RCW 103 – Revisiting a cooling neutron star

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ABSTRACT

Recent observations of the compact source embedded within the supernova remnant RCW 103 rekindle interest in the origin of this object’s emission. We contrast several models in which neutron-star cooling powers RCW 103. Specifically, either the presence of an accreted envelope or a sufficiently intense magnetic field can account for the X-ray emission from this object.

Subject headings: stars: neutron — stars: magnetic fields — radiative transfer — X-rays: stars

1. Introduction

Soon after the X-ray source 1E 161348-5055 was first detected by the Einstein observatory (Tuohy & Garmire 1980) near the center of the supernova remnant (SNR) RCW 103, Tuohy et al. (1983) proposed that this source is an isolated neutron star emitting thermal radiation. Optical and radio observations have failed to identify a counterpart (Tuohy & Garmire 1980; Tuohy et al. 1983; Dickel et al. 1996; Kaspi et al. 1996), bolstering the interpretation of this source as an isolated neutron star. Subsequent X-ray observations with Einstein and ROSAT have not all confirmed the initial detection (Tuohy & Garmire 1980; Becker & Trümper 1993).

Using recent observations of 1E 161348-5055 with the ASCA observatory and archival data from ROSAT, Gotthelf, Petre & Hwang (1997) verify the existence of this source and refocus attention on the interpretation of its emission. After subtracting a model for the emission of the surrounding SNR, Gotthelf, Petre & Hwang (1997) find that the point source spectrum is well described by a blackbody having a characteristic temperature $kT = 0.6$ keV and a flux of $6 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$. Estimates of the distance to RCW 103 vary from 3.3 kpc (Caswell et al. 1975) to 6.6 kpc (Leibowitz & Danziger 1983). Combining these values yields an estimated luminosity of $8d_{3.3}^2 \times 10^{33}$ erg s$^{-1}$ and an effective emitting area of $7d_{3.3}^2 \times 10^{10}$ cm$^2$ where $d_{3.3}$ is the ratio of the true distance to the X-ray source to 3.3 kpc. This is less than a percent of the total surface area of a neutron star. So, unless the emission originates from a tiny hotspot, a blackbody cannot account for the emergent spectrum. Gotthelf, Petre & Hwang (1997) also find no periodic variation in the flux greater than 13 % of the mean count rate. Variation of this order or larger would be expected from a rotating neutron star emitting from a small portion of its surface unless the hot spot coincides with the rotation axis, the object’s period is outside the range explored, or gravitational defocusing smooths the periodic signal.

Several models for this object have been proposed since its discovery. Gotthelf, Petre & Hwang (1997) argue that the object is unlikely to be a cooling neutron star, a plerion, or a neutron star with an ordinary
The dismissal of these models prompted Popov (1997) to argue that the emission from 1E 161348-5055 is powered by accretion onto a neutron star in a binary with another compact object. Unless the magnetic field of the neutron star is exceptionally weak ($B < 10^8$ G), it will channel the accreted material onto the polar caps producing hotspots and variability. For an apparently young object to have such a weak field, he argues that the neutron star is not coeval with the remnant, but that the remnant resulted from the supernova of the binary companion.

In this Letter, we revisit models of 1E 161348-5055 which account for its emission through neutron star cooling. In the first, a neutron star cooling through an accreted envelope naturally results in a spectrum which greatly departs from a blackbody. The second model, an ultramagnetized cooling neutron star, results in anisotropic emission from a hotspot with a spectrum which qualitatively resembles a blackbody.

2. Analytic Models

The insulating envelope of a neutron star may be modeled analytically if the magnetic field is sufficiently strong or weak. We use the models of Hernquist & Applegate (1984) to describe the heat transport through an unmagnetized hydrogen envelope. The ultramagnetized models of Heyl & Hernquist (1997a) describe the relationship between core temperature and transmitted flux for ultramagnetized envelopes ($B > 10^{15}$ G). For such intense magnetic fields, these analytic models agree well with fully numerical calculations (Heyl & Hernquist 1998). Both sets of calculations adopt a plane parallel approximation to solve the thermal structure equation in the envelope and assume that the passage from the non-degenerate to the degenerate regime is abrupt.

The equations are solved from the surface toward the core using a zero flux boundary condition (Schwarzschild 1965). The core temperature is a function of the combination $F/g_s$ and $\psi$ (in the magnetized case). Here, $F$ is the transmitted heat flux, $g_s$ is the surface gravity, and $\psi$ is the angle between the radial and field directions, and all of these values are taken to be in the frame of the neutron star surface. In the zero field limit, the models are independent of angle and in the ultramagnetized limit $F/g_s \propto \cos^2 \psi$ for a fixed core temperature.

