THE DISTANCE TO THE VELA PULSAR GAUGED WITH HUBBLE SPACE TELESCOPE PARALLAX OBSERVATIONS

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ABSTRACT
The distance to the Vela pulsar (PSR B0833−45) has been traditionally assumed to be 500 pc. Although affected by a significant uncertainty, this value stuck to both the pulsar and the supernova remnant. In an effort to obtain a model-free distance measurement, we have applied high-resolution astrometry to the pulsar V ~ 23.6 optical counterpart. Using a set of five Hubble Space Telescope Wide Field Planetary Camera 2 observations, we have obtained the first optical measurement of the annual parallax of the Vela pulsar. The parallax turns out to be 3.4 ± 0.7 mas, implying a distance of 294 ± 56 pc, i.e., a value significantly lower than previously believed. This affects the estimate of the pulsar absolute luminosity and of its emission efficiency at various wavelengths and confirms the exceptionally high value of N_e toward the Vela pulsar. Finally, the complete parallax database allows for a better measurement of the Vela pulsar proper motion [μ_x, cos(δ) = −37.2 ± 1.2 mas yr^{-1}; μ_y = 28.2 ± 1.3 mas yr^{-1} after correcting for the peculiar motion of the Sun], which, at the parallax distance, implies a transverse velocity of ≈65 km s^{-1}. Moreover, the proper-motion position angle appears especially well aligned with the axis of symmetry of the X-ray nebula as seen by Chandra. Such an alignment allows us to assess the space velocity of the Vela pulsar to be 81 km s^{-1}.

Subject headings: astrometry — pulsars: individual (Vela pulsar) — stars: distances

1. INTRODUCTION
Assessing distances to isolated neutron stars (INSs) is a very challenging task that has been pursued using different techniques in different regions of the electromagnetic spectrum. Distances to pulsars with no glitching activity can be obtained through radio timing techniques (Bell 1998). However, only millisecond radio pulsars allow for positional accuracies high enough to be used for parallax measurements. Toscano et al. (1999) count six such cases in their list of 12 pulsars, the distances to which have been determined through parallax. For the remaining six objects, which are all classical pulsars with periods of a few hundreds of milliseconds, a very long baseline interferometry (VLBI) approach was used, requiring a suitable nearby calibrator. The difficulties of the VLBI technique, including the need to account for changing ionospheric conditions, are apparent from the significant revisions already published for two of the six parallax values. The parallaxes of PSR B0919+06 went from 0.31 ± 0.14 mas (Fomalont et al. 1999) to 0.83 ± 0.14 mas (Chatterjee et al. 2001), while for PSR B0950+08 the parallax went from 7.9 ± 0.8 mas (Gwinn et al. 1986) to 3.6 ± 0.3 mas (Brisken et al. 2000).

Even if limited to 12 objects, i.e., less than 1% of the pulsar family (Camilo et al. 2000), determining model-independent distances of nearby pulsars is a rewarding exercise. As summarized by Campbell et al. (1996) and Toscano et al. (1999), this allows us to trace the local interstellar medium. A distance value, coupled with the pulsar dispersion measure, yields the electron density along the line of sight, to be compared with the model of the Galactic N_e distribution (Taylor & Cordes 1993). Such a model is used to derive the distances to all of the remaining pulsars (>99% of the population). Moreover, a distance value transforms the pulsar proper motion into a firm transverse velocity, to be compared with the average pulsar three-dimensional velocities obtained by Lyne & Lorimer (1994) and Cordes & Chernoff (1998) on larger samples.

X-ray astronomy provides hints about the distance of the score of pulsars detected so far (Becker & Trümper 1997) through the measurement of the absorption of their soft X-ray emission. Unfortunately, distances derived from X-ray absorption are as uncertain as those derived from the dispersion measure. In general, the radio distances are greater than the X-ray ones.

With the detection of pulsars in the optical (see, e.g., Caraveo 2000), distance measurements became possible using classic optical astrometry techniques, based on parallax measurements. Measuring tiny parallactic displacements is never easy, and the task can become really challenging when the targets are intrinsically faint, like INSs. It requires high angular resolution coupled with high sensitivity, rendering the Hubble Space Telescope (HST) the instrument of choice to measure proper motions and parallaxes of faint objects. The astrometric capabilities of HST were used to obtain model-free measurements of the distance to Geminga (Caraveo et al. 1996) and RX J1856−3754 (Walter 2001), two radio-quiet INSs for which radio astronomy could not provide any input.

