Astron. Astrophys. 344, 367–370 (1999)

ASTRONOMY
AND
ASTROPHYSICS

A new HST measurement of the Crab Pulsar proper motion[*]

P.A. Caraveo[1,2] **and R.P. Mignani**[3]

[1] Istituto di Fisica Cosmica del CNR, Via Bassini 15, I-20133 Milan, Italy (pat@ifctr.mi.cnr.it)
[2] Istituto Astronomico, Via Lancisi 29, I-00161 Rome, Italy
[3] STECF-ESO, Karl-Schwarzschild-Strasse 2, D-85740 Garching, Germany (rmignani@eso.org)

Received 27 October 1998 / Accepted 23 December 1998

Abstract. We have used a set of archived HST/WFPC2 exposures of the inner regions of the Crab Nebula to obtain a new measurement of the pulsar proper motion, the first after the original work of Wyckoff & Murray, more than 20 years ago. Our measurement of the pulsar displacement, $\mu = 18 \pm 3$ mas yr^{-1}, agrees well with the value obtained previously. This is noteworthy, since the data we have used span less than 2 years, as opposed to the 77 years required in the previous work.

With a position angle of $292^\circ \pm 10^\circ$, the proper motion vector appears aligned with the axis of symmetry of the inner Crab nebula, as defined by the direction of the X-ray jet observed by ROSAT. Indeed, if the neutron star rotation is to be held responsible both for the X-ray jet and for the observed symmetry, the Crab could provide an example of alignment between spin axis and proper motion.

Key words: stars: pulsars: individual: Crab – astrometry

1. Introduction

The Crab pulsar has been the second pulsar to be associated with its supernova remnant (Comella et al. 1969) and the interaction between the two has been subject of deep and detailed studies (e.g. Kennel & Coronoti 1984). Recently, associating the ROSAT/HRI picture of the pulsar and its surroundings with HST/WFPC2 images of the remnant, Hester et al. (1995) have drawn a convincing picture of the central part of the Crab Nebula “symmetrical about the (presumed) rotation axis of the pulsar” with such an axis lying “at an approximate position angle of 115° east of north”. However, linking the pulsar rotation to the remarkably symmetrical appearance of the high resolution X and optical data is clearly a kind of default solution since “the only physical axis that exists for the pulsar is its spin axis”. Although generally correct, this statement may not represent a complete description of the Crab pulsar, which is known to move. Here we want to draw attention to the possible relationship between the Crab pulsar proper motion and the symmetric appearence of the inner Crab Nebula.

Isolated Neutron Stars are fast moving objects (e.g. Caraveo 1993; Lyne & Lorimer 1993; Lorimer 1998), and the Crab is no exception. Measurements of the proper motion of Baade’s star (later recognized to be the optical counterpart of the Crab pulsar) were attempted several times (e.g. Trimble 1968), yielding vastly different values. This prompted Minkowski (1970) to conclude that the proper motion of the star was not reliably measurable.

The situation changed few years later, when Wyckoff & Murray (1977) obtained a new value of the Crab proper motion which allowed to reconcile the pulsar birthplace with the center of the nebula, i.e. the filaments’ divergent point. The *relative* proper motion, measured by Wyckoff & Murray over a time span of 77 years, amounts to a total yearly displacement of 15 ± 3 mas, corresponding to a transverse velocity of 123 km s^{-1} for a pulsar distance of 2 kpc.

What matters here is the direction of such a motion, i.e. its position angle of $298^\circ \pm 10^\circ$. Taken at face value, this direction is certainly compatible with the Crab axis of symmetry, defined by Hester et al. (1995), hinting an alignement between the pulsar proper motion and the major axis of the nebula.

Given the non trivial consequences of this evidence, we have sought an independent confirmation of the pulsar proper motion. Owing to the dramatic evolution of telescopes as well as optical detectors in the last 20 years, we are now in a position to measure anew the Crab proper motion in a time span much shorter than the 77 years required by Wyckoff & Murray.

