ABSTRACT

PSR B0656+14 was observed by the Rossi X-ray Timing Explorer (RXTE) with the proportional counter array (PCA) and the high-energy x-ray timing experiment (HEXTE) for 160 ksec during August 22 – September 3, 1997. No pulsation was firmly found in the timing analysis, in which the contemporaneous radio ephemeris and various statistical tests were applied for searching evidence of pulsation. A marginal detection of pulsation at a confidence level of 95.5% based on the $H$-test was found with data in the whole HEXTE energy band. In the energy band of 2-10 keV the RXTE PCA upper limits are about one order of magnitude lower than that from ASCA GIS data. If the CGRO EGRET detection of this pulsar is real, considering the common trait that most EGRET-detected pulsars have a cooling spectrum in hard x-ray and gamma ray energy bands, the estimated RXTE upper limits indicate a deviation (low-energy turn-over) from a cooling spectrum starting from 20 keV or higher. It in turn suggests an outer-magnetospheric synchrotron-radiation origin for high-energy emissions from PSR B0656+14. The RXTE PCA upper limits also suggest that a reported power-law component based on ASCA SIS data in 1-10 keV fitted jointly with ROSAT data, if real, should be mainly unpulsed.

Subject headings: pulsars: individual: PSR B0656+14

1. Introduction

The pulsar PSR B0656+14 was discovered by Manchester et al. (1978), with a period of 384.9 millisecond, a characteristic age of $1.1 \times 10^5$ yr and an inferred surface dipole magnetic field of $4.7 \times 10^{11}$ G. After the report of its possible optical counterpart (Caraveo, Bigiarni, & Mereghetti 1994), its optical emission was recently observed to be pulsed at the radio period and shows a nonthermal origin (Shearer et al. 1997; Pavlov, Welty, & Córdova 1997; Kurt et al. 1998). X-ray pulsation at the period of PSR B0656+14 from the EINSTEIN x-ray source E0656+14 was found by Córdova et al. (1989). Subsequent observations with ROSAT showed thermal characteristics with a hard tail in its spectrum in 0.1-2.4 keV, which can be fit well by a helium-atmosphere blackbody model (Finley, Ögelman, & Kiziloglu 1992), or a two-component model comprising either two blackbodies or a blackbody plus a power law (Possenti, Mereghetti, & Colpi 1996). Using ACSA data jointly with ROSAT data, Greiveldinger et al. (1996) found that a two-component model cannot fit the spectrum well, and a three-component model (two blackbodies
plus a power-law) gives an acceptable fit. However, a recent study (Wang et al. 1998) did not confirm the necessity of invoking the third (power-law) component. At the high-energy end, PSR B0656+14 joined the EGRET-pulsar family with a relatively weak evidence of pulsation (Ramanamurthy et al. 1996). Like other EGRET pulsars, it shows a power-law spectrum in the EGRET energy band.

With the proposed power-law component from fitting ROSAT + ASCA data and that from the EGRET observation, it is apparent that the spectrum will bend, either gradually or more abruptly, between 10 keV and 100 MeV (Figure 2). Such a spectral bending can be used to constrain possible emission sites and mechanisms for these x-rays and gamma-rays (Chang & Ho 1997). On the other hand, observations around 10 keV will help to clarify the existence of the power-law component in the ROSAT + ASCA study. In this Letter we report the results of a 160-ksec RXTE Cycle 2 observation of PSR B0656+14 in the energy range of 2 - 250 keV. Though no pulsation was detected, our estimated upper limits for the pulsed flux are low enough to be used to support an outer-magnetospheric synchrotron-radiation origin for high-energy emissions from PSR B0656+14. They also suggest that the reported power-law component based on ASCA SIS data in 1-10 keV fitted jointly with ROSAT data, if real, should be mainly unpulsed.

2. Observation

The PCA and HEXTE on board RXTE were pointed at PSR B0656+14 during August 22 – September 3, 1997 (MJD 50682 – 50694), for about 160 ksec. The RXTE mission, spacecraft and instrument capabilities are described in Swank et al. (1995), Giles et al. (1995) and Zhang et al. (1993) The PCA consists of five essentially identical PCUs with a total effective area of 6729 cm$^2$. The HEXTE comprises two clusters of four scintillation counters. The net open area of the eight detectors is 1600 cm$^2$ (Rothschild et al. 1998). The two instruments PCA and HEXTE have no imaging capability. Their field of view is one degree.

