.

To summarize, our model based on collimated particle beams from pulsars, combined with free precession, can together explain the detailed morphology, as well as the complex variability of the Vela X-ray nebula and its components. We treat this as further

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[2] See http://chandra.harvard.edu/photo/2003/vela_pulsar/animations.html.

[3] Available at http://www.rri.res.in/~desh/VELA2.gif.

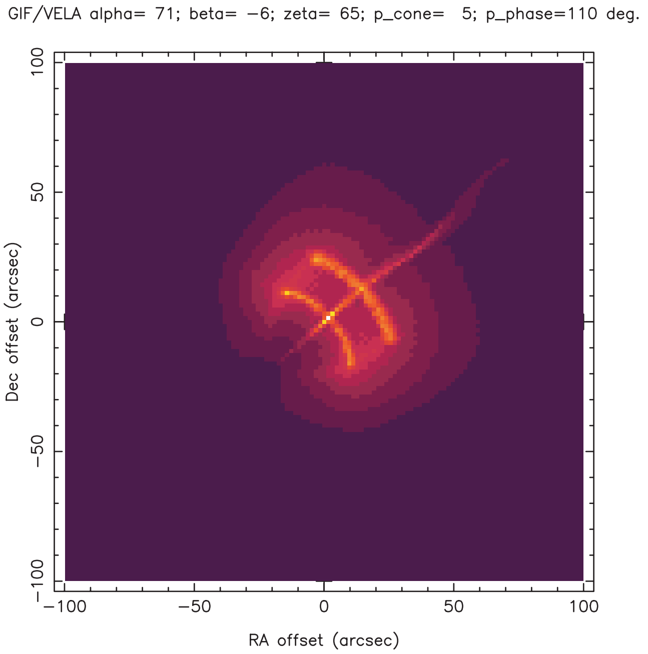

Fig. 1.—Simulated image of the X-radiation surrounding the Vela pulsar following the RD01 model, and assuming that the Vela pulsar is undergoing free precession with a period of about 330 days and with a precession cone width of ±2.5°. The intensity of the so-called jet component is enhanced for better visibility. The offsets (0, 0) correspond to the pulsar location.

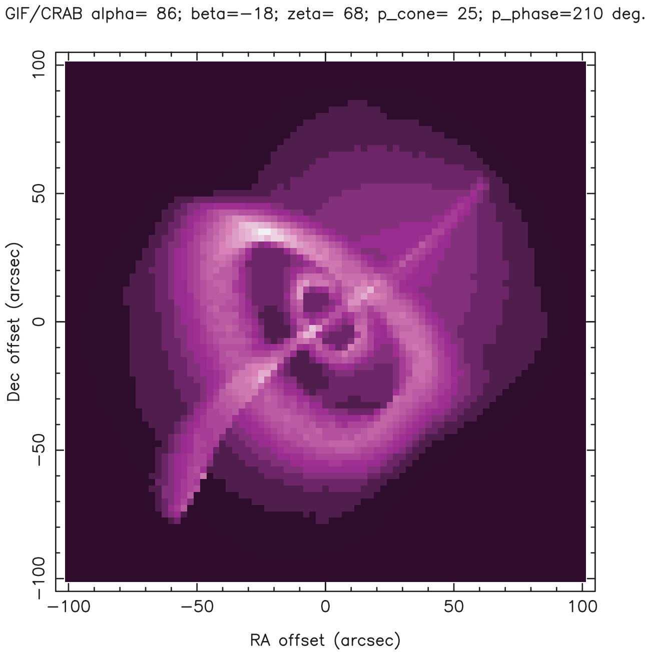

Fig. 2.—Similar to Fig. 1, but now showing a simulated image of the X-ray nebula surrounding the Crab pulsar. The assumed precession period for the Crab is 14 yr, with a precession cone width of ±12.5°. The apparent spatial scale of the jet bend is consistent also with other suitable combinations of values for the precession period and particle speeds. The magnitude of the bend would be consistent with a somewhat narrower precession cone size, but with slower particle speeds.

strong evidence for collimated particle beams from pulsars and for the free precession of the Vela pulsar.