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FIG. 1.—Relative parallactic factors in right ascension (dashed line) and declination (solid line) computed for the Vela pulsar position. The arrows mark the periods of the year corresponding to the observations listed in Table 1.

In this paper we address the Vela pulsar (PSR B0833 – 45), which provides a compelling case of a nearby INS with a highly disputed distance value and a relatively bright optical counterpart \((V \sim 23.6)\). The value of 500 pc, tentatively obtained after the original pulsar discovery \((e.g.,\ \text{Milne 1968; Prentice & Ter Haar 1969})\), has been assumed as a reference for both the pulsar and its surrounding supernova remnant (SNR). As such, it is still quoted in radio pulsar catalogs,\(^3\) in spite of the doubts raised by several independent investigations carried out at different wavelengths and targeting both the pulsar and the SNR. On the basis of their analysis of the ROSAT data, Page, Shibanov, & Zavlin (1996) placed the Vela pulsar at 285 ± 30 pc, while Pavlov et al. (2001b), using Chandra data fitted by a two-component model, obtain a distance of 210 ± 20 pc. On the other hand, studying the Vela remnant, Cha, Sembach, & Danks (1999) and Bocchino, Maggio, & Sciorino (1999) find a distance of 250 ± 30 pc and ≈280 pc, respectively. This agrees with an earlier suggestion by Jenkins & Wallerstein (1995) based on the remnant overall energetics. A different view is proposed by Gvaramadze (2001), who, on the basis of the pulsar scintillation velocity and its very uncertain interpretation, sees no reason to revise the canonical 500 pc distance.

We started our observations aimed at the measurement of the Vela pulsar parallax in 1997, during HST observing Cycle 6, but we had to wait until Cycle 8 to complete our program. Meanwhile, our data have also been used to reassess the proper motion of the Vela pulsar (De Luca, Mignani, & Caraveo 2000) and to quantify the overall reliability of our astrometric approach (De Luca, Mignani, & Caraveo, 2001). In the following we shall report the analysis of our HST data leading to the measurement of the Vela pulsar annual parallax and proper motion. The impact of our result on the current understanding of the Vela pulsar is also discussed. While HST was collecting the appropriate set of images, VLBI in the southern hemisphere came into existence, and Vela was one of the targets. The preliminary radio results \((\text{Legge 2000})\) will be compared with our optical ones.

2. THE OBSERVATIONS

The measurement of the annual parallax of a star through optical astrometry techniques requires a set of at least three observations of the field, preferably taken at the epochs of the maximum parallactic elongation. For the Vela pulsar \((\alpha_{2000} = 08^h35^m20^s6, \delta_{2000} = -45^\circ10'35.1'')\), the epochs of maximum parallactic elongation coincide with days 118 and 303 of the year for right ascension and days 20 and 204 for declination, with relative parallax factors \(\text{(see, e.g., Murray 1983)}\) at the maximum elongation of \(\sim0.97\) and \(\sim0.90\), respectively \(\text{(see Fig. 1). Although the relative parallactic factor at maximum elongation is somewhat larger in right ascension, observations at one of the corresponding epochs turned out to be difficult to schedule as a result of their very tiny visibility window. For this reason, the observations of Vela were scheduled close to the epochs of the maximum parallactic displacements in declination.} \)

Our program was originally approved for HST Cycle 6, but, unfortunately, only two observations of the planned triplet were executed. The whole program had to go through a new approval cycle and was rescheduled and successfully completed in Cycle 8. We thus obtained a total

| Table 1 Summary of HST WFPC2 Observations Used for the Measurement of the Vela Pulsar Parallax |
|-----------------------------------------------|
| Observation | Date     | \(P_a\) | \(P_d\) | Number of Exposures | Exposure Time (s) |
|-------------|----------|--------|--------|---------------------|------------------|
| 1           | 1997 Jun 30 | –0.467 | 0.850  | 2                   | 1300             |
| 2           | 1998 Jan 2  | 0.399  | –0.852 | 2                   | 1000             |
| 3           | 1999 Jun 30 | –0.478 | 0.852  | 2                   | 1000             |
| 4           | 2000 Jan 15 | 0.196  | –0.887 | 2                   | 1300             |
| 5           | 2000 Jul 5  | –0.394 | 0.883  | 2                   | 1300             |

