THE ASTROPHYSICAL JOURNAL, 421:L13–L14, 1994 January 20

REVISED PROPER-MOTION RESULTS FOR THE SOFT X-RAY–EMITTING RADIO PULSAR PSR 0656+14

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Received 1993 September 8; accepted 1993 November 1

ABSTRACT

A third set of astrometric observations of the soft X-ray–emitting radio pulsar PSR 0656+14 has been carried out with the NRAO Very Large Array. Our result for the magnitude of the proper motion, $0''.070 \pm 0''.010\ \mathrm{yr}^{-1}$, is in agreement with our previously reported result based on the first two observations. The direction of motion, however, has been found to be 180° from that previously reported. This casts doubt on a proposed connection between this pulsar and the Gemini-Monoceros X-Ray Enhancement.

Subject headings: astrometry — pulsars: individual (PSR 0656+14) — stars: neutron — supernova remnants

1. CALCULATION OF THE PROPER MOTION

We have now observed the radio pulsar PSR 0656+14 with the NRAO Very Large Array[2] in three epochs separated by a total of 3.9 yr. The dates of the three observing epochs are 1989 January 25, 1990 May 19, and 1992 December 23. A proper-motion result based on the first two epochs was presented in Thompson et al. (1991, hereafter Paper I). The observing procedure for the third epoch was identical to that of the first two epochs (as discussed in Paper I) except that an additional, higher quality position calibrator was used.

The method of measuring the proper motion of the pulsar (described in detail in Paper I) will be discussed briefly here. The pulsar and the background radio sources with flux levels >1 mJy were identified in a low-resolution "dirty" image of the field. Positions for the sources were then determined from high-resolution, "cleaned" images of the sources. The source positions were corrected for contractions or expansions of the field of view due to the motion of Earth toward or away from the pulsar.

A total of 10 background sources were used for the proper motion analysis. The positions of PSR 0656+14 and these background sources (along with their fluxes), as derived from the epoch 3 data, are given in Table 1. Similar data from epochs 1 and 2 are given in Paper I. After accurate positions for the sources were determined, the separations between the pulsar and each background source were measured for each epoch. Separations between background source pairs were also measured. As offsets between VLA images can occur between observing epochs, the pulsar-background source separations were compared, between each individual epoch, to measure any proper motion of the pulsar. Background source pair separations should not change from one epoch to another (within their positional errors) if they are indeed stationary sources. This is indeed the case observed for the three epochs.

Weighted means for the R.A. and decl. proper motion results for each epoch pair, along with the final proper-motion value are given in Table 2. The weighting factor used was σ^{-2}, where σ was the error of the individual measurements. As the three epoch-pair proper-motion values are not statistically independent, simply averaging the values is not a valid procedure for determining the final proper-motion value. Consequently, the final value given in Table 2 was determined by taking a weighted linear regression of the 30 pulsar-background pair separations, evaluated separately for right ascension and declination with two free parameters (one-dimensional proper motion and an initial reference frame offset). The magnitude of the overall proper motion, $0''.070 \pm 0''.010\ \mathrm{yr}^{-1}$, is consistent with that given in Paper I.

The motion is in the direction of position angle 114° (in the R.A.-decl. plane, measured north through east). This is 180° away from the direction presented in Paper I (294°). This is due to an error in the original interpretation of the direction of motion (based on epochs 1 and 2). The direction of motion is determined from the sign of the difference of the individual pulsar-background source separations from one epoch to the next. A negative result indicates that the pulsar has moved away from the background source (producing a greater separation than during the previous epoch), and analogously, a positive difference indicates that the pulsar has moved toward the background source (thus decreasing the separation). The error of Paper I was made in interpreting the signs of the R.A. and decl. pulsar-background source separation changes as simply the sign of the proper motion in each direction. A linear shift in the positions of the pulsar and background sources between epochs 1 and 2 (possibly due to a poor quality position calibrator) led to a change in the pulsar's coordinates; this appeared to confirm the erroneously determined direction of motion. The examination of the data from epoch 3 led us to discover this error and to correct the previously determined direction of proper motion.