4. THE X-RAY CRAB STORY: TRACING THE ROTATIONAL HISTORY

In our earlier paper (RD01) we had commented that, given the similarities observed between the morphologies of the surrounding nebulae, as well as other properties of the Vela and Crab pulsars, it would not surprise us if a similar arc structure is revealed around the Crab pulsar by observations with improved spatial resolution. We soon realized after viewing the smoothed *Chandra* image of the X-radiation from the Crab nebula (Weisskopf et al. 2000) that the arc structure is indeed apparent even at the existing resolution, thanks to the large size of the nebula. It is of interest therefore to see if our model would apply equally well to this case.

Using some of the estimates of viewing geometry available from the existing radio polarization observation, along with the RD01 model, we try to simulate the image of an X-ray nebula surrounding the Crab pulsar. The spatial extent of the Crab X-ray nebula is about 5 times bigger than that of the Vela pulsar, although comparable in angular size. From the *Chandra* X-ray image, we estimate the two radii associated with the arc structure and find their ratio to be about 5:2, suggesting a very shallow profile for the cavity wall. A picture in which the pulsar has moved just above the central neck of an hourglass-shaped cavity seems consistent with the implied shallowness of the cavity surface and the counterjet extending well outside the extent of diffuse emission. The visible extent of the arcs in the *Chandra* image implies a wider spread of radiation (more than ±130°) from the beam trace at the wall, in comparison with that for the Vela case. Similarly, the latitudinal spread resulting in the jetlike emission is also wider, judging by the extent of the feature. The observed jet here is highly bent, deviating from the symmetry axis (i.e., the projected rotation axis) on either side of the equator. These deviations are quite systematic and display striking antisymmetry with respect to the star's equatorial plane.

Such a systematic pattern on scales of several light-years between the so-called jet and counterjet needs attention. In the commonly endorsed model of the jets as due to particle flows along the rotation axis, and moving in the opposite direction, the bends in the jets are believed to be due to exotic instabilities (e.g., Nakamura & Meier 2004) developed due to interaction with the surroundings, combined with the effect of proper motion of the central star. If this picture were to be true, the clear antisymmetric signature would require remarkable continuing communication between the distant parts of the particle flows even well after they have parted ways from the center in opposite directions.

In contrast to this, our model of the apparent jet combined with possible precession of the star would provide a ready explanation of the observed shape of the jet, as well as any variability in this and other features (Hester et al. 2002; Mori et al. 2004), as demonstrated already for the Vela case. It is time to recall the works of Wills et al. (1982) and Tompkins et al. (1997), in which they examined the ratio of main pulse to interpulse intensities in gamma rays from the Crab pulsar, the former suggesting a 14 yr periodicity associated with the observed variation in the intensity ratio. Assuming this value of 14 yr as the period of precession, we assess the signature it would imply for the shape of the jet feature, as well as the overall morphology.

Figure 2 shows the result of our simulation along the lines described above, assuming a viewing geometry given by $\alpha = 86^\circ$ and $\beta = -18^\circ$ and particle speeds to be very close to that of light. The precession cone is assumed to be ±12.5° wide. The gratifying qualitative agreement with the *Chandra* observation[4] not only lends strong support to our model of the X-ray nebulae surrounding

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[4] See http://chandra.harvard.edu/photo/0052/0052_xray_lg.jpg.

