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ROSAT OBSERVATIONS OF PSR 0656+14: A PULSATING AND COOLING NEUTRON STAR

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ABSTRACT

PSR 0656+14, an X-ray–emitting radio pulsar, was observed for ~3200 s with the Position Sensitive Proportional Counter (PSPC) on board *ROSAT* on 1991 March 25. The source background–subtracted counting rate was 1.96 ± 0.03 counts s^{-1}. Pulsations at the radio period, ~0.385 s, were detected at a pulsed fraction of 14% ± 2% making PSR 0656+14 one of only a handful of known isolated X-ray–emitting pulsars. The spectral distribution of counts can be described by various model fits. A blackbody description yields a surface temperature of $\sim(9.0 \pm 0.4) \times 10^5$ K, an equivalent column density of $\sim(1.0 \pm 0.2) \times 10^{20}$ cm^{-2}, and a stellar radius of 10 km under the assumption of a 500 pc source distance. An alternative description is a blackbody modified by the presence of a He atmosphere with surface temperature $\sim(3.0 \pm 0.5) \times 10^5$ K, column density $\sim(2.0 \pm 0.4) \times 10^{20}$ cm^{-2}, and a source distance ≤250 pc. A positive correlation exists between the phase of the pulsed emission and the X-ray hardness, suggesting that the pulsations have their seat in a "hot spot" on the neutron star surface. Implications of the models with regard to the cooling curve of neutron stars is discussed.

Subject headings: pulsars: individual: PSR 0656+14 — stars: neutron — X-rays: stars

1. INTRODUCTION

The X-ray source E0656+14 was discovered in an *Einstein* satellite survey of ultrasoft sources (Córdova et al. 1991). The source was observed in the field of the nearby radio pulsar PSR 0656+14, and the identification of E0656+14 with the radio pulsar PSR 0656+14 was first reported by Córdova et al. (1989) based upon VLA observations of the *Einstein* error box of E0656+14 where a radio source with a steep, nonthermal spectrum was observed. Córdova et al. (1989) found that the VLA position was 4″ from the *Einstein* HRI source position and was coincident with the position of PSR 0656+14 as determined by a pulse timing analysis (Dewey et al. 1988) of the radio signals. No optical counterpart to the X-ray source was detected down to a limiting magnitude of 23 in the *B* band. The energy distribution of the *Einstein* satellite IPC X-ray data was found to be consistent with a blackbody at a temperature of $3–6 \times 10^5$ K with an equivalent hydrogen column density of $<4 \times 10^{20}$ cm^{-2} and a distance of ≤550 pc under the assumption of emission from the surface of a 16 km radius neutron star (Córdova et al. 1989). There was a suggestion that the emission was pulsed at the 0.385 s period of the pulsar at the 98% confidence level with an amplitude of 18% ± 6% (Córdova et al. 1989). PSR 0656+14 lies close to the geometric center of the soft X-ray–emitting Gemini-Monoceros enhancement, a 20° diameter "ring." The pulsar's relative proximity to the remnant's center and soft spectrum have led, in the past, to a suggested association of the two (Nousek et al. 1981). This association was strengthened when Thompson et al. (1991), using the VLA, measured the proper motion of PSR 0656+14 and found that the pulsar was moving away from the ring's center.

PSR 0656+14, at a relatively young spin-down age of 10^5 yr, is an important object to study with regard to the thermal evolution of neutron stars. We report here on a 3200 s *ROSAT* observation acquired during 1991 March with the Position Sensitive Proportional Counter (PSPC). In § 2 we briefly describe the parameters of the instrument and the observations. The results of a search for pulsations at the radio period and the spectral fitting of the energy distribution of the counts can be found in § 3. Finally, a discussion of the implications of the findings is presented in § 4.

