RX J1856.5-3754: BARE QUARK STAR OR NAKED NEUTRON STAR?

S. Zane [a] R. Turolla [b] J.J. Drake[c]

[a]Mullard Space Science Laboratory, UCL, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK

[b]Dept. of Physics, University of Padova, via Marzolo 8, 35131 Padova, Italy

[c]Smithsonian Astrophysical Observatory, MS 3, 60 Garden Street, Cambridge, MA 02138, USA

Recent *Chandra* observations have convincingly shown that the soft X-ray emission from the isolated neutron star candidate RX J1856.5-3754 is best represented by a featureless blackbody spectrum, in apparent contrast with the predictions of current neutron star atmospheric models. Moreover, the recently measured star distance ($\approx 120 - 140$ pc) implies a radiation radius of at most $\sim 5 - 6$ km, too small for any neutron star equation of state. Proposed explanations for such a small radius include a reduced X-ray emitting region (as a heated polar cap), or the presence of a more compact object, as a bare quark/strange star. However, both interpretations rely on the presumption that the quark star or the cap radiates a pure blackbody spectrum, and no justification for this assumption has been presented yet. Here we discuss an alternative possibility. Cool neutron stars ($T \lesssim 10^6$ K) endowed with a rather high magnetic field ($B \gtrsim 10^{13}$ G) may suffer a phase transition in the outermost layers. As a consequence the neutron star is left bare of the gaseous atmosphere ("naked"). We computed spectra from naked neutron stars with a surface Fe composition. Depending on B, we found that the emission in the 0.1-2 keV range can be featureless and virtually indistinguishable from a blackbody. Moreover, owing to the reduced surface emissivity, the star only radiates $\sim 30 - 50\%$ of the blackbody power and this implies that the size of the emitting region is larger than for a perfect planckian emitter for the same luminosity. When applied to RX J1856.5-3754 our model accounts for the observed X-ray properties and solves the paradox of the small radius: we predict an apparent star radius of $\sim 10 - 12$ km, consistent with equations of state of a neutron star. The optical emission of RX J1856.5-3754 may be explained by the presence a thin gaseous shell on the top of the Fe condensate.

1. Introduction

The family of thermally emitting isolated neutron stars (NSs) includes seven peculiar objects serendipitously discovered in *ROSAT* PSPC pointings (see e.g. [1] for a review). These sources are characterized by similar properties: a blackbody-like, soft spectrum with $T_{bb} \sim 100$ eV; low X-ray luminosity, $L_X \approx 10^{30} - 10^{31} \mathrm{erg\,s^{-1}}$; low column density, $N_H \sim 10^{20}$ cm^{-2}; pulsations in the 5-20 s range (detected in four sources so far). Due to their proximity and to the fact that they are "truly isolated" (i.e. not associated with a supernova remnant), they are excellent candidates to probe directly the emission from the star surface. On the other hand, since they are dim and extremely soft, until recently high quality spectra were not available. PSPC data only provided evidence that a hard tail is absent in all cases and that a blackbody gives a satisfactory spectral fit. The situation has recently improved for the two brightest and closest objects, RX J1856.5-3754 and RX J0720.4-3125, which have been target of deep observations with *Chandra* and *XMM-Newton* ([2,4,5]). The hope was to probe directly the neutron star surface composition, by detecting some of the spectral feautures predicted by atmospheric models at different chemical composition and/or magnetic field strenght. Surprisingly/disappointingly, in both sources no spectral features have been detected. In the case of RX J1856.5-3754, the result is particularly robust and striking: a very long (~ 500 ks) *Chandra* pointing has shown that the spectrum is better fitted by a simple blackbody than by more sophysticated atmospheric models. Also, upper limits on the pulsed fraction of RX J1856.5-3754 are extremely tight, $\lesssim 3\%$ ([5]).[1] The sources is known to exhibit an "optical excess": accurate photometry of the optical counterpart with combined Very Large Telescope

[1]A few weeks before this meeting, J. Trümper reported at the 34^{th} COSPAR Scientif Assembly an even more stringent limit, $\sim 1\%$. This result is now published on [6].

and Hubble Space Telescope data has shown that the UV-optical emission from RX J1856.5-3754 exceeds the Rayleigh-Jeans tail of the X-ray best-fitting blackbody by a factor ~ 6 ([7]). The value of the distance ($d \approx 120 - 140$ pc; [8,7]), used in conjunction with *Chandra* data, yields a radiation radius of only $\sim$ 5-6 km ([5]), too small for any known NS equation of state.

