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Modeling the Atmosphere of RX J1856.5–3754

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Abstract. The nearby compact object RX J1856.5–3754 may be a paradigm for the vast majority of neutron stars. Its spectral energy distribution lacks any non-thermal continuua or lines. Study of the thermal surface has provided insights into the surface and interior properties of neutron stars. We report on attempts to model the spectrum. Non-magnetic heavy metal atmospheres reproduce the overall spectral energy distribution, but not the lack of absorption lines.

1. Introduction

RX J1856.5–3574 is the brightest example of a radio-quiet isolated compact object (RICO). The RICOs are valuable astrophysical laboratories because, unlike the low mass X-ray binaries where the emission is dominated by accretion heating, or unlike the radio pulsars where the emission is dominated by non-thermal magnetospheric processes, we see the surface of the compact object. Therefore, we can determine the angular diameter, given the spectral energy distribution (SED) and the effective temperature. The parallax then gives the radius, R. In principle, spectral lines reveal the surface composition, gas temperature, T, the surface gravity, g, and the gravitational redshift, z. R, z, and g give two independent estimates of the stellar mass M. The ratio M/R constrains the equation of state of matter at nuclear and supranuclear densities. In principle, straightforward astrometric and spectroscopic observations of such stars can be of interest not only to astronomers but also to nuclear physicists.

1.1. RX J1856.5–3574

RX J1856.5–3574 (hereafter RX J1856) was discovered as a bright soft X-ray source in the CrA star forming region (Walter, Wolk & Neuhäuser 1996). The 8.5±0.9 mas parallax yields a 117±12 pc distance (Walter & Lattimer 2002). The 332.4±0.4 mas yr^{-1} proper motion (185 km s^{-1} transverse velocity) at a $100\overset{\circ}{.}45\pm 0\overset{\circ}{.}04$ position angle tracks back towards the Upper Sco OB association. For radial velocities between –20 and +30 km s^{-1}, the trajectory intercepts Upper Sco about 5×10^5 years ago. The temperature and luminosity are consistent with a neutron star on the standard cooling curve at that age. There are no other likely birth places for a young neutron star along this trajectory.

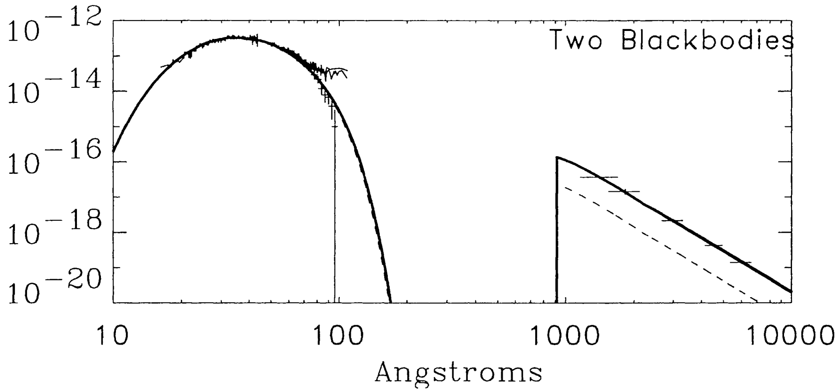

Figure 1. Two blackbody fit to the full SED. The dashed line is the X-ray blackbody. The components have temperatures of 64 and 32 eV. The surface area corresponds to a radius of 16.4 ± 0.3 km at 120 pc.

The X-ray emission is best fit by a 62 eV blackbody. The optical SED is the λ^{-4} Raleigh-Jeans tail of a hot blackbody, with $T(R/D)^2 = 0.59$ keV. This flux level exceeds the extrapolation of the X-ray blackbody by a factor of seven. The X-ray source is not variable, with a pulse amplitude $< 1.3\%$ (Burwitz et al. 2003). Overall, its properties are similar to those of the other RICOs.

Van Kerkwijk & Kulkarni (2001) showed that RX J1856 is preceded by a bow shock with a standoff distance $\sim 1''$. This suggests the presence of a relativistic wind, implying that it is magnetized and rotating. It may be a dead pulsar, or it may be a mis-directed pulsar, whose beam does not cross the Earth.

2. The Spectral Energy Distribution

No lines or absorption edges are seen in the X-ray spectrum. The best fit to the full SED is a two-component black body (Fig. 1). Blackbodies are unphysical, and at best represent a simple approximation of the true emission mechanism. Neutron stars likely either have optically thin atmospheres (e.g., Rajagopal & Romani 1996; Pavlov et al. 1996; Pons et al. 2002), or solid surfaces.

Pons et al. (2002) showed that the broadband SED of isothermal heavy element atmospheres can fit the observed SED. The major failing of these models is that they predict the presence of observable absorption lines and edges. On the other hand, an isothermal atmosphere can explain the lack of variability in RX J1856. Neutron stars can have atmospheres: the burster EXO 0748–676 (Cottam, Paerels & Mendez 2002) has at least a transient atmosphere, and cyclotron lines can be formed only in gaseous atmospheres.