\(\text{Note.—In all cases the observations were taken with the same instrument setup, i.e., through the F555W filter and with the target positioned at the center of the PC. For each observation, the columns give the sequence number, the observing epoch and the corresponding parallactic factor in right ascension and declination (} \(P_a, P_d\), the number of repeated exposures, and the exposure time in seconds. Observations 1–4 are those used by De Luca et al. (2000) and De Luca et al. (2001) to reassess the Vela pulsar proper motion.} \)
of five observations of the field with the Wide Field Planetary Camera 2 (WFPC2) between 1997 June and 2000 July. The complete journal of the observations is summarized in Table 1. At each epoch, two exposures of the field were acquired with the WFPC2 "V" filter F555W ($\lambda = 5252$ Å, $\Delta \lambda = 1225$ Å) and with similar integration times. In order to maximize the angular resolution, in all cases the pulsar optical counterpart was centered on the Planetary Camera (PC) chip of the WFPC2 (pixel size of 0.045).

3. DATA REDUCTION AND ANALYSIS

The data reduction was performed using the IRAF/STSDAS package. After the standard pipeline processing of the frames (debiasing, dark subtraction, and flat-fielding), which was performed using the most recent reference files and tables, each couple of co-aligned images was co-added for a first filtering from cosmic-ray hits. Residual hits were later rejected using specific cosmic-ray subtraction algorithms in IRAF. Figure 2 shows the resulting image for 2000 July.

The cleaned images have then been used for the definition of a relative reference frame to be used as a starting point for our astrometric procedure. Since all the observations have been taken with different telescope roll angles and with small relative offsets, the definition of a relative reference frame must rely on a very accurate image superposition.

Following the approach applied successfully in previous astrometric works (e.g., Caraveo et al. 1996; Caraveo & Mignani 1999; De Luca et al. 2000; Mignani, Caraveo, & De Luca 2001; Mignani, De Luca, & Caraveo 2000), this is done by computing a linear coordinate transformation (i.e., accounting for two independent translation factors, two scale factors, and a rotation angle) between a set of reference objects.

The selection of the reference grid objects is critical. They must be pointlike, present in all observations (but not too close to the field edges), and bright enough to allow for an accurate positioning (but not saturated). A set of 26 such objects (labeled in Fig. 2) was selected in the reference frame of the PC.

Since the shape of the PC point-spread function (PSF) is known to be position dependent (Krist 1995), we did not use simulated PSFs for source fitting. On the other hand, the number of good reference stars was not sufficient to compute a template PSF directly from the images. Thus, the reference object coordinates were computed by fitting a two-dimensional Gaussian function to their intensity profiles, using optimized centering areas. This yielded positional uncertainties on the order of 0.01–0.05 pixels, depending on the objects’ brightness and position on the chip. Special care was devoted to characterizing the errors involved in the centroid determination. Following De Luca...
et al. (2001), we addressed both statistical errors (i.e., due to each object’s signal-to-noise ratio) and systematic ones (due, e.g., to the telescope jitter, defocusing of the camera, charge transfer in the CCD, background fluctuations, and so on). Moreover, we checked that our results were not biased by the algorithm used for the fitting. The coordinates were corrected for the “34th row error” (Anderson & King 1999) and for the significant, well-known instrument geometrical distortion using the most recent mapping of the PC field of view (Casertano & Wiggs 2000). The centroids of the Vela pulsar optical counterpart were obtained in the same way, yielding errors ranging between 0.02 and 0.04 pixels.

Having secured a reference grid, we registered all the frames on the 1999 June grid, taken as a reference and previously aligned along right ascension and declination according to the telescope roll angle. The rms of the residuals on the reference object coordinates were less than 0.05 pixels in right ascension and less than 0.04 pixels in declination. The overall accuracy of the frame registration, accounting for errors in the centroid determination and in the geometric distortion’s mapping, as well as the accuracy of the fit have been discussed in detail by De Luca et al. (2001).