2. Defining the data set

Proper motion measurements rely on accurate relative astrometry. In order to measure the tiny angular displacement of the Crab pulsar, we need high resolution images taken at different epochs. Currently, the best instrument to pursue this task is the Wide Field Planetary Camera 2 (WFPC2), onboard the Hubble Space Telescope. Luckily enough, the Crab pulsar is a conspicuous target so that, since the first telescope refurbishing, it has been repeatedly observed (Hester et al. 1995, 1996; Blair et al. 1997). Of course, different observers used different filters and placed the pulsar either in one of the Wide Field Camera (WFC) chips or, more often, in the Planetary Camera (PC).

Send offprint requests to: P.A. Caraveo

[*] Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555

Table 1. 547M filter data set selected from the Crab observations available in the HST public database. For each exposure we list the date, the chip containing the pulsar and the exposure time in seconds.

Obs.	*Date*	*Camera*	*Exp. (s)*
1	Mar 9^{th} 1994	WFC#2	2 000
2	Jan 7^{th} 1995	WFC#3	3 600
3	Aug 15^{th} 1995	PC	2 000
4	Nov 6^{th} 1995	PC	2 000
5	Dec 29^{th} 1995	PC	2 000
6	Jan 20^{th} 1996	PC	2 000
7	Jan 26^{th} 1996	PC	2 000
8a	Jan 26^{th} 1996	WFC #2	2 000
8b	...	WFC #3	2 000
8c	...	WFC #4	2 000
9	Feb 2^{nd} 1996	PC	2 000
10	Apr 16^{th} 1996	PC	2 000

In order to define a homogeneous data set, first we have gone through the exposure list to single out images obtained through the same filter. Since the 547M medium bandpass ($\lambda = 5454\,\text{Å}; \Delta\lambda = 486.6\,\text{Å}$) turned out to be the most frequently used, we have examined all the images taken through this filter. The 547M data set (listed in Table 1) has been retrieved from the HST public database, and, after combining and cosmic ray cleaning, all images have been inspected to define a suitable set of "good quality" reference stars.

When doing astrometric studies, the presence of good reference stars is very important. An outstanding image without at least 4 reference objects, chosen to be well below the saturation limit, but bright enough to yield sufficient counts for precise positioning, is of no use for our purposes. This is particularly true for the Planetary Camera which, in spite of its much sharper angular resolution (0.0455 arcsec/px as opposed to 0.1 arcsec/px of the WFC), suffers from the limited dimensions (35 $\times$ 35 arcsec) of its field of view. Indeed, among the several PC observations listed in Table 1, only #3, which is shown in Fig. 1, contains 4 reference stars.

Thus, only observations #1,2,3 and 8, covering a time span of 1.9 years, appear suitable for our astrometric analysis.

3. The relative astrometry

Precise alignement of these images is our next task. The traditional astrometric approach would call for a linear image-to-image trasformation, requiring at least four constants, namely two independent (x and y) translations, rotation and image scale. However, since the paucity of reference stars would have hampered the overall accuracy of the superposition, we applied the *rotate-shift* procedure devised by Caraveo et al. (1996) in order to reduce the plate constants to be computed. This method takes advantage of the accurate mapping of the geometrical distorsion of the WFPC2 to define the instrument scale, while the telescope roll angle is used to *a priori* align our images in RA and DEC. Thus, the statistical weigth of the few common stars is used only to compute the x and y shifts.

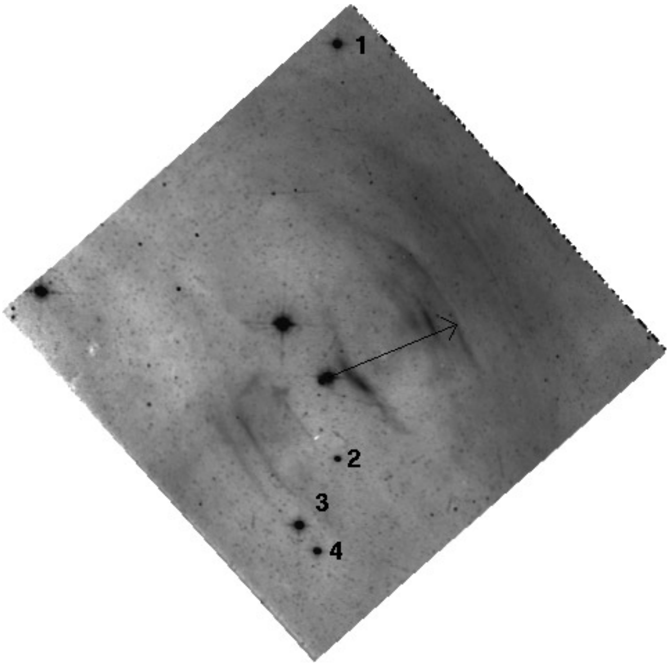

Fig. 1. 2 000 s PC image of the inner Crab Nebula taken in August 1995 through the F547M filter (obs.#3 in Table 1). North to the top, East to the left. The labels mark the stars used for relative astrometry. The arrow shows the Crab pulsar proper motion direction.