Data were first screened according to the following two criteria: (1) the offset, that is, the difference between the source position and the pointing of the satellite, is less than 0.02 degree; and (2) the elevation angle, that is, the angle between the Earth’s limb and the target viewed from the satellite, is larger than 10 degrees. During the whole observation, the five PCUs of the PCA were all on. The total exposure for the PCA is 152.4 ksec $\times$ 6729 cm$^2$, which is equal to 1.026 $\times$ 10$^9$ sec cm$^2$. One detector in Cluster B of the HEXTE has lost its spectral capability, and we excluded all the photons detected by that detector in our analysis. The total exposure for the HEXTE is then 153.9 ksec $\times$ 1600 cm$^2$ $\times$ $\frac{7}{8}$, which is 2.155 $\times$ 10$^8$ sec cm$^2$.

Around the same epoch of the RXTE observation, PSR B0656+14 was also monitored at Jodrell Bank Radio Observatory. The radio ephemeris is summarized in Table 1 and used as the input for pulsation search.

3. Analysis and Results

The data were reduced to the solar system barycenter and analyzed using the JPL DE200 ephemeris, the pulsar position listed in Table [1] and the RXTE-related tasks in the software package FTOOLS v.4.0.

In the timing analysis, PCA data were divided into five energy bands with each covering PCA channels 6-16 (2.1-6.1 keV), 17-26 (6.1-9.8 keV), 27-55 (9.8-20.5 keV), 56-107 (20.5-40.4 keV), and
index larger than -1.5, assuming that the index increases from -2.8 above 100 MeV monotonically toward plausible that the spectrum of the pulsed flux below 20 keV, if detected, should have a photon spectral keV are about one order of magnitude lower than that from ASCA which includes both pulsed and unpulsed fluxes, and the 3-σ for the pulsed flux are plotted in Figure 2. Our estimated 3-σ 0.5-2 keV and 100% as a 3-σ three-component spectral model, which consists of two blackbodies with temperature at 7 1σ fraction was estimated to be 71% as a 3-σ. Assuming a duty cycle of 0.5 we obtain the following 3-σ RXTE from PSR B0656+14 in the in Figure 2: for PCA, 1. 0.5-2 keV, 5 (1991) Assuming a duty cycle of 0.5 we obtain the following 3-σ variation in the corresponding probability for different frequencies. None of these trials gives significant 90.6%, while the (the Rayleigh test, which is more appropriate if the underlying pulse profile is sinusoidal), the probability is 90.6%, while the Z2σ test gives a probability of 98.4%. In our analysis, the χ²-test and the H-test were repeated in an interval of pulsation frequencies near the radio one. Unlike the spiky dependence of the χ²-value on frequencies, the H-test gives a smooth variation in the corresponding probability for different frequencies. None of these trials gives significant evidence of pulsation. A higher probability was found at a frequency lower than the radio one by 9 × 10⁻⁸ Hz. At this frequency, the H-test gives a 98.2% probability of pulsation detection in the HEXTE data covering channels 14-234.

Based on these analyses, we do not consider the current observation provides evidence of pulsation from PSR B0656+14 in the RXTE energy band.

The upper limit of pulsed flux is estimated following the prescription given by Ulmer et al. (1991) Assuming a duty cycle of 0.5 we obtain the following 3-σ upper limits, which are also shown in Figure 2 for PCA, 1.3 × 10⁻⁶ cm⁻²s⁻¹keV⁻¹ in 2.1-6.1 keV, 1.1 × 10⁻⁶ cm⁻²s⁻¹keV⁻¹ in 6.1-9.8 keV, 5.6 × 10⁻⁷ cm⁻²s⁻¹keV⁻¹ in 9.8-20.5 keV, 3.8 × 10⁻⁷ cm⁻²s⁻¹keV⁻¹ in 20.5-40.4 keV, and 1.4 × 10⁻⁷ cm⁻²s⁻¹keV⁻¹ in 40.4-98.5 keV; for HEXTE, 1.1 × 10⁻⁶ cm⁻²s⁻¹keV⁻¹ in 15-60 keV, 6.6 × 10⁻⁷ cm⁻²s⁻¹keV⁻¹ in 60-125 keV, and 3.4 × 10⁻⁷ cm⁻²s⁻¹keV⁻¹ in 125-250 keV.

