

Research Note

The Vela pulsar (PSR B0833-45) proper motion revisited with HST astrometry[★]

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Abstract. Using all the HST WFC/WFPC2 images of the field collected so far, we have performed an accurate relative astrometry analysis to re-assess the value of the Vela pulsar proper motion. Although covering a much shorter time span, our measurement clearly confirms the previous result obtained by Nasuti et al. (1997) using ground-based optical data and nails down the proper motion value to $\mu = 52 \pm 3 \text{ mas yr}^{-1}$.

Key words: astrometry – stars: pulsars: individual: PSR B0833-45

1. Introduction

The Vela pulsar is one of the isolated neutron stars with the widest observational database, spanning from radio waves to high-energy γ -rays. Nevertheless, the value of its distance is still in debate. The canonical value of 500 parsec, derived by Milne (1968) from the radio signals dispersion measure, has been recently questioned by several independent investigations. Studies of both the kinematics of the host supernova remnant (Cha et al. 1999; Bocchino et al. 1998) and constraints on the neutron star radius imposed by the pulsar soft X-ray spectrum (Page et al. 1996) have suggested a significant downward revision of the distance. In both cases, a value of ≈ 250 parsec appears more likely than the canonical one. A model-free evaluation of the distance which could settle the question can be obtained only by measuring the annual parallax of the pulsar. To this aim we have been granted a triplet of consecutive HST/WFPC2 observation to be performed six months apart at the epochs of the maximum parallactic displacement.

In this paper we present a first result of our program: an accurate re-assessment of the pulsar proper motion. This is another open point in the Vela pulsar phenomenology: although

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Table 1. Previous estimates of the Vela pulsar proper motion in literature

| Optical | μ mas yr ⁻¹ | $\mu_{\alpha} \cos \delta$ mas yr ⁻¹ | μ_{δ} mas yr ⁻¹ |
|--------------------------|-------------------------------|--|--|
| Bignami & Caraveo 1988 | < 60 | – | – |
| Ögelman et al. 1989 | 38 ± 8 | –26 ± 6 | 28 ± 6 |
| Markwardt & Ögelman 1994 | 49 ± 4 | –41 ± 3 | 26 ± 3 |
| Nasuti et al. 1997 | 52 ± 5 | –47 ± 3 | 22 ± 3 |
| Radio | | | |
| Bailes et al. 1989 | 49 ± 4 | –40 ± 4 | 28 ± 2 |
| Fomalont et al. 1992 | 116 ± 62 | –67 ± 20 | –95 ± 75 |
| Fomalont et al. 1997 | 53 ± 19 | –50 ± 5 | –16 ± 18 |

certainly present, its actual value is still uncertain. Previous estimates obtained through radio and optical observations led to conflicting results (see Table 1 for a summary), spanning from 38 mas yr⁻¹ (Ögelman et al. 1989) to 116 mas yr⁻¹ (Fomalont et al. 1992). These discrepancies are due both to the rather poor angular resolution of the first optical images of the field, which reduced the accuracy of relative astrometry, and to the timing irregularities of the Vela pulsar signal, which possibly affected the reliability of radio positions. However, the newly operational southern VLBI has already been used on the Vela pulsar yielding preliminary results of vastly improved accuracy (Legge 1999).

2. The data analysis

The best way to gauge the angular displacement of an object between different epochs is to perform relative optical astrometry measurements. This needs:

- a set of “good” reference stars, accurately positioned, to provide the relative reference frame for each image

Table 2. HST observations of the Vela pulsar field. The columns give the image number, the observing epoch, the instrument used, the pixel size in arcsec, the filter, the total number of repeated exposures for each observation and the exposure duration in seconds.

| | Date | Instrument | Pixel size (arcsec) | Filter | N° exposures | Exposure (s) |
|---|------------------|------------|---------------------|--------|--------------|--------------|
| 1 | 1993 February 26 | WFC | 0.1 | F555W | 4 | 400 |
| 2 | 1997 June 30 | WFPC2 | 0.045 | F555W | 2 | 1300 |
| 3 | 1998 January 2 | WFPC2 | 0.045 | F555W | 2 | 1000 |
| 4 | 1999 June 30 | WFPC2 | 0.045 | F555W | 2 | 1000 |