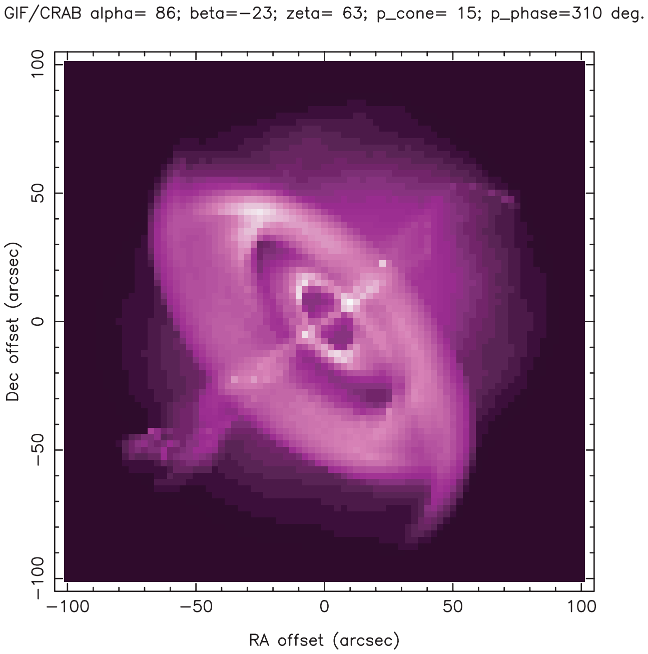

Fig. 3.—Another simulation of the X-ray nebula surrounding the Crab pulsar, now illustrating the effect of a spread in particle energies. A smaller precession cone width of ±7.5° is used in this case, and the assumed combination of the precession phase and the mean impact angle (β) is suitably adjusted to approximately match the apparent viewing geometry with that in Fig. 2. The contribution from lower speed particles to the jetlike feature results in relatively sharp apparent bends, comparable with those seen in Fig. 2 for a wider precession cone size combined with higher particle speeds. However, the average bend is milder, consistent with the reduced values of the cone size. The spread in speed ($0.1c$ to c) causes, as expected, a spread in the apparent relative orientations/distortions of the arcs traced by different speed particle beams, together giving a torus-like appearance for the pair of traces, and with the lower speed beams showing noticeable antisymmetric distortion at the tips of the traced ellipses.

young pulsars but also suggests that the Crab pulsar too is undergoing free precession with a period of about 14 yr or so. The modeling of the bent jet as due to precession of the central star is sensitive to the phase of the precession cycle assumed at the central location, as well as its variation across the simulated volume. The latter depends linearly on the distance from the center and inversely on the product of the particle speeds with the precession period. The magnitude of the apparent bend scales directly with the assumed size for the precession cone. Although our simulation shown in Figure 2 assumes the precession cone size of ±12.5°, a smaller cone size with slower particle speeds would also be consistent with the magnitude of the bend. Since it is reasonable to expect a spread of energies, we explore the effect it would have in a simulation shown in Figure 3, where the assumed cone size is ±7.5°.

Our Crab nebula simulations indicate that, unlike in the Vela case, the side of the rotation axis pointing closer to the observer is in the same sense as the star's proper-motion direction. The extent of the diffuse emission depends on the shape and the size of cavity, and in the absence of any particular information about these details a simple ellipsoidal shape is assumed. Again, several other fine details of interest could be extracted through future quantitative comparison of our model with the *Chandra* observations. Further, the implications of the free precession for the timing data also need to be assessed carefully. In doing so, the role of glitches in the rotation history of these pulsars, including their interplay with precession, would need to be understood, but this is beyond the scope of the present discussion.

It is indeed remarkable the way the rotational history of the central pulsar is evident, and can be traced, from these X-ray images of the surrounding nebula. The application of our model to the two cases discussed above allows ready interpretation of the observed spatial and temporal structure to trace the rotational history of the central pulsar and the details of the surrounding cavity.

5. DISCUSSION

The cavity shapes suggested by our modeling of the observed X-ray nebulae might appear to differ significantly in the two cases (namely, the Vela and the Crab) discussed here. The part of the cavity profile sampled by the particle beams from the Crab pulsar appears to be significantly shallower than that in the case of the Vela pulsar. Given the age and the proper motion of the Vela pulsar, the relative dimensions of its X-ray arcs appear to favor an hourglass-shaped cavity, rather than an ellipsoid. The visibility of the jetlike feature apparently extending well beyond the diffuse component is not inconsistent with both of these components sharing a common origin, i.e., the latitudinal spread of a small fraction of the otherwise collimated particle flow, since the apparent relative brightness of the two components could differ significantly for intrinsic reasons, as well as those dictated by the viewing geometry.