The small apparent radius and the blackbody X-ray spectrum led to the intriguing suggestion that RX J1856.5-3754 might host a quark star ([5,9]). The motivation is that the radiation radius is compatible only with equations of state (EOSs) involving strange matter and that bare quark stars, i.e. those not covered by a layer of ordinary matter which act as an atmosphere, would *presumably* emit a pure blackbody spectrum. While a quark star is a conceivable option, present observations of RX J1856.5-3754 do not necessarily demand this solution. Other more conventional model fits, based on two blackbodies, can account for both the X-ray and optical emission of RX J1856.5-3754, giving at the same time acceptable values for the stellar radius ([10,7,11]). In this scenario X-rays originate in a relatively large ($\theta \sim 20^\circ$) heated polar cap, while the rest of the surface is colder (~ 30 eV) and produces the optical emission. However, since both regions should be covered with an optically thick atmosphere, the reason why they should produce a featureless spectrum has not been thoroughly understood yet.

In this paper we suggest an alternative possibility. As pointed out by [12] (see also [13]) NSs may be left *without an atmosphere* by the onset of a phase transition that turns the gaseous outer layers into a solid. This happens if the surface temperature drops below a critical value T_{crit} which in turn depends on the star magnetic field. The source then appears as a "naked" or "bare" neutron star: we only detect the emission from the solid layers. While it appears difficult even for the coolest isolated NSs to meet the requirements for the onset of a phase transition in light element (H, He) surface layers, this may be the case if the external layers are dominated by heavy elements (such as Fe). The uncertainties on the conditions for Fe condensation are currently quite large, but, depending on the magnetic field, it is possible that the surface temperature of RX J1856.5-3754 falls below the critical value.

If condensation occurs, the emitted spectrum is not necessarily a blackbody: an overall reduction of the surface emissivity and strong absorption features are in fact expected when the photon energy becomes lower than the plasma frequency of the medium. However these absorption features may or may not appear at soft X-ray energies depending on the model parameters. In the following we investigate the emission properties of naked NSs and discuss the relevance of our model in connection with the NS candidate RX J1856.5-3754. For all details we refer to [14].

After this work has been completed we become aware that similar conclusions have been independently reached by [6] and have been reported by J. Trümper at the 34^{th} COSPAR Scientif Assembly. These authors attempted a fit to combined UV-optical and X-ray data of RX J1856.5-3754 with a depressed blackbody plus an enhanced Rayleigh-Jeans tail, by miming phenomenologically the situation here described theoretically. Their results for the star radius are close to ours.

2. The Model

2.1. Bare Neutron Stars

Theoretical research on matter in superstrong fields started over 40 years ago and, although many uncertainties still remain, much progress has been made especially for H and He compositions (see [13] for a recent review and references therein). At $B \gg B_0 = m_e e^3 c/\hbar^3 \simeq 2.35 \times 10^9$ G strong magnetic confinement acts on electrons, and atoms attain a cylindrical shape. It is possible for these elongated atoms to form molecular chains by covalent bonding along the field direction. Interactions between the linear chains can then lead to the formation of three-dimensional condensates. The critical temperature below which phase separation between condensed H and vapor occurs is given by [12]

$$\begin{aligned} T^H_{crit} &\approx 0.1 \Big[194.1 B_{12}^{0.37} - 4.4 \left(\ln B_{12} - 6.05\right)^2 - \hbar\omega_{p,p} \\ &- \frac{\hbar}{2}\left(\omega_{B,p}^2 + \omega_{p,p}^2\right)^{1/2} + \frac{1}{2}\hbar\omega_{B,p} \Big] \ \mathrm{eV}\,, \qquad (1) \end{aligned}$$

where $B_{12} = B/(10^{12}\,\mathrm{G})$, $\omega_{B,p}$ and $\omega_{p,p}$ are the proton cyclotron and plasma frequencies. For heavier elements (such as Fe) all estimates are still quite crude. T_{crit} is obtained by equating the ion density of the condensed phase near zero pressure to the vapor density, but all available models are approximate near zero pressure. The most recent estimate of T_{crit} for Fe phase separation, as given by [13], is $T_{crit}^{Fe} \approx 27 B_{12}^{2/5}$ eV. The density of the condensate (at zero pressure) is $\rho_s \approx 560 Z^{-3/5} B_{12}^{6/5}\,\mathrm{g\,cm^{-3}}$ (here Z denotes the atomic number of the constituent element). This expression should be regarded as accurate to within a factor of a few while Eqs. (1) and especially T_{crit}^{Fe} represent typical upper limits for the critical temperature.