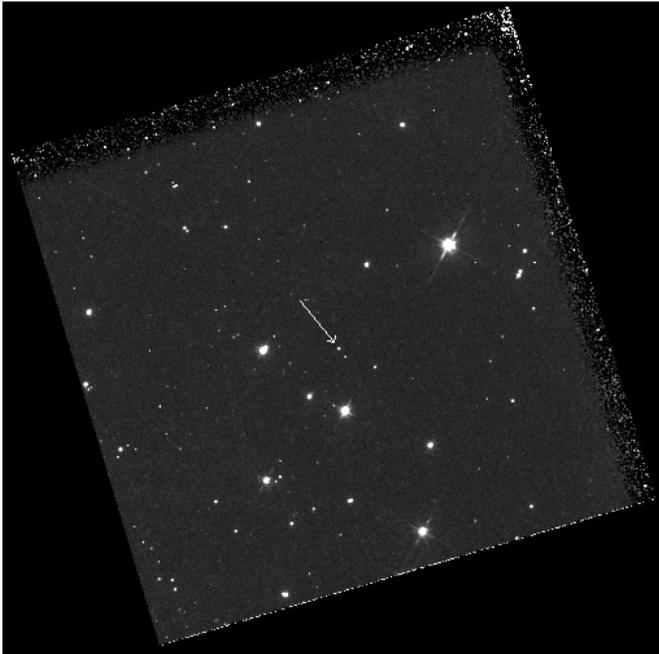


Fig. 1. Planetary Camera image of the Vela pulsar field taken in 1997 through the F555W filter. North is up, East is left. The arrow marks the position of the Vela pulsar.

– a reliable procedure to align the reference frames

In our relative astrometry analysis we have used all the images of the Vela pulsar field collected so far by the HST (see Table 2). The observations, all taken through the F555W “V filter”, have been obtained either using the original WFC and the WFPC2, with the pulsar positioned in one of the WFC chips or in the PC one, respectively. Observation #1 has been retrieved from the ST-ECF database and recalibrated on-the-fly by the archive pipeline using the most recent reference data and tables, while observations #2 and #3 were obtained as part of our original parallax program, included in cycle 6 but never completed. The program is now being repeated in cycle 8 and image #4 is indeed the first of the new triplet of WFPC2 observations. For each epoch, cosmic-ray free images were obtained by combining coaligned exposures.

The choice of reference stars was limited to the chip containing the pulsar optical counterpart (see Caraveo & Mignani 1999 for a qualitative discussion of the inter-chip astrometry). 25 common stars were selected in the PC images of 1997, 1998

and 1999; 19 of them were identified in the 1993 WFC image. This defines our set of reference stars. Their coordinates were calculated by 2-D gaussian fitting of the intensity profile. The evaluation of the positioning errors was conservative; for each reference star the fit was repeated several times on centering regions of growing areas, till errors showed no more dependence on the background conditions (see Caraveo et al. 1996). Uncertainties on the centroid positions were typically of order $0.02 \div 0.06$ pixel (i.e. $1 \div 3$ mas) per coordinate in the WFPC2 images and $0.03 \div 0.06$ pixel (i.e. $3 \div 6$ mas) per coordinate in the WFC one.

The values of the coordinates of reference stars have been then corrected for the effects of the significant geometrical distortion of the WFC and the WFPC2 CCDs. This correction has been applied following two different mappings of the instrument field of view: (i) the solution determined by Gilmozzi et al. (1995), implemented in the STSDAS task *metric* and (ii) the solution determined by Holtzman et al. (1995). The procedures turned out to be equivalent, with the rms residuals on the reference stars coordinates after image superposition (see below) consistent within few tenths of mas.

As a reference for the image superposition, we have chosen the 1997 one. Given the abundance of reference stars, the alignment has been performed following the traditional astrometric approach, consisting of a linear transformation with 5 free parameters i.e. 2 independent translation factors, 2 scale factors for X and Y and a rotation angle. The residuals of reference stars positions clustered around 0 and appeared randomly distributed on the field of the image, showing no systematic effect. Thus, we are confident that our analysis is bias free and reliable. As expected, the average rms residual on the reference stars positions is higher in the WFC-to-PC superposition (of order 4 mas) than in the PC-to-PC case (of order 2 mas). We note that in all cases the relative orientation of the images coincide, within few hundredths of degree, with the difference between the corresponding telescope roll angles. The alignment procedure has been repeated after applying different image sharpening algorithms (e.g. gaussian filtering), yielding very similar results.

