RX J1856.5-3754: a Strange Star with a Solid Quark Surface?

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Abstract

The featureless spectra of isolated "neutron" stars may indicate that they are actually bare strange stars (BSS), but a definitive conclusion on the nature of the compact objects cannot be reached until accurate and theoretically calculated spectra of the bare quark surface are known. However, due to the complex nonlinearity of quantum chromodynamics, it is almost impossible to present a definitive and accurate calculation of the density-dominated quark-gluon plasma from the first principles. Nevertheless, it was suggested that cold quark matter with extremely high baryon density could be in a solid state. Within the realms of this possibility, we have fitted the 500ks Chandra LETG/HRC data for the brightest isolated neutron star RX J1856.5-3754 with a phenomenological spectral model, and found that electric conductivity of quark matter on the stellar surface is about $> 1.1 \times 10^{18}\mathrm{s}^{-1}$.

Introduction

- Neutron stars provide a unique opportunity for obtaining experimental information of matter in extremely high density, especially of the density-dominated quark matter if the so called strange stars, exist.
- Strange stars
  - A special kind of neutron stars
  - Difficult to identify
  - Probably bare (no atmosphere), and the bare quark surface is valuable to distinguish them from ordinary neutron stars.
- X-ray spectra of isolated neutron stars
  - The X-ray spectra (observed by *Chandra* or *XMM-Newton*) of most isolated neutron stars are featureless
  - This may indicate that they are BSS's.
- Identify strange stars and obtain electric conductivity?
  - An ordinary neutron star needs very high magnetic fields to produce a featureless spectrum.
    - For instance, the field of RX J1856.5-3754 should be $> 10^{13}$G for Fe and $> 10^{14}$G for H atmospheres, respectively (Zane et al. 2003).
  - Alternatively, a solid BSS with normal magnetic field ($\sim 10^{12}$ G) can also do.
  - The thermal spectrum from a solid quark surface looks more or less like that of metals.
  - It is possible to obtain the electric conductivity of solid quark matter from observation. The electric conductivity is meaningful to constrain the physical properties of solid quark matter in the study of color interaction.

Emissivity model

If the surface thermal emission of a solid bare strange star is an analogy of that of metals with conductivity σ, the spectral emissivity $\psi(\nu, T)$ is,

$$\psi(\nu, T) = \alpha(\nu) \cdot B(\nu, T), \qquad (1)$$

where

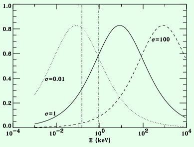
$$\alpha(\nu) = 1 - \frac{2\frac{\sigma}{\nu} + 1 - 2\sqrt{\frac{\sigma}{\nu}}}{2\frac{\sigma}{\nu} + 1 + 2\sqrt{\frac{\sigma}{\nu}}},$$

$$B(\nu, T) = \frac{2\pi h\nu^3}{c^2}\frac{1}{e^{h\nu/(kT)} - 1}.$$

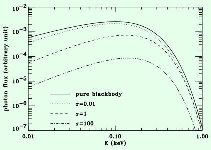
When $\nu \ll \sigma$, one comes to

$$\alpha(\nu) = 2\sqrt{\frac{\nu}{\sigma}} - 2\frac{\nu}{\sigma} + (\frac{\nu}{\sigma})^{3/2} + ...,$$

which is the experiment law of Hagen & Rubens for metals (Born & Wolf 1980).



The vertical lines indicate the energy range used in the fitting of the Chandra HETG/HRC spectrum of RXJ1856.5-3754 (σ is in the unit of $10^{18}\mathrm{s}^{-1}$).



Comparison of the emissivity $\psi(\alpha, E)$ with a pure blackbody (σ is in the unit of $10^{18}\mathrm{s}^{-1}$).

XSPEC local model

- An *XSPEC* local model is built based on the exact expression of $\alpha(\sigma)$.
- In the local model, σ is in the unit of $10^{18}\mathrm{s}^{-1}$, and photon energy E (in keV) is used instead of frequency (hz).