2. OBSERVATIONS

PSR 0656+14 was observed with the Position Sensitive Proportional Counter (PSPC) at the focus of the X-ray telescope on board *ROSAT*. Detailed descriptions of the satellite, X-ray mirrors, and detectors can be found in Trümper (1983) and Pfeffermann et al. (1986). Briefly, *ROSAT* contains an X-ray mirror assembly with a 2° field of view. The PSPC is a gas-filled proportional counter sensitive over the energy range 0.1–2.4 keV with an energy resolution $\Delta E/E \sim 0.43$ at 0.93 keV, and a spatial resolution of ~25″ in the center of the focal plane. The effective timing resolution is ~130 μs, electronics limited, and the accuracy of absolute timing with respect to UTC is ~a few milliseconds. The observations reported here were obtained on 1991 March 25 (JD 2,448,341.5) with a total effective exposure time of 3190 s. Due to Earth occulation, radiation belt passage, and observation of other targets, the data consisted of two uninterrupted intervals of ~1330 and ~1860 s separated by ~15,000 s.

The PSR 0656+14 source counts were extracted from a circle of radius 70″ which included about 99% of the source events. The background was determined from a source free annulus of inner radius 120″ and outer radius 360″ centered on the source. The net count rate from PSR 0656+14 was 1.96 ± 0.03 counts s^{-1} in the 0.1–2.4 keV range, excluding the $\sim$3% deadtime correction. The position (J2000) of PSR 0656+14 was determined to be $\alpha = 6^h59^m48\overset{s}{.}0$, $\delta = 14°14'12''$ which, considering the 6″ accuracy of the satellite attitude, is in good agreement with the radio position (J2000) of $\alpha = 6^h59^m48\overset{s}{.}11$, $\delta = +14°14'21\overset{''}{.}12$ (Taylor 1991). The radial profile of the events was consistent with what would be expected for a soft point source. The data preparation and handling was carrried out with the MIDAS/EXSAS software as provided by the European Southern Observatory (ESO) and the Max-Planck-Institut für Extraterrestrische Physik (MPE), respectively.

3. RESULTS

3.1. *Pulsations*

To search for pulsations from the source at the radio period ($P = 0.384883$ s referenced to JD 2,448,063.5 [Taylor 1991]) the arrival times of the source counts were reduced to the Solar System Barycenter using the JPL DE200 ephemeris. The adopted J2000 coordinates of PSR 0656+14 were $\alpha = 6^h59^m48\overset{s}{.}11$, $\delta = +14°14'21\overset{''}{.}12$ (Taylor 1991). The Z_1^2 statistic (Buccheri et al. 1986) was then calculated over a narrow range of periods bracketing the expected radio period (this statistical test is often referred to as the Rayleigh Test in the literature). The resultant periodogram had a maximum Z_1^2 value of 40.38 at $P = 384.884 \pm 0.006$ ms referenced to JD 2,448,341.0. The expected period from extrapolation of the radio ephemeris (P_0, $\dot{P}_0$) to the epoch of the X-ray data is $P = 384.8846$ ms. The chance probability of getting this value of the Z_1^2 statistic at the exact radio period is $\sim 2 \times 10^{-9}$. This detection firmly establishes PSR 0656+14 as an X-ray pulsar for the first time. The pulse profile of PSR 0656+14 folded at the X-ray period of 384.884 ms is displayed in Figure 1*a*. The profile appears as a broad feature at a pulsed fraction of 14% ± 2% with a rise to maximum which is more gradual than the decline to minimum. This profile showed no statistically significant changes as a function of energy.