In our picture, the observed extents of the jetlike features, after due accounting of the projection effect, provide lower limits for the dimension of the cavity in the latitudinal direction, which appears to exceed the equatorial dimension, at least in the Vela case. The apparent asymmetry in the jet and the counterjet extents in the Vela nebula is consistent with our expectation of the associated radiation being symmetric with respect to the direction of the magnetic axis, modified by the viewing geometry. If the jetlike emission were to be due to any physical flow of matter at relativistic speeds along the rotation axis (e.g., as estimated by Pavlov et al. 2003), the counterjet should have been more prominent, in both its extent and its brightness, given that it would be pointing closer to our sight line. This is definitely not what is observed, and in fact, this aspect was noted as a cause for concern by Pavlov et al. (2003). Further, such a physical jet flow cannot escape its dissipation and consequent termination at the relevant region of the cavity wall where a caplike emission feature should have been apparent but is not observed. In their "physical jet" picture, the jet instabilities leading to bending, etc., are expected to be due to and along the proper motion of the star. The Crab case is clearly inconsistent with this expectation, implying at the least that the apparent bending has little to do with the motion of the star. These inconsistencies and the other aspects discussed by RD01 argue strongly against a physical jet along the rotation axis.

Apparent bends in the jetlike features in general, and particularly those with antisymmetry about the equatorial plane, are interpreted in our model as due to possible free precession. Its successful application to the Crab and the Vela pulsars, differing in the viewing geometry and rotation history, is not a chance coincidence. It would not surprise us, therefore, if the bent jetlike feature in the X-ray nebula around pulsar B1509−58 (Gaensler et al. 2002) would have a similar interpretation. The variability of these and other features is then a natural consequence of such a rotational history, as illustrated by the multiepoch observations of the Vela X-ray nebula. The variability seen in the Crab nebula at optical wavelengths would be another illustration of the same effect, although on much longer timescales. If our assumed precession period of 14 yr for the Crab pulsar is correct, a significant change in the orientation of the jetlike feature should be expected in the coming years. As commented earlier, the yet unexplored interplay between the glitches and possible precession would determine how the rotation/precession history evolves with time. Hence, it is not at all clear whether free precession, if any, would be unaffected through the glitch episodes, and even if it does, whether any clear signature of free precession of the star would be apparent from the radio pulsar timing residuals obtained after fitting for period glitches and the associated recoveries commonly observed in young pulsars. It remains to be seen if any significant variation in the shape and intensity of the radio pulses from the Crab pulsar reveals a signature consistent with the rotational history of the star suggested by the above-mentioned observations at high energies.

There have been suggestions of free precession in a few pulsars, but they are based on apparent changes in pulse shapes and intensities (e.g., DM96; Shabanova et al. 2001) or in pulse arrival times (Stairs et al. 2000). We wish to point out that a direct and independent way of probing any changes in the orientation of the rotation axis of the star, as in precession, is through monitoring of the polarization P.A. sweep across the radio pulses and measuring systematic changes, if any, particularly in the P.A. sweep rate (Hari Dass & Radhakrishnan 1975). We have indeed begun recently such a monitoring of the Vela pulsar using the Giant Metrewave Radio Telescope (GMRT) in India.

To summarize, we find compelling evidence for collimated particle beams from pulsars and for free precession of the Vela and the Crab pulsars, based on the *Chandra* observations of the respective X-ray nebulae and their apparent systematic variability. Quantitative estimates of the intensities and the locations of the different elements of the nebulae and their variability, when compared in the framework of our simple interpretation, should pave the way to important clues on the properties of the cavities created by the pulsars and the energy spectra associated with the collimated particle beams.

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