To ensure that our procedure was not affected by any displacement of our 26 reference objects (due to either proper motions or parallaxes), we have repeated the frame registration 26 times, i.e., each time excluding one of the objects from the fit. In addition, to exclude any possible bias due to the arbitrary choice of the reference frame, we have repeated the whole procedure, cycling it over the five epochs. In all cases, we obtained statistically indistinguishable results. We are thus confident that our procedure is correct and free of systematics. Last, we have applied the coordinate transformations to the positions of the Vela pulsar; the resulting relative positions are shown in Figure 3.

If fitted with a simple proper motion, all the points in Figure 3 are seen to deviate from the straight line. Their residuals with respect to the proper-motion fit, however, are not randomly distributed. Rather, they follow the trend expected for an object also affected by parallactic displacement.

4. ANALYSIS OF THE PULSAR DISPLACEMENTS

The geocentric right ascension and declination \( [x_d(t), \delta_d(t)] \) of the pulsar at a given epoch \( t \) can be expressed in the form

\[
\begin{align*}
\alpha_d(t) &= \alpha_d(t_0) + \mu_x \cos(\delta)(t-t_0) + \pi P_d(t) \\
\delta_d(t) &= \delta_d(t_0) + \mu_d(t-t_0) + \pi P_d(t),
\end{align*}
\]

(1)

where \( [\alpha_d(t_0), \delta_d(t_0)] \) are the barycentric coordinates at a reference time \( t_0 \), \( \mu_x, \mu_d \) are the right ascension and declination components of the proper motion, \( \pi \) is the annual parallax, and \( [P_d(t), P_d(t)] \) are the parallactic factors shown in Figure 1. A system of equations like equation (1) can be written for each of the five epochs corresponding to our observations.

Setting 1999 June 30 as the reference epoch, one can obtain five pairs of equations relating the observed coordinates of the pulsar to the five unknowns \( \pi, \mu_x, \mu_d, \alpha_d(t_0), \) and \( \delta_d(t_0) \). A least-squares fit yields the following values for the parallax and the proper motion: \( \pi = 3.4 \) mas, \( \mu_x \cos(\delta) = -45.0 \) mas yr\(^{-1} \), and \( \mu_d = 25.8 \) mas yr\(^{-1} \), corresponding to a reduced \( \chi^2 \) of 0.11 (5 degrees of freedom).

To evaluate the uncertainties and the confidence levels on the fit parameters, we ran a Monte Carlo simulation for a theoretical source featuring proper motion and parallax values equal to our best-fit ones. Each synthetic data set was obtained by perturbing a coordinate set representing the expected source geocentric positions at the epochs of our observations. The experimental error (per coordinate) for each data point in each simulated data set was computed from a normal distribution with a standard deviation equal to the overall uncertainty (per coordinate) affecting the pulsar positioning estimated in § 3 (i.e., \( \leq 2 \) mas per coordinate in 1999 June 30; 2.5–2.9 mas per coordinate in the remaining epochs).

After \( 10^5 \) simulations, we estimate the 1 \( \sigma \) error bar, to be attached to the parallax value, at 0.7 mas, while the uncertainties on the proper motion are 1.1 mas in \( \alpha \) and 1 mas in \( \delta \). Thus, our best evaluation of the Vela pulsar displacements is as follows:

\[
\begin{align*}
\pi &= 3.4 \pm 0.7 \text{ mas} \\
\mu_x \cos(\delta) &= -45.0 \pm 1.1 \text{ mas yr}^{-1} \\
\mu_d &= 25.8 \pm 1.0 \text{ mas yr}^{-1} 
\end{align*}
\]

corresponding to a position angle of 299°8 ± 1°2.

The Vela path in the sky, as predicted from the best-fitting proper motion and parallax, is plotted in Figure 4, together with the measured pulsar positions. The agreement between the expected positions and the measured ones is remarkably good.

4.1. The Proper Motion

Our best fit to the pulsar proper motion improves the result of De Luca et al. (2001) by confirming the overall
the ionospheric correction approach, nor on the correction for Galactic rotation (on top of the Sun peculiar motion), so we cannot assess the accuracy of the radio data analysis. Since the optical approach we have used is free from all such systematics, we conclude that our distance determination, based as it is on direct measurement, with a well-known error determination procedure, is to be taken as the most reliable estimate of the true distance of this celestial object.