In Fig. 1 we have plotted the critical condensation temperatures for H and Fe, as a function of B, toghether with the coolest, thermally emitting NSs for which an estimate of the magnetic field (as computed from the spin-down formula) is available (see Tab. 1). We have also drawn an horizontal line at the surface temperature of RX J1856.5-3754, for which B is unknown. We used as a color temperature the value derived from a blackbody fit in the X-rays, T_{bb}. The surface temperature T_{surf} follows by applying the gravitational red-shift factor.

As we can see from Fig. 1, most sources have T_{surf} well in excess of the H critical temperature. Therefore, if surface layers are H-dominated, the presence of a gaseous atmosphere is unescapable. The only exception is RX J1308.6+2127, for which an exceptionally strong field has been reported by [15]. However, this value is probably preliminary and a re-analysis of the timing properties of this source is presently under way (Haberl, as reported at the 34^{th} COSPAR meeting). Similarly, H condensation in RX J1856.5-3754 requires the star to be a magnetar ($B \gtrsim 10^{14}$ G).

On the other hand, if NSs have not accreted much gas, we might detect thermal emission directly from the iron surface layers. If this is the case, for $B \gtrsim 10^{13}$ G the outermost layers of RX J1856.5-3754 might be in the form of hot condensed matter and the usual radiative transfer computations do not apply.[2] The question of the nature of the emitted spectrum then arises.

2.2. The Emitted Spectrum

We consider a NS with metallic Fe surface layers and repeat a computation, first carried out by [22] and based on the evaluation of the surface reflectivity, for the parameter range relevant to cold isolated NSs. At each magnetic co-latitude θ we first compute the total reflectivity $\rho_\omega(i,\beta,\theta)$ of the surface element for incident unpolarized radiation. Here i and β are the co-latitude and the azimuthal angle of the incident wave vector, relative to the surface normal. The absorption coefficient is then $\alpha_\omega = 1 - \rho_\omega$, and Kirchhoff's law is used to derive the emissivity $j_\omega = \alpha_\omega B_\omega(T)$, where T is the local temperature and B_ω is the blackbody function. The monochromatic flux dF_ω emitted by the surface element is computed by averaging over all incident directions, and further integration over the star surface gives the total flux

$$F_\omega = \int_0^\pi dF_\omega = \int_0^\pi B_\omega(T)\sin\theta\, d\theta \times \int_0^{2\pi}\int_{-\pi/2}^{\pi/2} \alpha_\omega(i,\beta,\theta)\sin i\, di\, d\beta\,. \qquad (2)$$

In performing the last step we assumed a dipolar field, $B = B_p[(4-f)\cos^2\theta + f]^{1/2}/2$, where B_p is the polar field strength and $f \simeq 1.2$ accounts for general-relativistic corrections in a Schwarzschild space-time. We computed two sets of models either by taking a constant surface temperature or allowing for a meridional temperature dependence as given by [23]. We also explored the parameter space by varing the electron plasma frequency, ω_p, around $\omega_{p,0} \equiv \omega_p(\rho = \rho_s)$, to account for possible deviations of the surface density from its zero-pressure value ρ_s (see e.g. [13]).

For $B \gtrsim 10^{13}$ G, features related to the strong absorption around the electron cyclotron frequency fall well outside the X-ray range accessible to the *Chandra* LETGS and *XMM-Newton* EPIC-PN, and are of no immediate interest. However, even above this field, we do not expect the spectrum emitted by the solid to be, in general, a

Table 1
Isolated Neutron Stars Parameters

Source	T_{bb} (eV)	B (10^{12} G)	Refs.[a]
RX J1856.5-3754	61.1 ± 0.3	–	[4,5]
RX J0720.4-3125	86.0 ± 0.6	$21.3^{+0.1}_{-0.1}$	[2,3]
RX J1308.6+2127	90.6 ± 1.6	500^{+150}_{-150}	[15]
Vela	128.4 ± 7	3.3	[16,17]
Geminga	$48.3^{+6.1}_{-9.5}$	1.5	[18,19]
PSR 0656+14	69.0 ± 2.5	4.7	[16,20]
PSR 1055-52	$68.1^{+10.2}_{-17.2}$	1.1	[16,21]

[2]The case of RX J0720.4-3125 is less certain, because the source falls only marginally within the region where Fe condensation is possible.