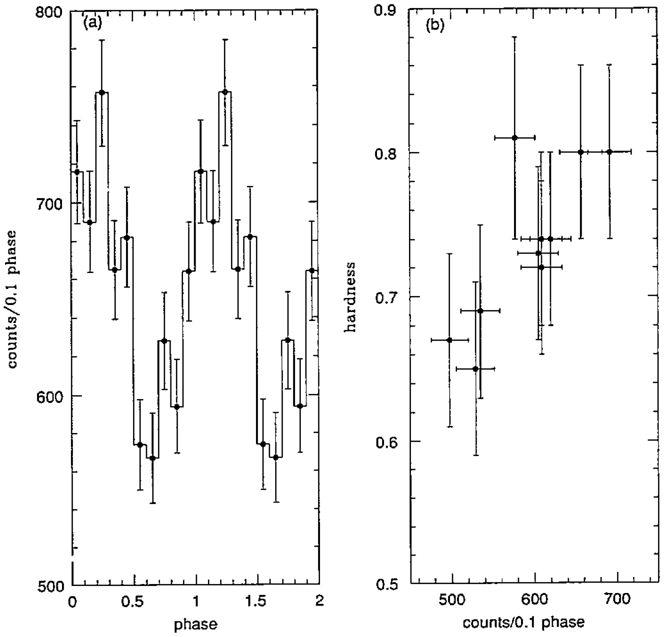

FIG. 1.—(*a*) Pulse profile for PSR 0656+14. Two cycles are plotted for clarity. (*b*) Correlation chart of the hardness and pulse phase for the data between channels 7 and 50. The correlation coefficient is 0.78.

TABLE 1

MODEL PARAMETERS FOR PSR 0656+14

PARAMETER	MODEL Blackbody	MODEL He Atmosphere
Reduced χ^2	1.43	1.20
$N_H(10^{20}\ cm^{-2})$	0.8–1.2	1.6–2.3
T_∞(K)	860,000–940,000	220,000–260,000
R_∞(km)	8–12	11.5–18.6
Distance(pc)	500	100–250

NOTE.—Parameter ranges are 90% confidence level ranges. The radius for model 1 was derived assuming a source distance of 500 pc. The column density, temperature, and distance for the He atmosphere model (Romani 1987) are appropriate for a range of radii from 8 to 16 km. The values of the temperature and radius are the appropriate redshifted values.

3.2. *Spectrum*

The high counting rate from PSR 0656+14 provided enough photons ($\sim$6500) in the 3190 s observation that a statistically meaningful spectral fit could be performed. The best-fit blackbody spectrum had a marginally acceptable reduced χ^2 of 1.43 for 161 DOF. The best-fit parameters of this model in the 90% confidence range are $kT \sim 0.074$–0.081 keV ($\sim$860,000–940,000 K) for the surface temperature of the neutron star, and $N_H \sim 0.8$–1.2×10^{20} cm^{-2} (see Table 1). The model gives an unabsorbed 0.08–2.4 keV flux of (5–15) $\times 10^{-12}$ ergs cm^{-2} s^{-1} (90% confidence) corresponding to a luminosity of $3 \times 10^{32}(D/500\ \mathrm{pc})^2(F/10^{-11}\ \mathrm{ergs\ cm^{-2}\ s^{-1}})$ ergs s^{-1}. These parameters imply a stellar radius of 8–12 km for an assumed distance to PSR 0656+14 of 400–600 pc and a bolometric luminosity of (3–6) $\times 10^{32}$ ergs s^{-1} for the same range of radius and distance. The best-fit temperatures listed above are for an observer at ∞; as measured on the surface of the neutron star, these temperatures should be increased to $T_s \sim (1.1$–$1.2) \times 10^6$ K. A power-law spectrum with a steep spectral index of -4.8 also produced an acceptable fit to the data as would be expected for the Wien end of a blackbody curve. The range of N_H is consistent with the limit of $<4 \times 10^{20}$ cm^{-2} established by the *Einstein* IPC data (Córdova et al. 1989) and with the column density which would be expected for a pulsar with a radio dispersion measure of 14 cm^{-3} pc (Manchester & Taylor 1981). The best-fit temperature range is, however, outside of the 90% range of 300,000–600,000 K reported by Córdova et al. (1989). Our derived flux does, on the other hand, compare favorably with their 90% confidence range of (2–10) $\times 10^{-12}$ ergs cm^{-2} s^{-1} for the flux above $E \geq 0.15$ keV. A dominant contribution to the high value of the reduced χ^2 was a high-energy tail which is poorly fitted by a simple blackbody and may be indicative of an additional hard component. Since *ROSAT* is still in the early stages of its mission, it may be necessary to reevaluate these parameters as better in-flight calibrations become available.