As noted by Braje & Romani (2002), one can decrease the contrast of the absorption lines by decreasing the temperature gradient. One can do this by immersing the atmosphere in a pulsar magnetosphere, and heating the atmosphere from above. High pressure atmospheres will also reduce the line contrast (Fig. 2). Strong magnetic fields, which surely exist but are not yet incorporated

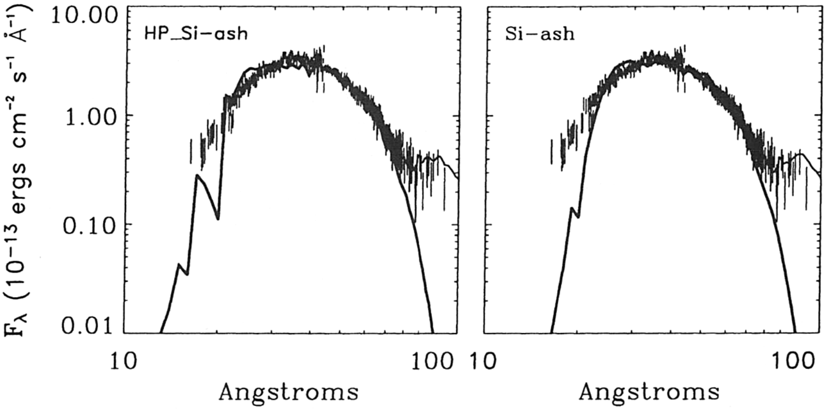

Figure 2. Comparison of high top pressure (10^{11} dynes cm^{-2}; left panel) and standard (right) Si-ash model atmospheric fits to the *Chandra* LETG spectrum. The high pressure atmospheres suppress the lines and edges, but not enough to make these fits acceptable.

into heavy element atmospheres, can broaden absorption lines, as can rapid rotation (although milli-second periods are required).

Lenzen & Trümper (1978) first suggested that neutron stars might have solid surfaces. The SED is essentially a dilute blackbody. Lai (2001) estimated the temperature below which the atmosphere will condense to be $27B_{12}^{2/5}$ eV for iron. If the magnetic field exceeds 10^{13} G, the surface of RX J1856 may be solid iron. Turolla, Zane & Drake (2004) have developed this idea. They show that emission from a solid Fe surface can indeed reproduce the X-ray blackbody.

A positive aspect of the solid surface models is that they naturally explain the lack of spectral features. These models do not naturally account for the optical excess. Burwitz et al. (2003) account for this with an energy-dependent absorption coefficient; Turolla et al. (2004) employ a layer of hydrogen which is optically thick in the optical, but thin in X-rays. These models are still in their infancy, and we can expect much progress in the near future.

Table 1. Radio-quiet isolated compact objects.

RX J	V (mag)	P (sec)	1.4-GHz Flux Limit (mJy)	kT (eV)	$\frac{f_{opt}}{f_X}$	Pulsed Fraction	Note
0420.0–5022	>25.5	22.7	—	57	—	0.43	
0720.4–3125	26.6	8.4	< 0.2	70	5	0.24	B mag.
0806.4–4132	—	11.4	< 0.05	94	—	0.06	
1308.6+2127	28.6	10.3	< 0.10	100	5	0.23	B mag.
1605.3+3249	26.8	—	—	92	14	<0.36	
2143.7+0654	>22	—	—	90	—	<0.30	
1856.5–3754	25.7	—	< 0.6	62	7	<0.013	

3. The RICOs

RX J1856 is not unique: it is the nearest and brightest of the RICOs (Table 1). All the RICOs have X-ray spectra that are well-characterized as blackbodies with 60 eV $< kT <$ 100 eV. All are very faint in the optical, but all that have been detected have modest optical excesses over the extrapolation of the X-ray blackbody. None have yet been detected as 1.4 GHz radio sources, although Malofeev, Malov & Teplykh (these proceedings) have reported detection of RX J1308.6+2127 at 100 MHz. Four have fairly long periods; two have insignificant upper limits to any pulsation amplitude.

4. Conclusions

One must be careful when claiming that a small object is a quark star, because size does not reveal all. For masses between 1 and 2 $M_\odot$, self-bound strange stars have radii $R > 10$ km (Lattimer & Prakash 2001), not much smaller than "normal" neutron stars. While the single-component blackbody fits to the X-ray data indeed yield very small radii, they do not account for the optical flux. All the models which account for the optical excess yield much larger radii, from ~16 km for a simple two-component blackbody fit, to as much as 15–18 km for heavy element atmospheres or as little as 9–14 km for a solid surface. These radii are perfectly consistent with the predicted 11–20 km radii of neutron stars and of hybrid stars with strange matter cores. As less exotic physics can also explain the lack of spectral features, we conclude that there is no evidence that RX J1856 is a self-bound strange quark star.

RX J1856 differs from the other RICOs only in its extraordinary lack of variability. This can be explained away by fortuitous geometry: either a coaligned rotator, or one whose rotation axis points near the Earth, should not appear as a pulsar. It is not yet clear how to explain the SED of any of the RICOs. Neither the heavy element atmospheres nor the solid surfaces are yet satisfactory.

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