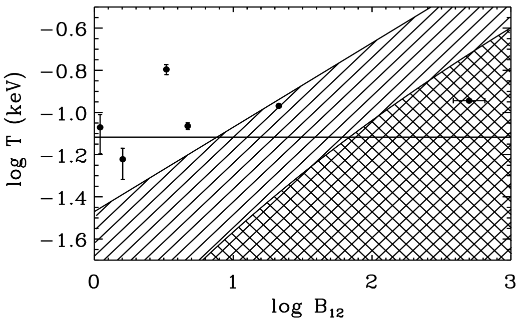

Figure 1. T_{crit} for H and Fe as a function of B. Condensation is possible in the shaded region for Fe and in the cross-hatched region for H. Filled circles mark the position of the sources listed in Tab. 1; the horizontal line corresponds to the surface temperature of RX J1856.5-3754.

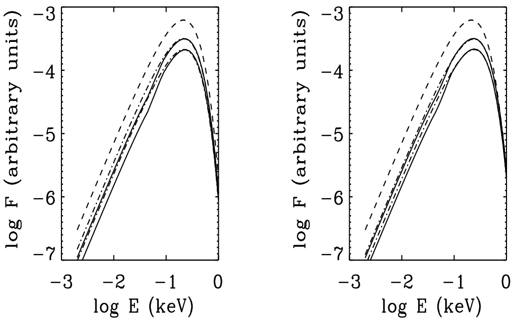

Figure 2. The spectrum at the star surface for $B_p = 3 \times 10^{13}$ G, $T_{eff} = 75$ eV and two values of ω_p: $\omega_{p,0}$ (upper solid curve) and $2.5\omega_{p,0}$ (lower solid curve). Left and right panels refer to the uniform and meridional temperature distributions, respectively. The dashed line is the blackbody at T_{eff} and the dash-dotted line the best-fitting blackbody in the 0.1-2 keV range.

blackbody. For $T \lesssim 100$ eV, the mean energy of the refracted waves is comparable to (or lower than) the plasma frequency of the solid. Therefore, we encounter modes with very large refractivity (like whistlers in the terrestrial atmosphere), modes which are frozen in the medium, or modes highly damped which just enter the NS crust and disappear within a small penetration depth. All these effects may modify the spectrum through the production of features and edges, which in turn may or may not appear in the X-rays depending on the model parameters.

In particular we found that, for $B_p \approx 3 - 5 \times 10^{13}$ G, the spectrum in the soft X-rays, (0.1-2 keV) band, shows negligible departures (within $\lesssim 10\%$) from the best-fitting blackbody and exhibits no features whatsoever. We point out that larger deviations are at the lowest energies, and that the agreement with the planckian is better than 2% if we restrict to the interval 0.14-2 keV. Spectra are shown in Fig. 2 for $B_p = 3 \times 10^{13}$ G and $T_{eff} = 75$ eV, which corresponds to 60 eV once the gravitational red-shift is applied. The constant temperature models have virtually no hardening, while we get $T_{bb}/T_{eff} \equiv \gamma \simeq 1.14$ accounting for a meridional temperature variation. An important point is that, despite being close to planckian *in shape*, the spectrum is substantially depressed with respect to the blackbody at T_{eff}, owing to the reduced emissivity of the surface. The total power radiated by the star in the 0.1-2 keV band is $\sim$ 30-50% with respect to that of a perfect blackbody emitter and decreases with increasing ω_p (Fig. 3).