5. DISCUSSIONS

After Geminga (Caraveo et al. 1996) and RX J1856–3754 (Walter 2001), this is the third measurement of the optical parallax of an INS to be added to the list of a dozen radio parallaxes summarized by Toscano et al. (1999). At variance with the two previous cases, which had no firm distance estimates, the new value for the distance of the Vela pulsar is significantly smaller than the traditionally accepted one, confirming the earlier claims by Jenkins & Wallerstein (1995), Page et al. (1996), Bocchino et al. (1999), Cha et al. (1999), and Pavlov et al. (2001b).

While adding an important piece of information to the study of the distribution of electrons in the local environment, a distance of \( \leq 300 \) pc has several implications for the Vela pulsar physics as well as for its kinematics. In what follows we shall address each of these points.

5.1. Local Interstellar Medium

Toscano et al. (1999) used the 12 radio pulsars with a measured parallax to map the local interstellar medium and deduce electron densities along their different lines of sight. The Vela pulsar was added to the sample on the basis of a distance of 250 pc, suggested by Cha et al. (1999) for the SNR. Coupling the Vela dispersion measure (67 cm\(^{-3}\)) with such a distance, Toscano et al. (1999) computed an \( N_e \) of \( 0.270 \) cm\(^{-3}\), to be compared with the average density of \( 0.02 \) cm\(^{-3}\) of the Taylor & Cordes (1993) model for the local region. Indeed, the \( N_e \) toward Vela is the maximum in their sample, and it is 5–10 times higher than the values found for four other pulsars in the third Galactic quadrant. These pulsars already show \( N_e \) values systematically higher than a comparable number of objects in the first Galactic quadrant. Our distance value, while slightly lowering the \( N_e \) value to 0.23 cm\(^{-3}\), confirms the extremely high electron density toward Vela, possibly pointing toward the existence of ionized clouds in the Vela region direction, at the edge of the so-called \( \beta \) CMa tunnel. This problem has been recently addressed by Cha et al. (2000), who, doing the “astronephography” of the region (three-dimensional mapping of interstellar clouds), found three distinct absorption systems with different velocities, consistent with an enhanced density of ionized material toward PSR B0833–45.

5.2. Multiwavelength Emission

For 20 years, up to 1993, the Crab and Vela pulsars were the only neutron stars detected throughout the entire electromagnetic spectrum, from radio to optical to high-energy \( \gamma \)-rays. Remarkably similar in high-energy \( \gamma \)-rays, the behavior of the two pulsars is very different at all other wavelengths (see, e.g., Thompson 2001). Furthermore, our current understanding of the pulsar emission mechanisms at wavelengths other than radio has been biased by the phenomenology of Crab and Vela, since theories have been
shaped to account for the multiwavelength behavior of these two objects. The significant downsizing of the Vela pulsar luminosity (by a factor of $\approx 3 \pm 1$) presented here implies some revision of the current view of pulsars' multiwavelength behavior. However, lowering the distance to the Vela pulsar does not have the same impact in the various spectral domains.

Vela has a very special place in the high-energy $\gamma$-ray sky, where it is by far the brightest source, outshining the Crab by a factor of $\approx 4$. Its radiation is totally pulsed (Kambbach et al. 1994), and its spectral shape varies throughout the light curve. Of course, to convert the measured flux into a luminosity, one needs to know the pulsar distance, together with its beaming factor. While the $\gamma$-ray community never disputed the traditional 500 pc value for the Vela distance, the beaming solid angle remains unknown, ranging from the size of a neutron star polar cap to $4^4$. With such a beaming value, the high-energy luminosity of the Vela pulsar is now $7 \times 10^{33}$ ergs s$^{-1}$, comparable to that of the much older PSR B1055−52 and 10 times lower than that of PSR B1706−44, a pulsar remarkably similar to Vela in its $P$, $P'$, and overall energetics. Moreover, the efficiency with which Vela converts its rotational energy loss into $\gamma$-rays becomes 0.001, similar to that of the much younger Crab and 20 times smaller than that of PSR B1706−44. Not surprisingly, the Vela pulsar is now well below any best-fitting line correlating the $\gamma$-ray luminosity to pulsar parameters such as the number of accelerated particles (Thompson et al. 1999) or the value of the open field line voltage (Thompson 2001). This will require a critical reexamination of the position of Vela in the $\gamma$-ray-emitting pulsar family. Vela may become an underluminous pulsar, an apparent paradox considering its brightness in the $\gamma$-ray sky.