2.1. An Accreted Envelope

As a baseline model, we consider a neutron star that has accreted sufficient unprocessed material since its birth to have a light-element envelope. We consider a hydrogen layer which extends all the way down to a density $\rho \sim 10^{10}$ g cm$^{-3}$. The total mass of accreted hydrogen would be $\sim 10^{-8}$M$_\odot$ (Heyl & Hernquist 1997b).

To obtain the core temperature as a function of transmitted flux, we recalculate the models of Hernquist & Applegate (1984) with the atomic number ($Z$) and weight ($A$) equal to unity. Since Hernquist & Applegate (1984) examine iron envelopes for which $Z + 1 \approx Z$, we have to make several alterations to their results to account for the pressure contributed by the ions in the non-degenerate regime.

Specifically, if the conductivity has a power-law form,

$$\kappa = \kappa_0 \frac{T^\beta}{\rho^\alpha},$$

(1)
then the relation of temperature to density in the non-degenerate regime follows a solution such that the conductivity is a constant

\[ \kappa = \frac{\alpha + \beta F(Z + 1)k}{\alpha g_s Am_p}. \]  

(2)

The relationship between \( T \) and \( \rho \) takes the form,

\[ T = \left( \frac{\alpha + \beta F(Z + 1)k}{\alpha g_s Am_p} \right)^{1/\beta} \rho^{\alpha/\beta}. \]  

(3)

We assume that free-free scattering dominates the opacity through the non-degenerate portion of the envelope; consequently,

\[ \alpha = 2, \beta = \frac{13}{2}, \kappa_0 = \frac{16\sigma}{3}m_u \frac{196.5 A^2}{24.59 Z^2} \frac{g}{cm^5 K^{7/2}}. \]  

(4)

Since electrons dominate the pressure in the degenerate regime, we use equations (2.22) through (2.29) of Hernquist & Applegate (1984) without alteration to determine the core temperature given the temperature at the onset of degeneracy calculated using Equation 3. The more detailed unmagnetized models of Potekhin, Chabrier & Yakovlev (1997) show that neutron stars with partially accreted envelopes exhibit cooling evolution between that of objects with fully accreted envelopes and standard cooling scenarios.

### 2.2. An Ultramagnetized Iron Envelope

We use the calculations for ultramagnetized iron envelopes described in Heyl & Hernquist (1997a). As in the unmagnetized case, we assume that free-free scattering dominates the opacity in the non-degenerate regime. However, we apply an anisotropy factor to account for the effect of the magnetic field on the scattering rates. We use the results of Pavlov & Panov (1976) and Silant’ev & Yakovlev (1980) to estimate this effect.

In the degenerate regime, we proceed analytically to a density where the first Landau level fills. Below this density, the relationship between chemical potential and density is analytically invertible in the fully degenerate limit; consequently, for an iron envelope with \( B = 10^{16} \) G, we can analytically integrate the structure equations up to a density of \( 1.5 \times 10^{10} g \text{ cm}^{-3} \) using the conductivities for the liquid and solid phases presented by Hernquist (1984). For the magnetized envelopes the emission is anisotropic along the surface. The average flux over the entire surface is a factor of 0.4765 times its peak value at the magnetic poles (Heyl & Hernquist 1997a).

With each of these models we determine the relationship between \( T_\text{eff} \) and \( T_c \) for \( 10^5K<T_\text{eff}<10^7K \) and calculate the cooling curves as described in Heyl & Hernquist (1997c). Figure 1 traces the cooling evolution for both ultramagnetized and unmagnetized iron envelopes, and unmagnetized hydrogen envelopes. We find that an intense magnetic field increases the emitted flux from a neutron star at a given time during the neutrino-cooling epoch by an amount sufficient to account for the observed luminosity of the point source in RCW 103 of \( \sim 10^{34} \) erg s\(^{-1} \), if the neutron star is approximately 1,000 years old. This age estimate is consistent with the observations of the remnant (Tuohy et al. 1973, Nugent et al. 1984, Carter, Dickel & Bomans 1997). However, the effective temperature, \( kT = 0.2 \) keV, falls short of the observed characteristic blackbody temperature of 0.6 keV.
The presence of a fully accreted envelope dramatically increases the effective temperature for a given core temperature. For a 1,000-year-old neutron star the effective temperature \( kT = 0.3 \) keV is only a factor of two below that observed. The total luminosity is \( \sim 10^{35} \text{ erg s}^{-1} \), greatly exceeding that observed.

Due to gravitational fractionation, a neutron star which has accreted any hydrogen will have a hydrogen atmosphere. The presence of a hydrogen atmosphere shifts the emission blueward from that of a blackbody.