Therefore, our alignement recipe is as follow:

- first, the frames have been corrected for the WFPC2 geometrical distorsion (Holtzman et al. 1995) using the *wmosaic* task in *STSDAS*, which also automatically applies the scale transformation between the PC and WFC chips. As a result, all the "corrected" images have the same pixel size, corresponding to 0.1 arcsec (i.e. 1 WFC px);
- second, the frames have been aligned in right ascension and declination according to their roll angles;
- third, the "best" positions of the Crab pulsar, as well as those of the reference stars, have been computed by 2-D gaussian fitting of their profiles, using specific MIDAS routines. Particular care was used for the pulsar itself, in order to make sure that the object's centroid is not affected by the emission knot observed $\sim$ 0.7 arcsec to the SE. A positional accuracy ranging from 0.02 px to 0.03 px was achieved for the pulsar ($V = 16.5$) as well as for the reference stars ($17 \leq V \leq 19$). It is worth noting that this result is by no means an exceptional one; Ibata & Lewis (1998) obtain similar accuracies for significantly fainter objects.
- Finally, we used the common reference stars (1 to 4 in Fig. 1) to compute the linear shifts needed to overlay the different frames onto image # 1, which was used as a reference. This procedure did not always achieve the same degree of accuracy. While obs.#3-to-obs.#1 and obs.#8a-to-obs.#1 yielded residuals close to 0.04 WFC pixels, the superpositions involving obs.# 2 and #8b,c resulted in higher residuals ($\geq$ 0.1 px). Unfortunately, we cannot offer an explanation for this effect, other than noting that it arises when compar-

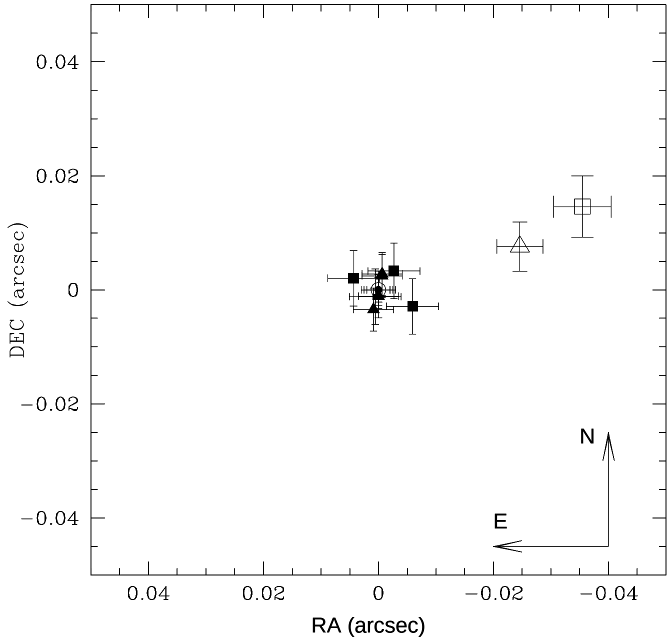

Fig. 2. Relative positions measured for the 4 reference stars (filled symbols) as well as for the Crab pulsar (open symbols) in the (α, δ) plane measured at three different epochs (circle:1994, always in the 0,0 point, since the 1994 observation has been used as our reference; triangle:1995; square:1996). Axes in arcsec.

ing images obtained with different chips of the Wide Field Camera. Therefore, we were forced to reduce our data set to just one Wide Field chip. Since we had no a priori reason to prefer one particular chip, we selected the chip which maximized the time span. This turns out to be chip#2, with obs.#1 and #8a. To these, PC observation #3 can be added. These three images, accurately superimposed, are our final data set.