In the X-ray domain, the situation is different. The X-ray emission phenomenology already prompted a number of authors (Page et al. 1996; Pavlov et al. 2001b; Helfand, Gotthelf, & Halpern 2001) to opt for a distance smaller than the “canonical” one. Indeed, for a distance of 500 pc, the soft X-ray flux, most probably originated by the hot surface of the neutron star, pointed toward an emitting area ($R^o = 3$–4 km) far too small to be compatible with the whole neutron star surface (Ögelman, Finley, & Zimmerman 1993). On the other hand, a very small emitting hot spot is obviously incompatible with the shallow pulsation seen at these energies. Reducing the pulsar distance to half its canonical value, Pavlov et al. (2001b) find that for a pure blackbody emission, a radius of the emitting area of just 1.9–2.4 km could explain the flux observed by Chandra. Introducing a modified blackbody with a pure H atmosphere eases the emitting area problem, allowing for the whole surface of a 13 km radius neutron star at 210 pc to emit at a temperature significantly smaller than that obtained in the pure blackbody case. Our new, independent distance determination now freezes one of the parameters of the model, allowing for a better determination of both the neutron star radius and its temperature.

The parallax distance fixes the overall Vela X-ray luminosity (0.2–8 keV) to be about $5.5 \times 10^{12}$ ergs s$^{-1}$, divided between a thermal component dominating at low energies and a nonthermal one emerging only at higher energies. If compared with the available rotational energy loss, such an X-ray emission accounts for $8 \times 10^{-5}$ of the pulsar reservoir, significantly less than the average ratio of $\approx 10^{-3}$ found for the majority of the young X-ray-emitting pulsars (Becker & Trumper 1997). Moreover, such an already low conversion efficiency shrinks to $10^{-6}$ if one considers only the nonthermal component, confirming the severe underluminosity of PSR 0833−45 in the X-ray domain. The interpretation of such an underluminosity, however, is complicated by the composite nature of the Vela emission. It is certainly dominated by thermal emission for $E \geq 1.8$ keV, with a weaker magnetospheric component emerging only at $E \geq 1.8$ keV (Pavlov et al. 2001b). Because of such a composite nature, the Vela pulsar X-ray emission cannot readily be compared to other purely magnetospheric cases (e.g., the Crab and PSR B0540−69).

The X-ray data can also be used to further map the local interstellar medium. The comparison between distance and hydrogen column density, $N_H$, responsible for the X-ray absorption, provides an assessment of the reliability of this parameter as a distance indicator for nearby sources.

In the optical domain, the reduction in the pulsar luminosity has important implications. Here the emission is certainly magnetospheric—as witnessed by its double-peaked light curve (Wallace et al. 1977; Manchester et al. 1978; Gouiffes 1998) and by its flat 3600–8000 Å spectrum (Naasuti et al. 1997; Mignani & Caraveo 2001). However, the revised value of the $B−U$ optical luminosity, $L_{\text{opt}} \approx 5.5 \times 10^{28}$ ergs s$^{-1}$, is now quite low with respect to the prediction of the classical Pacini & Salvati (1983) model, based on synchrotron emission at the light cylinder. Such an underluminosity could be ascribed neither to the spectral shape of the optical emission, which follows a flat Crab-like power law (Mignani & Caraveo 2001) nor to the shape of the light curve (see, e.g., Gouiffes 1998), which covers a broader phase interval than the Crab emission, resulting, if anything, in an increase of the optical output.

The behavior of the Vela pulsar in the optical domain should be considered in light of its “transition” position between the group of the young energetic pulsars, characterized by pure magnetospheric emission, and that of the middle-aged pulsars, characterized by composite spectra and lower emission efficiency (see, e.g., Caraveo 1998; Mignani & Caraveo 2001).