3. The Case of RX J1856.5-3754

3.1. The X-ray Emission

It has been recently proposed by a number of authors ([10,7,11]) that the multiwavelength spectral energy distribution (SED) of RX J1856.5-3754 may be explained in terms of a two-temperature surface distribution in a cooling NS. Although these models appear promising, they are all based on the *presumption that the emitted spectrum is planckian in shape.* A number of mechanisms (magnetic smearing, rotation..) have been suggested in order to suppress the spectral features predicted by atmospheric models, but *no conclusive evidence* has been provided yet that a nearly blackbody, featureless spectrum can be emitted by an extended atmosphere covering the stellar crust. [11] discuss in detail the role of rotation, showing that phase-dependent Doppler shifts in a rapidly rotating neutron star ($P \approx 1$ ms) wash out all features,

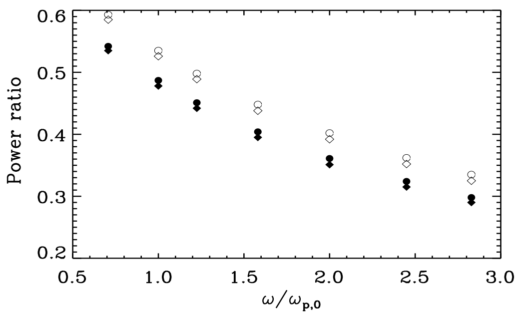

Figure 3. Ratio of the emitted to the blackbody power in the 0.1-2 keV band for different values of the plasma frequency. Circles refer to $B_p = 3 \times 10^{13}$ G and diamonds to $B_p = 5 \times 10^{13}$ G. Filled and open symbols are for the uniform/meridional variation temperature distributions respectively.

leaving a nearly planckian spectrum. Although such a short period can not be excluded on the basis of present data, the detected periods of other thermally emitting INSs are in the range $\approx$ 0.1-10 s, about two orders of magnitude larger. Also, in the picture by [11] the genuine surface temperature should correspond to the cooler blackbody at $T \sim 15$ eV. Conventional cooling curves then imply a star's age of $\approx 10^6$ yr, which is hardly compatible with a ms period. Furthermore, the energetics of the bow-shock nebula implies $P = 4.6\left(B/10^8\ \mathrm{G}\right)^{1/2}$ ms. A ms spin period therefore necessary demands for a very low field star. Such a low field seems hard to reconcile with the limit on the age derived again from the bow shock energetics, $(B/10^{12}\ \mathrm{G})(\tau/10^6\ \mathrm{yr}) \sim 3-4$.

Without a measured period and period derivative, the magnetic field of RX J1856.5-3754 is still a mystery. We found that, for the surface layers of RX J1856.5-3754 to be in the form of condensed Fe, its field should be in excess of 10^{13} G, and more probably at least 3-5$\times 10^{13}$ G (Fig. 1). Although rather high, this field strength is well below the magnetar range and is noticeably shared by another *ROSAT* isolated NS: RX J0720.4-3125 [3]. When combined with the limit derived from the bow shock energetics, $(B/10^{12}\ \mathrm{G})(\tau/10^6\ \mathrm{yr}) \sim 3-4$, such field demands for a middle-aged NS ($\tau \approx 10^5$ yr). The spectrum from a bare NS with a dipolar field in this range is shown in Fig. 2. In the 0.15-2 keV band the spectrum is featureless; deviations from the best-fitting blackbody are $\lesssim 2\%$, well within the limits of calibration uncertainties of the *Chandra* LETGS ($\sim 10\%$, as reported by [11]). Our surface emissivity is angle-dependent, and we checked that no pulsations are expected to within 3%, the latest published value ([5]).

For the radiation radius to be representative of the true star radius the emission properties of the surface need to be accounted for and, at least for thermal emission, we can use the spectral hardening γ to quantify spectral deviations from a pure blackbody. Denoting the fraction of the stellar surface responsible for the observed emission and the ratio of emitted to blackbody power by f_A and f_E, the radiation radius is

$$R_\infty = 4.25\, f_A^{-1/2} f_E^{-1/2} \gamma^2 d_{100} \left(\frac{T_{bb}}{60\,\mathrm{eV}}\right)^{-2} \mathrm{km}, \quad (3)$$

where $d_{100} \equiv d/(100\,\mathrm{pc})$. The "angular size" of RX J1856.5-3754 reported by [5] is $R_\infty/(d/100\,\mathrm{pc}) = 4.12 \pm 0.68$ km. If we correct this value by assuming $d = 130$ pc, emission from the entire surface ($f_A = 1$) and uniform temperature ($\gamma = 1$), we get 7.7 ± 1.3 km$\lesssim R_\infty \lesssim 9.9 \pm 1.6$ km in correspondence to $1 \leq \omega_p/\omega_{p,0} \leq 2.8$ (see Fig. 3). For the same range of plasma frequencies, models with meridional temperature variation give larger radii, between 9.4 ± 1.5 km and 12 ± 2 km. Therefore, even this simple approach can provide $R_\infty \sim$ 10-12 km, compatible with (soft) EOSs for $M \sim 1.4 M_\odot$ ([24]).