Therefore, let $\sigma_0 = \frac{\sigma}{10^{18}\mathrm{s}^{-1}}$, then

$$x \equiv \frac{\sigma}{\nu} = \frac{\sigma}{10^{18}\mathrm{s}^{-1}}(\frac{h\nu}{\mathrm{keV}})^{-1}(\frac{10^{18}\mathrm{s}^{-1}h}{\mathrm{keV}}) = 4.136\frac{\sigma_0}{E}$$

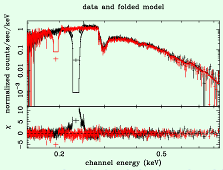
and

$$\alpha(E) = 1 - \frac{2x + 1 - 2\sqrt{x}}{2x + 1 + 2\sqrt{x}} = 1 - \frac{x + 0.5 - \sqrt{x}}{x + 0.5 + \sqrt{x}}$$

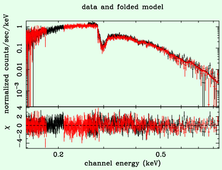
Data Analysis and Results

Data Reduction

- $\sim$500 ks Chandra LETG/HRC observations of RX J1856.5-3754 in 2000 and 2001.
- Spectra were extracted from the event2 files and arf files were generated following the CIAO threads.
- The spectra were combined and grouped so that each channel has at least 300 counts.
- The plus order and minus order spectra were combined separately, and a joint fitting was performed.



Spectrum and residual with the thermal model shown in Eq. (1). The features across the gaps between CCDs are obvious.



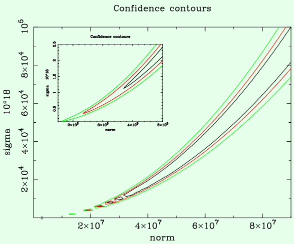
To avoid the effect of this instrumental feature, we ignore these spectrum channels: 0.18–0.21 keV in the plus order and 0.21–0.26 keV in the minus order.

Fitting Result

- Models: a) pure black-body model, and b) the thermal model given in Eq. (1), (both with interstellar absorption).
- The distance of RXJ1856 is taken as 120pc.
- Since σ and R_{bb}^{∞} are coupled together in Model b), we can only obtain the lower limits for σ and R_{bb}^{∞}. In the table, the lower limits of σ and $R_{\mathrm{b}b}^{\infty}$ are at 1σ, 2σ and 3σ confidence levels, respectively.

Model	nH	$kT_{\mathrm{b}b}^{\infty}$	$R_{\mathrm{b}b}^{\infty}$	σ	χ^2/dof
	$10^{20}\mathrm{c}m^{-1}$	eV	km (d/120pc)	$10^{18}\mathrm{s}^{-1}$	
(a)	0.86 ± 0.03	64.1 ± 0.5	4.1 ± 0.1	-	830/970
(b)	0.72 ± 0.03	59.5 ± 0.5	>(7.3, 5.9, 4.9)	>(1.12, 0.38, 0.14)	809/969

- We noticed a systematic change of all the parameters (especially the ISM column density) of both models with the increase of the bin size of the spectra. However, the lower limits of σ and R_{bb}^{∞} are not sensitive to the rebinning.



Confidence contour of σ and the normalization of the black-body model, which is proportional to the square of R_{bb}^{∞}.

Other Sources

RX J0720, the other isolated neutron star in Motch's list (2000) with Chandra LETG/HRC observation, is dimmer than RX J1856 and with shorter exposure time. We process the data from the Chandra LETG/HRC observations of RX J0720, but no constraint to σ can be obtained due to the poor statistics of the data.

Conclusions and discussions

- Within the realms of solid quark surface, we have fitted the 500ks Chandra LETG/HRC data for the brightest isolated neutron star RX J1856.5-3754 with a phenomenological spectral model. It is found that electric conductivity of quark matter on the stellar surface is $\sigma > 1.1 \times 10^{18}$ s^{-1}, the temperature is $T \sim 59.5 \pm 0.5$ eV, and the stellar radius, which is coupled with σ, is $R_{\mathrm{bb}}^{\infty} > 7.3km$ (all at 1σ level).
- If the electrons near the Fermi surface are responsible for the conduction, the fitted σ implies the relaxation time $\tau >\sim 8 \times 10^{-21}$ s, while the $e - e$ collision timescale $\tau \sim 2.3 \times 10^{-16}$ s.
- No general relativistic effect is included in our fitting. The parameters fitted are for observers at infinity.
- The GR effect can easily be considered if the spectrum is Plankian, i.e., of blackbody (e.g., Haensel 2001): $T_\infty = T\sqrt{1 - (R_s/R)}$, $R_\infty = R/\sqrt{1 - (R_s/R)}$, where $R_s = 2GM/c^2$ is the Schwartzschild radius for a compact star with mass M and radius R. However, if the thermal emission is not Plankian, like that of Eq.(1) for instance, the GR effect has not fully been considered. We call for such a study, which may modify our results in order to obtain better parameters.

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