2. DISCUSSION

As discussed in Paper I, PSR 0656+14 lies near the center of a 20° diameter "ring" of soft X-ray emission known as the Gemini-Monoceros X-Ray Enhancement, or Monogem Ring (Nousek et al. 1981). A primary goal of this proper motion project was to connect PSR 0656+14 with the Monogem Ring, thus strengthening the contention (based on similar distances of ~300 pc and ages of $\sim 10^5$ yr for the pulsar and the ring) that the ring is actually a supernova remnant. With the previous, erroneous, result for the direction of the pulsar's

[1] Guest User of the NRAO Very Large Array.
[2] The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation.

TABLE 1

EPOCH 3 POSITIONS

Source	α (1950)	δ (1950)	mJy
PSR	$06^h56^m57^s.942 \pm 0^s.004$	$14°18'33''.80 \pm 0''.02$	2.46
BG1	06 56 57.759 ± 0.012	14 16 40.42 ± 0.10	1.47
BG2	06 56 56.374 ± 0.004	14 15 25.65 ± 0.03	10.71
BG3	06 56 42.148 ± 0.006	14 13 07.94 ± 0.04	15.28
BG4	06 56 42.273 ± 0.008	14 13 04.04 ± 0.07	18.54
BG5	06 56 40.374 ± 0.002	14 12 03.44 ± 0.01	9.37
BG6	06 56 38.040 ± 0.004	14 12 18.77 ± 0.03	3.15
BG7	06 55 56.153 ± 0.002	14 14 46.09 ± 0.01	26.24
BG8	06 57 32.172 ± 0.004	14 05 00.48 ± 0.03	7.70
BG9	06 57 48.968 ± 0.006	14 19 13.79 ± 0.04	3.50
BG10	06 57 07.946 ± 0.012	14 20 45.48 ± 0.08	1.58

TABLE 2

PROPER-MOTION-RESULTS

Epoch 1–Epoch 2	
α	$0''.073 \pm 0''.017\ yr^{-1}$
δ	$-0''.035 \pm 0''.012\ yr^{-1}$
Total	$0''.081 \pm 0''.016\ yr^{-1}$
Epoch 2–Epoch 3	
α	$0''.058 \pm 0''.017\ yr^{-1}$
δ	$-0''.054 \pm 0''.010\ yr^{-1}$
Total	$0''.079 \pm 0''.013\ yr^{-1}$
Epoch 1–Epoch 3	
α	$0''.062 \pm 0''.011\ yr^{-1}$
δ	$-0''.028 \pm 0''.007\ yr^{-1}$
Total	$0''.068 \pm 0''.010\ yr^{-1}$
Final Proper Motion	
α	$0''.064 \pm 0''.011\ yr^{-1}$
δ	$-0''.028 \pm 0''.004\ yr^{-1}$
Total	$0''.070 \pm 0''.010\ yr^{-1}$

NOTE.—Position angle 114° (north through east in the R.A.-decl. plane).

proper motion, the pulsar appeared to be moving *away* from the center of the ring. It was, therefore, plausible that the Monogem Ring was the supernova remnant of the pulsar's progenitor. The result reported here for the pulsar's direction of motion, i.e., moving approximately *toward* the center of the ring, casts doubt upon this interpretation. This does not rule out the possibility that the Monogem Ring *is* a supernova remnant. However, in spite of the provocatively similar ages and distances of the pulsar and ring, it appears less likely that the Monogem Ring resulted from the explosion of the progenitor of PSR 0656 + 14.

We wish to acknowledge R. Kollgaard and S. Laurent-Muehleisen for their assistance in the planning and data reduction phases of the third observing epoch, S. Anderson for deriving the statistical method used to evaluate the final proper motion value, and E. Fomalont for many helpful discussions. R. J. T. is supported by a NASA Space Grant College Fellowship through Penn State University.

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