We have investigated the possibility of spectral variations as a function of the phase of the 0.385 s rotation period. Since the statistics did not allow meaningful phase-resolved spectroscopy, we employed a hardness parameter defined as the ratio of counts in channels 26–50 ($\sim$0.26–0.50 keV) to the counts in

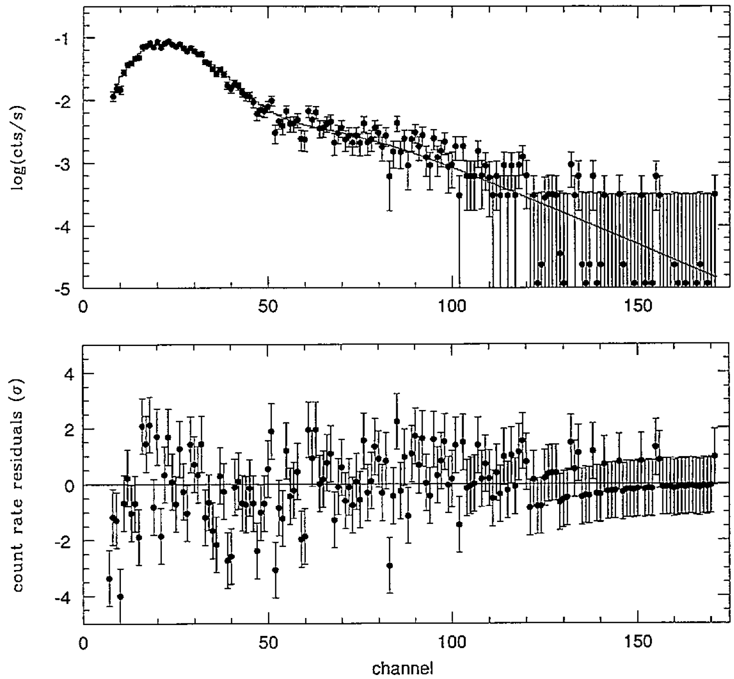

FIG. 2.—Spectrum of PSR 0656+14 along with the He atmosphere model (*histogram*) with T_s = 270,000 K, $N_H = 2.3 \times 10^{20}$ cm^{-2}, and R = 16 km. The bottom panel is the counting rate residuals in units of σ.

channels 7–25 (~0.07–0.25 keV). This choice of channels includes ~90% of the source counts and roughly divides them in equal parts. This ratio was calculated as a function of the 10 pulsar phase bins and the correlation evaluated. The correlation chart is displayed in Figure 1*b*. The hardness is seen to increase as the pulsar moves from minimum to maximum emission. The correlation coefficient is 0.78 and has a chance probability of ~0.7% that the observed correlation arose from an uncorrelated population. The average energy per unit phase and the phase of the pulsed emission display a similar correlation. The implied temperature difference between maximum and minimum emission is ~4% under the assumption of a blackbody spectrum. This is consistent with the interpretation of the entire 14% ± 2% intensity modulation arising in a region of higher temperature on the neutron star surface sweeping through the field of view. Due to the poor statistics above channel 50, we were unable to detect significant pulsations in the high-energy tail of the spectrum and phase-relate it to the soft component.