In the X-ray domain Vela behaves as a middle-aged object (see, e.g., Pavlov et al. 2001b), while in the optical and $\gamma$-ray energy ranges, its phenomenology is reminiscent of that of the younger pulsars but with a low emission efficiency. The multiwavelength luminosities of the Vela pulsar, stemming from the newly determined distance, will help us to discriminate between the emission mechanisms at work in the different energy domains and to assess their evolution throughout the life of the pulsars.

5.3. Proper Motion

The parallax fit also yields, as a by-product, the best proper-motion value obtained so far at optical wavelengths, corresponding to a transverse velocity of $\approx 65$ km s$^{-1}$. The space direction of the Vela proper motion has been correlated with the axis of symmetry of the Chandra X-ray structure by a number of authors (Mignani et al. 2000; Helfand et al. 2001; Pavlov et al. 2001a). Since the X-ray nebula axis of symmetry should trace the pulsar rotational axis, an alignment between such an axis of symmetry and the pulsar proper motion would have important bearings on the kick
mechanism responsible for the neutron star ejection. Lai, Chernoff, & Cordes (2001), noting that the proper-motion axis-of-symmetry alignment also seems to be present for the Crab pulsar (Caraveo & Mignani 1999), considered different spin-kick alignment mechanisms. Also, in view of the pulsars’ low velocities, they concluded that both natal kicks, whether hydrodynamic or neutrino-magnetic, as well as postnatal ones, such as the Harrison & Tademaru (1975) electromagnetic kick, could account for the alignments.

Here, we reassess the case for the Vela proper-motion X-ray jet alignment by comparing our “corrected” proper-motion position angle of 30°7.2 ± 1°6 with the value of 30°7 ± 2° computed by Pavlov et al. (2001a) for the axis of symmetry of the structure seen by Chandra. Assuming a uniform probability distribution for the two vectors in space, we estimate the chance occurrence probability to be 1.2 × 10−3, thus strengthening the case for an alignment between the Vela rotation axis and its proper motion. Figure 5 shows an update of Figure 2 from Mignani et al. (2001), with our corrected proper-motion vector superposed on the high-resolution Chandra image of the Vela nebula. Taking advantage of such an alignment, we can use the angle of 53°2, computed by Helfand et al. (2001), between the axis of the X-ray torus and the line of sight to convert our measured transverse velocity into the pulsar three-dimensional velocity. Thus, the space velocity of the Vela pulsar turns out to be 81 km s−1. While hardly compatible with the Lyne & Lorimer (1994) mean value of 400 km s−1, our value is also on the low side of the low-velocity component of the bimodal fit by Cordes & Chernoff (1998), classifying Vela as a rather slow moving pulsar.

6. CONCLUSIONS

We have presented the first direct measurement of the distance to the Vela pulsar at optical wavelengths. Our value is significantly smaller than the canonical one, implying a downgrading of the luminosity of the Vela pulsar and positioning Vela among the underluminous pulsars. High-energy γ-ray astronomy is the most affected by our result since it pertains to the brightest, and hence most conspicuous, source in the γ-ray sky. The optical domain is also seriously affected by our overall luminosity reduction, while the X-ray side is only marginally altered. The distance determination also confirms the anomalously high density of electrons toward the Vela pulsar, pointing to the presence of ionized clouds in the local interstellar medium.

As a by-product of the parallax fit, we have obtained a very accurate proper-motion value, which appears nicely aligned along the axis of symmetry of the X-ray nebula, and hence the pulsar rotation axis. Moreover, our proper motion, together with our distance determination, fixes the transverse velocity of Vela to 65 km s−1. Using the inclination of the X-ray torus as measured by Helfand et al. (2001), we can convert our transverse velocity into the three-dimensional one, yielding a value of 81 km s−1. For a pulsar, this is certainly a low velocity.

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Fig. 5.—X-ray image of the Vela pulsar and synchrotron nebula taken with the Chandra High-Resolution Camera (north is to the top, and east is to the left). The image has been smoothed with a low-pass filter in order to highlight the large-scale structures. The arrow indicates the direction of the pulsar proper motion corrected for the peculiar motion of the Sun, as discussed in §5.3.
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