4. Discussion

In the study with ROSAT PSPC and ASCA SIS data, Greiveldinger et al. (1996) reported a three-component spectral model, which consists of two blackbodies with temperature at 7.8 × 10⁵ K and 1.5 × 10⁶ K and a power-law with a photon spectral index of -1.5. Based on the ASCA GIS data, the pulsed fraction was estimated to be 71% as a 3-σ upper limit in 0.5-10 keV, or 31±10% at a 2-σ level of detection in 0.5-2 keV and 100% as a 3-σ upper limit in 2-10 keV. For comparison, the proposed power-law component, which includes both pulsed and unpulsed fluxes, and the 3-σ upper limit in 2-10 keV from ASCA GIS data for the pulsed flux are plotted in Figure 2. Our estimated 3-σ upper limits from RXTE PCA data in 2-10 keV are about one order of magnitude lower than that from ASCA GIS data. These new upper limits make it plausible that the spectrum of the pulsed flux below 20 keV, if detected, should have a photon spectral index larger than -1.5, assuming that the index increases from -2.8 above 100 MeV monotonically toward
EGRET pulsars all have power-law spectra typically covering two orders of magnitude in the EGRET band with best-fit photon spectral indices in the range of $-1.4$ to $-1.8$ except for the Crab and PSR B0656+14 (Fierro 1995; Nolan et al. 1996; Merck et al. 1996). Their spectra all turn flatter at lower energies. For example, PSR B1951+32, though with a steeper spectrum in the EGRET band, has a spectrum with a photon spectral index of $-1.5$ around 1-10 MeV. This spectral behavior has been discussed and used to form an argument which provides a useful diagnostic to constrain possible emission locations and mechanisms for these high-energy emissions (Chang & Ho 1997). The key issue in that argument is a ‘bending energy’ below which the spectrum starts deviating from a cooling one. A cooling spectrum is due to a cooling model of a steady-state electron/positron distribution and has a photon spectral index of $-3/2$ for the dominant cooling mechanism being synchrotron radiation and $-5/3$ for curvature radiation. In the parameter space of the electron/positron energy and the distance from the stellar center, which characterizes the strength of magnetic fields and the curvature radius of fieldlines, one can find a line along which the radiative cooling time scale for a certain radiation mechanism is comparable to the dynamical time scale of the relativistic motion of the charges. The observed radiation is expected to occur around a distance characterized by a point on that equal-time-scale line at which the critical energy of radiated photons for the corresponding parameters is equal to the observed bending energy. At any other distances, the cooling population of radiating charges, if exists, will have a cooling spectrum with a bending energy either higher or lower than the observed one. In view of the common trait in the spectral behavior of most EGRET pulsars, it is very likely that if PSR B0656+14 has a spectrum with a photon spectral index around -1.5 at some energies below 100 MeV, it must start getting flatter toward low energy from above 20 keV as required by the RXTE PCA upper limits. A bending energy higher than 20 keV for PSR B0656+14 suggests an emission location at a distance larger than a couple of $10^8$ cm from the stellar center and the synchrotron radiation being the dominant emission mechanism for radiating charges with a typical pitch angle of about 0.1 to 0.001. Curvature radiation does not yield a reasonable emission location within the light cylinder. More observations with the RXTE and the future INTEGRAL are very much desired for providing better statistics and helping advance our understanding of high-energy emissions from neutron stars.

Up to date, existing observations show that except for the Crab, the bending energies for other gamma-ray pulsars are all higher than a few tens of keV, though many of them are not yet well determined. On the other hand, some observations also reveal possible nonthermal x-ray emissions around keV from some of the gamma-ray pulsars. However, they may have an origin different from that of the whole continuum from several tens of keV up to a few GeV. For example, the reported nonthermal emissions around 1 keV for the Geminga and PSR B1951+32 both have a photon spectral index of about -1.5 (Halpern & Wang 1997; Safi-Harb, Ögelman & Finley 1995), which, together with their flux magnitudes, makes them a separate component from that of higher energies; see Figure 6 in Strickman et al. (1996) and Figure 2 in Chang & Ho (1997).