3.2. The UV-Optical Excess

The UV-optical flux from RX J1856.5-3754 is enhanced with respect to the extrapolation of the X-ray best-fitting blackbody. All proposed interpretations for the full SED (from optical to X-ray) require two components: either a cold surface plus an hotter cap or a bare quark star plus a thin crust with flux redistribution. Similarly, also our scenario requires the presence of a second component. A natural possibility is that the optical flux emitted from the NS surface is reprocessed in a thin, ionized gas layer on the top of the Fe solid. Hydrogen can be deposited on the surface as the result of very slow accretion ($\approx 10^9$ g in $\approx 10^5$ yr). The free-free absorption depth in the optical ($\sim$ 1-10 eV) is $\approx 10^3$ times larger than in the X-rays ($\sim$ 100 eV), thus in a range of average densities (around $\approx 10^{-3}\,\mathrm{g\,cm^{-3}}$) the gasoues layer is optically thin in the X-rays and thick to optical photons. The scale-height derived from hydrostatic equilibrium is $\approx 0.1 - 1$ cm, comparable with the scale-height at which electron conduction from the crust keeps the gas almost isothermal at the star surface temperature ($\approx 10^6$ K). Preliminary calculation of the multiwavelength SED are shown in Fig. 4. Parameters are the same as for the model with $2.5\omega_{p,0}$ shown in Fig. 3 and the density at the base of the layer is $2 \times 10^{-3}\,\mathrm{g\,cm^{-3}}$. As expected the low-energy SED follows a Rayleigh-Jeans distribution at the gas (and star) temperature. With increasing energy the optical depth of the layer drops below unity and therefore X-rays emitted by the solid surface emerge unchanged from the layer. However, since the X-ray spectrum emitted by the star surface is depressed with respect to the blackbody at the star temperature, the optical emission appears enhanced. In the model presented here the optical-UV excess over the best-fitting X-ray blackbody is a factor $\sim$ 3-4, somewhat lower than the value ~ 6 reported by [7]. Larger ratios might be obtained with a slightly larger gas temperature and a more thorough investigation is in progress.

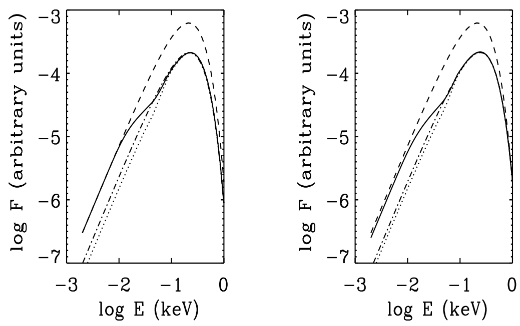

Figure 4. The multiwavelength SED of a bare neutron star covered by a thin H layer (full line); the dotted line is the spectrum emitted by the solid. Details as in Fig. 2.

4. Conclusions

We have shown that the observed X-ray-to-optical spectra of RX J1856.5-3754 can be plausibly explained in terms of the emission from the surface of a "naked" neutron star. The absence of an atmosphere is due to a phase transition to a solid condensate, which can occur on cool ($< 10^6$ K) neutron stars endowed with strong magnetic fields ($B \gtrsim 10^{13}$ G) and with metal-dominated outer layers. We have shown that, when $B \approx 10^{13}$ G, the X-ray spectrum is featureless and planckian in shape. The observed UV-optical enhanced emission can be explained by the presence of a gasoues, thin H shell, where the optical flux is reprocessed.

While we caution that current limitations in our understanding of metallic condensates in strong magnetic fields renders our estimates of the surface reflectivity of bare NSs somewhat uncertain, we have shown that our model for RX J1856.5-3754 predicts a value for the apparent radius of $R_\infty \lesssim 12$ km. For a canonical NS of mass 1.4 $M_\odot$, such a radius favors soft EOSs.

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