4. Results

It is now possible to compare the positions obtained for the Crab pulsar over 1.9 years. This is done in Table 2, where we give positions, relative displacements and errors, measured for the Crab pulsar as well as for the four reference stars. While the positions measured for the Crab pulsar in obs.#3 and #8a show a small variation, marginal in y but certainly significant in x, no significant displacement is seen in any of the reference objects. This is shown in Fig. 2, where we have plotted in the (α, δ) plane the coordinate offsets measured in obs.#3 and #8a wrt obs.#1, which represents the 0,0 point in the figure. While the positions of the reference stars at the three different epochs are virtually unchanged, the pulsar is clearly affected by a proper motion to NW. A linear fit to the α and δ displacements yields the Crab proper motion relative to the reference stars. This turns out to be

$$\mu_\alpha = -17 \pm 3\,\mathrm{mas\ yr}^{-1}\ , \quad \mu_\delta = 7 \pm 3\,\mathrm{mas\ yr}^{-1}$$

corresponding to an overall annual displacement $\mu = 18 \pm 3$ mas yr^{-1} in the plane of the sky, with a position angle of $292^\circ \pm 10^\circ$. This vector is also shown in Fig. 1.

Our result is to be compared with the value of

$$\mu_\alpha = -13 \pm 2\,\mathrm{mas\ yr}^{-1}\ , \quad \mu_\delta = 7 \pm 3\,\mathrm{mas\ yr}^{-1}$$

with a position angle of $298^\circ \pm 10^\circ$, obtained by Wyckoff and Murray over a time span of $\simeq$ 77 years.

5. Conclusions

With two independent, fully consistent measurements, we can now proceed to compare the Crab pulsar proper motion direction with the axis of symmetry of the inner nebula. This task is an easy one, since we can use Fig. 8 of Hester et al. (1995), where such axis is coincident with the direction defined by the Knot1-Knot2 alignment. According to Hester et al. the position angle of this direction is $\simeq 115^\circ$, to which an offset of 180° is to be added to take into account the direction of the Crab motion. This yields a value of $\simeq 295^\circ$, to be compared to our value $\simeq 292^\circ$ or to that of Wyckoff & Murray ($\simeq 298^\circ$).

Although all these values are affected by non negligible errors, both known, as in the case of the proper motion, and unknown, as in the case of the roughly defined axis of symmetry, an alignement between the pulsar proper motion and the "axis of symmetry" of the inner nebula seems to be present. In fact, the experimental evidence gathered so far shows that the Crab pulsar is moving along the major axis of the Crab Nebula (Wyckoff & Murray 1977) and that both the knots and the X-ray jet appear aligned to the pulsar proper motion. Although the significant uncertainties of the relevant parameters leave open the possibility of a chance coincidence, it is interesting to speculate on the implications of such an alignement.

Since a neutron star acquires its proper motion at birth, there is no doubt that the pulsar motion has been present "ab initio", well before both knots and jets came into existence. However, the proper motion energy content is far too small to account for the surrounding structures and their rapid evolution. Therefore, the link, if any, between proper motion and axis of symmetry must be through some basic characteristics which was also present when the Crab pulsar was born. Hester et al. (1995) proposed a scenario associating the symmetrical appearence of the Nebula with the pulsar spin axis. Under this hypothesis, the neutron star motion would turn out to be aligned with the spin axis, reflecting an asymmetry of the supernova explosion along the progenitor's spin axis. Proper motion spin axis alignements have been discussed in the literature (see e.g. Tademaru 1977), but no conclusive evidence was found.

If the X-ray jets do indeed trace the pulsar spin axis, and the relation between proper motion and axis of symmetry is not a fortuitous one, the Crab would provide the first example of such an alignement. While this would shed some light on the mechanisms responsible for the pulsar kick (e.g. Spruit & Finney 1998), one must immediately add that nothing similar has yet been found for the very limited sample of the young pulsars we know. PSR 0540−69, the twin of the Crab in the Magellanic

Table 2. Pixel coordinates (x, y) and relative displacements $(\Delta x, \Delta y)$ measured at three different epochs for the Crab pulsars as well as for the four reference stars. All frames have been aligned in right ascension and declination (x and y increasing Westward and Northward) before being overlaid to obs.# 1. While for obs.# 1 the errors are due only to the centroid fitting algorithm, for obs.#3 and #8a they also include the uncertaity arising from the image superposition (0.03 and 0.04 px for obs.# 3 and # 8a, respectively).