3. The proper motion

The displacement of the Vela pulsar position can be immediately appreciated in the isophotal plot of Fig. 2, which shows the zoomed superposition of all the frames taken at the different epochs. To measure the pulsar proper motion, we have performed linear fits to its RA/Dec displacements vs time. As a

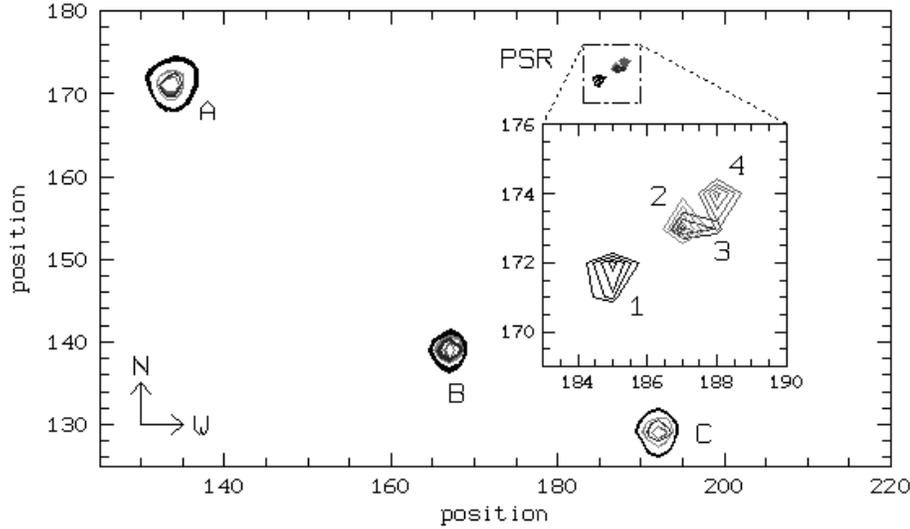


Fig. 2. Contour plot obtained from the four images of Table 1, after the superposition procedure described in the text. For clarity, the images have been finally aligned in RA and Dec according to the roll angle of image 2. Axis units are PC pixels ($0''.045$). The objects labelled as A, B, C, easily identifiable in Fig. 1, are three of the reference stars used to compute the image superposition. The pulsar environment has been enlarged for clarity in the inset, where numbers refer to the images numbers of Table 2.

first step, we used all the available points to have a longer time span. However, owing to the coarser angular resolution of the 1993 image, taken with the WFC, almost indistinguishable results are obtained using only the 1997-1999 points, all obtained with the PC. We also tried a direct comparison of the 1997 and 1999 points, taken exactly at the same day of the year i.e. with identical parallax factors, which should lead to the clearest measurement of the proper motion. All of the steps described above yielded results largely consistent within the errors.

Since all the proper motion values obtained through different image processing/frame superposition/displacement fit are consistent within $\approx 2 \text{ mas yr}^{-1}$ from each other, we have conservatively assumed the value of 2 mas yr^{-1} (per coordinate) as our overall error estimate. Thus, our final estimate of the Vela pulsar proper motion is:

$$\mu_{\alpha} \cos \delta = -46 \pm 2 \text{ mas yr}^{-1}$$

$$\mu_{\delta} = 24 \pm 2 \text{ mas yr}^{-1}$$

for a total proper motion of:

$$\mu = 52 \pm 3 \text{ mas yr}^{-1}$$

with a position angle of $297^{\circ} \pm 2^{\circ}$.

4. Conclusions

Analysis of HST data yielded the most accurate measure of the Vela pulsar proper motion. Our value is in excellent agreement with the one of Nasuti et al. (1997), but the errors are now reduced. What is worth mentioning here is that our data refer to a time span much shorter than the 20 years interval of the previous work. Indeed, two years of HST observations are vastly enough to improve over 20 years observations from the ground. Once more, this is a clear demonstration of the excellent potentialities of HST astrometry.

Transforming proper motion into a transverse velocity requires the knowledge of the object's distance. At the canonical, although uncertain, 500 pc distance the implied velocity would

be $\approx 130 \text{ km s}^{-1}$, somewhat on the low side for the fast moving pulsar family (Lorimer et al. 1997). A reduction of the pulsar distance will similarly reduce the transverse speed to an embarrassingly low value. Nailing down the pulsar proper motion is the first step to assess the annual parallactic displacements of the source. Our next observations will, hopefully, yield a direct measurement of the Vela pulsar distance.

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