The current observation, since no pulsation was detected, cannot confirm the power-law component proposed in Greiveldinger et al. (1996) for PSR B0656+14. However, the estimated upper limits ensure that if that component is real, it must be mainly unpulsed. An unpulsed power-law spectrum is not easy to be attributed to magnetospheric emissions. Though in the analysis of Wang et al. (1998) the power-law component was not confirmed, its existence and being unpulsed could just be a good example supporting the idea of the ‘electron-positron blanket’ proposed by Wang et al. (1998) Future AXAF and XMM observations will be able to solve this issue.
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REFERENCES

Buccheri, R., et al. 1983, A&A, 128, 245
Caraveo, P. A., Bignami, G. F., & Mereghetti, S. 1994, ApJ, 422, L87
Chang, H.-K., & Ho, C. 1997, ApJ, 479, L125
Córdova, F. A., et al. 1989, ApJ, 345, 451
De Jager, O.C., Swanepoel, J.W.H., & Raubenheimer, B.C. 1989, A&A, 221, 180
Fierro, J.M. 1995, Ph.D. thesis, Stanford University
Finley, J. P., Ögelman, H., & Kızıloğlu, Ü. 1992, ApJ, 394, L21
Giles, A.B., Jahoda, K., Swank, J.H., & Zhang, W. 1995, Publ. Astron. Soc. Australia, 12, 219
Greiveldinger, C., et al. 1996, ApJ, 465, L35
Halpern, J. P., & Wang, F. Y.-H. 1997, ApJ, 477, 905
Kurt, V. G., Sokolov, V. V., Zharikov, S. V., Pavlov, G. G., & Komberg, B. V. 1998, A&A, 333, 547
Leahy, D.A., et al. 1983a, ApJ, 266, 160
Leahy, D.A., Elsner, R.F., & Weisskopf, M.C. 1983b, ApJ, 272, 256
Manchester, R. N., et al. 1978, MNRAS, 185, 409
Merck, M., et al. 1996, A&AS 120, C465
Nolan, P. L., et al. 1996, A&AS 120, C61
Pavlov, G. G., Welty, A. D., & Córdova, F. A. 1997, ApJ, 489, L75
Possenti, A., Mereghetti, S., & Colpi, M. 1996, A&A, 313, 565
Ramanamurthy, P. V., Fichtel, C. E., Kniffen, D. A., Sreekumar, P., & Thompson, D. J. 1996, ApJ, 458, 755
Rothschild, R. E., et al. 1998, ApJ, 496, 538
Saﬁ-Harb, S., Ögelman, H., & Finley J. P. 1995, ApJ, 439, 722
Shearer, A., et al. 1997, ApJ, 487, L181
Strickman, M. S., et al. 1996, ApJ, 460, 735
Swank, J.H., Jahoda, K., Zhang, W., & Giles, A.B. 1995, in The Lives of the Neutron Stars, ed. M.A. Alpar, Ü. Kızıloğlu, & J. van Paradijs (NATO ASI Series C, 450)(Boston: Kluwer), 525
Ulmer, M.P., Purcell, W.R., Wheaton, W.A., & Mahoney, W.A. 1991, ApJ, 369, 485
Wang, F. Y.-H., Ruderman, M., Halpern, J. P., & Zhu, T. 1998, ApJ, 498, 373
Zhang, W., et al. 1993, Proc. SPIE, 2006, 324
Fig. 1.— The folded lightcurve of PSR B0656+14 from RXTE HEXTE data.

Fig. 2.— The spectrum of PSR B0656+14 from 2 keV up to 2 GeV. Upper limits are all for pulsed flux and at a 3-σ level. The ASCA upper limit in 2-10 keV is based on the ASCA GIS data (Greiveldinger et al. 1996). The dotted line is the power-law component with a photon spectral index of -1.5 proposed by Greiveldinger et al. (1996) from fitting ASCA SIS data in 1-10 keV together with ROSAT PSPC data, which includes both pulsed and unpulsed components. It was not confirmed by a later analysis (Wang et al. 1998). This power law is plotted in this figure with an extension to a higher energy. It intersects with the EGRET spectrum at about 100 MeV.
Table 1. Radio ephemeris of PSR B0656+14$^a$

| Parameter       | Value                                      |
|-----------------|--------------------------------------------|
| Validity interval (MJD) | 50606 - 50797                              |
| Epoch, $t_0$ (MJD)      | 50701.000002341                            |
| $\alpha_{2000}$          | 6$^h$59$^m$48$^s$.126                      |
| $\delta_{2000}$          | 14$^\circ$14$'$21$''$.15                  |
| $\nu$ (Hz)              | 2.5981054226747                            |
| $\dot{\nu}$ (Hz/s)      | $-3.71150 \times 10^{-13}$                 |
| $\ddot{\nu}$ (Hz/s/s)   | $8.33 \times 10^{-25}$                    |

$^a$provided by Andrew Lyne (1998, private communication)