Obj	*Obs.#*	*x*	Δx	*y*	Δy
Crab	#1	−167.42 (.03)	–	92.84 (.03)	–
	#3	−167.19 (.04)	+0.23 (.05)	92.91 (.04)	+0.07 (.05)
	#8a	−167.09 (.05)	+0.33 (.07)	92.98 (.05)	+0.14 (.07)
1	#1	−160.80 (.02)	–	334.59 (.02)	–
	#3	−160.80 (.04)	0.00 (.05)	334.58 (.04)	−0.01 (.05)
	#8a	−160.80 (.05)	0.00 (.07)	334.58 (.05)	−0.01 (.07)
2	#1	−160.70 (.03)	–	33.59 (.03)	–
	#3	−160.69 (.04)	+0.01 (.05)	33.62 (.04)	+0.03 (.05)
	#8a	−160.67 (.05)	+0.03 (.07)	33.62 (.05)	+0.03 (.07)
3	#1	−188.43 (.02)	–	−14.64 (.02)	–
	#3	−188.42 (.04)	+0.01 (.05)	−14.62 (.04)	+0.02 (.05)
	#8a	−188.37 (.05)	+0.06 (.07)	−14.67 (.05)	−0.03 (.07)
4	#1	−175.42 (.02)	–	−33.30 (.02)	–
	#3	−175.43 (.04)	−0.01 (.05)	−33.32 (.04)	−0.02 (.05)
	#8a	−175.46 (.05)	−0.04 (.07)	−33.28 (.05)	+0.02 (.07)

Cloud, is too far to allow for proper motion measurements in any reasonable time span. PSR 1509−58 does not have a definite optical counterpart. The significantly older Vela pulsar does not show any alignement between its 50 mas/y proper motion (Nasuti et al. 1997) and the X-ray jet proposed by Markwardt & Ögelman (1995).

Before speculating any further, better data are needed to improve our knowledge on the geometry of the Crab pulsar surroundings.One more HST observation could easily improve the determination of the proper motion position angle. A very accurate proper motion measurement, however, will not settle the problem without a substantial improvement on the X-ray side. A sharper X-ray image is needed to better assess the position angle of the jet(s) together with their shape and overall dimension. The AXAF High Resolution Camera could improve significantly on the fuzzy picture of the inner Crab Nebula obtained by ROSAT.

Irrispective of future developments, however, the presence of an observed motion adds a definite direction to the cilindrically symmetrical appearence of the Crab.

References

Blair W.P., Davidson K, Fesen R.A., et al., 1997, ApJS 109, 473
Caraveo P.A., Bignami G.F., Mignani R., Taff L., 1996, ApJ 461, L91
Caraveo P.A, 1993, ApJ 415, L111
Comella J.M., Craft H.D., Lovelace R.V.E., Sutton J.M., Tyler G.L., 1969, Nat 221, 453
Hester J.J., Scowen P.A., Sankrit R., et al., 1995, ApJ 448, 240
Hester J.J., Stone J.M., Scowen P.A., et al., 1996, ApJ 456, 233
Holtzman J., Hester J.J., Casertano S., et al., 1995, PASP 107, 156
Ibata R.A., Lewis G.F., 1998, AJ, in press (astro-ph/9809070)
Kennel C.F., Coroniti F.V., 1984, ApJ 283, 694
Lorimer D., 1998, Adv. in Space Research Vol. 21 n.1/2, 177
Lyne A., Lorimer D., 1993, Nat 369, 127
Markwardt C., Ögelman H., 1995, Nat 375, 40
Minkowski R., 1970, PASP 82, 470
Nasuti F.P, Mignani R., Caraveo P.A., Bignami G.F., 1997, A&A 323, 839
Spruit H., Finney E.S., 1998, Nat 393, 139
Tademaru E., 1977, ApJ 214, 885
Trimble V., 1968, ApJ 73, 535
Wyckoff S., Murray C.A., 1977, MNRAS 180, 717