We entertained the possibility that a neutron star atmosphere modifies the emergent spectrum producing deviations from blackbody (Romani 1987). Spectra for model atmospheres (Romani 1987) of pure He and pure Fe were redshifted at an assumed neutron star radius (8–16 km) and fixed mass (1.4 $M_\odot$), subjected to absorption in the interstellar medium using the model of Morrison & McCammon (1983), folded with the detector response and compared with the observations. The normalization then determines the source distance for the assumed stellar parameters. The spectra for a pure Fe atmosphere did not produce an acceptable fit while the pure He atmosphere with $T \sim 3.1 \times 10^5$ K ($R = 8$ km) and $T \sim 2.7 \times 10^5$ K ($R = 16$ km) produced an acceptable reduced χ^2 of 1.20. The data and the fitted model for $R = 16$ km as well as the residuals are displayed in Figure 2 and the parameters of the models are presented in Table 1. The improved χ^2 is mostly due to a better representation of the high-energy tail of the distribution; however, the residuals of all the spectra still show a similar nonrandom behavior and may be indicative of some remaining uncertainty in the detector calibration.

4. DISCUSSION

The detection of pulsed X-rays at the radio period from PSR 0656+14 makes it only the fifth pulsed X-ray–emitting isolated pulsar along with PSR 0531+21 (the Crab), PSR 0540−69 (the LMC pulsar), PSR 1509−58, and the Vela pulsar (Ögelman et al. 1991). At a spin-down age, $\tau_{\rm SD} = P/2\dot{P}$, of 1.1×10^5 yr, PSR 0656+14 is a "middle-aged" pulsar: about 100 times older than Crab, the LMC pulsar, and PSR 1509−58 ($\tau_{\rm SD} \sim 10^3$ yr); about 10 times older than the Vela pulsar ($\tau_{\rm SD} \sim 10^4$ yr); and about 10 times younger than the bulk of radio pulsars ($\tau_{\rm SD} \sim 10^6$ yr). PSR 0656+14 is the *oldest* isolated radio pulsar that shows pulsed X-ray emission. The very young pulsars ($\tau < 10^3$ yr) are believed to emit pulsed X-rays via magnetospheric processes (Cheng, Ho, & Ruderman 1986a, b). The pulsed X-ray luminosity of young pulsars is measured to be 0.1%–1.6% of their spin-down energy loss rate $\dot{E} = -I\Omega\dot{\Omega}$ (Seward 1985). In the case of PSR 0656+14, the pulsed X-ray emission is also ~1% of the spin-down luminosity of $\sim 4 \times 10^{34}$ ergs s^{-1}. However, according to the conventional interpretation of the magnetospheric emission process, such a soft spectrum would not be expected (Cheng et al. 1986a, b). Moreover, a neutron star with the characteristic age of PSR 0656+14 ($\tau \simeq 10^5$ yr) is *expected* to emit blackbody-like radiation due to various cooling scenarios (Nomoto & Tsuruta 1987; Shibazaki & Lamb 1989; see Ögelman 1991 for a review and further references). The fact that PSR 0656+14 has the softest spectrum of the known X-ray emitting pulsars and that the measured temperatures are in the right range lends further support to the cooling neutron star hypothesis.

In line with the above cooling hypothesis, the most reasonable interpretation of the observed correlation of hardness with pulse phase is that the pulsed emission originates in a region of higher temperature on the stellar surface. Various models of the temperature distribution on the surface of a neutron star incorporating geometric effects (Greenstein & Hartke 1983), the heat conducting properties of the outer crust (Gudmundsson, Pethick, & Epstein 1982), and the effects of the large magnetic field on the heat conduction (Van Riper 1988) have appeared in the literature. In all cases the deviations from a blackbody spectrum are expected to be small, $\leq 10\%$. Another interesting possibility for the origin of the hot spots may be the polar cap heating via electrostatic accretion of energetic particles in the magnetosphere (Cheng & Ruderman 1980; Arons 1981). In the Cheng & Ruderman (1980) model, the surface temperature of the caps are predicted to be $T_{\rm cap} \simeq 3 \times 10^5 E_B({\rm keV})$ K where E_B is the neutron star surface binding energy estimated to be ≤ 1 keV (Jones 1986). The expected polar cap temperatures from the above model is in the range of our measured temperatures for the He atmosphere model of Romani (1987). However, the area of the cap required to account for the observed luminosity is of the order of the total neutron star surface even if the source is at a distance of ~ 200 pc (see the subsequent discussion).

It has been suggested that the observed emission can be modified by the presence of a stellar atmosphere where the chemical composition introduces absorption edges (Romani 1987). More recent work along these lines incorporating the magnetic fields effect on the atomic binding energies, level splitting, and opacities of the atmosphere have been carried out (Ventura 1989; Miller 1991). For the present work only the models of Romani (1987) for pure He and pure Fe atmospheres were available. The model of Romani (1987) with a He atmosphere provided an acceptable fit to the data for $T_s \sim 270{,}000$ K and $N_{\rm H}$ of 2×10^{20} cm^{-2} for an assumed stellar radius of 16 km and stellar mass of 1.4 $M_\odot$. The implied source distance from this model is ~ 150–250 pc which is smaller than the distance of ~ 400 pc estimated from the dispersion measure of 14 cm^{-3} pc and a model of the electron density in the galaxy (Manchester & Taylor 1981) but not unreasonably so. For an 8 km radius neutron star the corresponding parameters are $T_s \sim 340{,}000$ K and $N_{\rm H}$ of 1.8×10^{20} cm^{-2}. The source distance derived in this model is 100–150 pc. The ranges of the parameters in Table 1 are representative of the results for both choices of stellar radius.

Various authors have discussed the thermal evolution of neutron stars in the recent literature (Nomoto & Tsuruta 1987; Shibazaki & Lamb 1989; Ögelman 1991 and references therein). The results for the two spectral model fits presented here lead to different conclusions in terms of the appropriate cooling scenario. The surface temperature of $\sim 10^6$ K from the pure blackbody fit can be accommodated by cooling scenarios with and without a superfluid component but lies well above what would be expected for the presence of exotic matter such as pion or kaon condensates in the inner core. On the other hand, the surface temperature of $\sim 300{,}000$ K from the He atmosphere model would favor the presence of exotic matter in that the majority of the standard cooling scenarios do not yield such a low temperature after 10^5 yr. However, recent work on the direct Urca process (Lattimer et al. 1991) has shown that if the proton concentration, which is determined by the poorly known symmetry energy of matter above nuclear density, is above a critical value, the cooling rate of a neutron star by neutrino emission is enhanced by a large factor. Lattimer et al. (1991) estimate that this condition on the proton concentration is satisfied in most of the current calculations. Possible retarded cooling of the neutron star due to thermal dissipation by vortex creep in the interior of the neutron star is estimated to generate a blackbody-like luminosity (Pines & Alpar 1985) $L \sim |\dot{\Omega}| \Sigma I_i \omega_i$, where $\Sigma I_i \omega_i$ is the summed effect of various pinned layers with moment of inertia I_i rotating with lag $\omega_i \equiv \Omega_i - \Omega_c$ with respect to the rotation rate Ω_c of the crust. Measurements of $\Sigma I_i \omega_i$ for PSR 1929+10 indicate that it is $< 10^{43}$ g cm^2 rad s^{-1} (Alpar et al. 1987). Thus, with $\dot{\Omega} \simeq 2.3 \times 10^{-12}$ rad s^{-2}, we expect that vortex creep reheating to contribute $< 10\%$ of the observed luminosity of PSR 0656+14.

In summary then, we have found PSR 0656+14 to be an emitter of pulsed X-rays at the radio period. The pulsed emission has its seat in a hotter region of the stellar surface as indicated by the positive correlation of the hardness with pulse phase. The data can be described by a blackbody spectrum at a surface temperature of 900,000 K, implying a standard cooling scenario with a possible superfluid component, or by a blackbody spectrum modified by the presence of a He atmosphere at a surface temperature of $\sim 300{,}000$ K which can be accomodated by a standard cooling scenario modified by the presence of exotic matter or the direct Urca process. For a given model the parameter ranges are found to be small indicating the high quality of the data. However, independent determinations of $N_{\rm H}$ and source distance are necessary to discriminate these two representations and thus provide valuable insight into the thermal evolution of neutron stars.

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