### 2.3. Analytic power-law atmosphere

In the LTE structure and NLTE spectrum formation limit of studying an atmosphere, it is straightforward to derive the spectrum for power-law conductivities. In general the conductivity and its associated opacities are given by

\[
\kappa = \kappa_0 \frac{T^\beta}{\rho}, \tilde{\kappa} = \frac{16\pi T^3}{3 \rho} \text{ and } \tilde{\kappa}_E = f(\gamma) \left( \frac{E}{kT} \right)^{-\gamma},
\]

where \( \tilde{\kappa}_E \) is the opacity as function of photon energy and \( f(\gamma) \) is obtained by calculating the Rosseland mean

\[
f(\gamma) = \int_0^\infty \frac{\partial B}{\partial T} \left( \frac{E}{kT} \right)^\gamma \frac{dE}{dE} = \frac{15}{4\pi^4} \int_0^\infty \frac{x^4 e^{x} x^\gamma}{(e^x - 1)^2} dx
\]

where \( B(E) \) is the Planck function for the intensity of blackbody radiation.

We know that along a solution to LTE structure equations \( dT/dz = F/\kappa \) where both \( F \) the flux and \( \kappa \) are constant. The optical depth at a given energy is given by

\[
\tau(E,T) = \int_0^z \tilde{\kappa}_E \rho dz = \int_0^T \tilde{\kappa}_E \frac{\kappa}{\rho} dT' = \int_0^T \frac{16}{3} \frac{T^{\beta+\gamma}}{T^\text{eff}} f(\gamma) T^\gamma dT' = f(\gamma) \left( \frac{T}{T^\text{eff}} \right) \left( \frac{T_E}{T} \right)^{-\gamma} \left( \frac{T_E}{T} \right)^{4 + \gamma}.
\]

where we have changed variables, assuming the radiative zero solution, and substituted for \( \tilde{\kappa}_E \) and \( F = \sigma T^4 \text{eff} \). We define \( T_E = E/k \).

In the limit of a blackbody atmosphere, we have \( \gamma = 0 \), \( f(\gamma) = 1 \), and \( T = T^\text{eff} \) where the spectrum forms, therefore we take \( \tau = 4/3 \) to determine the temperature at which photons of a given energy have their effective photosphere. After some rearrangement we obtain,

\[
\frac{T^\text{atm}}{T^\text{eff}} = f(\gamma) \left( \frac{4}{4 + \gamma} \right)^{-1/(4+\gamma)} \left( \frac{T_E}{T^\text{eff}} \right)^{\gamma/(4+\gamma)}.
\]

To calculate the spectrum, we make the following three assumptions

1. The Rosseland mean opacity is unaffected even though the spectrum diverges from a blackbody through the atmosphere,

2. If the optical depth for a photon of a given energy to escape to infinity is less than 4/3, it is completely free, and

3. If the optical depth is greater than or equal to 4/3, the photon is drawn from a blackbody distribution at the appropriate temperature.
At each layer of the atmosphere, flux conservation is imposed by scaling the blackbody contribution to the flux such that the total flux is equal to $\sigma T_{\text{eff}}^4$. With this prescription, it is straightforward to derive the emergent spectra as depicted in left panel of Figure 2. Even in this simple model, we find that an energy dependent opacity can shift the emergent spectra blueward of a blackbody. We find for $\gamma = 3$, appropriate for free-free scattering (Kippenhahn & Weigert 1990) that the peak is shifted blueward by nearly 40%, which would result in an underestimate of the emission region by a factor of about four.

To understand the dependence of the models on the first assumption, we can calculate the function $f(\gamma)$ using the emergent spectrum rather than a blackbody. By iterating from five to ten times, we find the appropriate values of $f(\gamma)$ to within one part per thousand. These iterated spectra are depicted in the right panel of Figure 2. For all values of $\gamma$ the blueward shift is less pronounced than in the direct prescription. For example for $\gamma = 3$, the peak is shifted blueward by 25%, which would result in an underestimate of the emitting area by a factor of 2.5. A self-consistent power-law atmosphere would require a recalculation of the mean opacity at each depth of the atmosphere. Within the model, according to assumptions (2) and (3), the spectrum at a given depth consists partly of a blackbody and partly of the emergent spectrum; therefore, we expect that a spectrum calculated self-consistently throughout the atmosphere would fall between these two limiting cases.

More detailed modeling of hydrogen atmospheres supports our conclusions. As shown in Figure 2, this effect is even more pronounced when one examines the detailed calculations of Zavlin, Pavlov & Shibanov (1996). They find that if one fits a blackbody to the emergent hydrogen spectrum one will overestimate the effective temperature by an even larger factor, $\sim 4.2$, than found in our models. Consequently, an ultramagnetized neutron star with an iron envelope and a hydrogen atmosphere can account for both the observed flux and characteristic temperature of 1E 161348-5055.

3. Conclusions

We find that a young neutron star cooling through a strongly magnetized or a partially accreted envelope can account for the observed emission from 1E 161348-5055. The detailed models of Potekhin, Chabrier & Yakovlev (1997) support the conclusions that we have found analytically in this Letter. Furthermore, the estimates of the emitting area of 1E 161348-5055 support the conclusion that the spectrum from this object is significantly harder than a blackbody and possibly results from emission through a hydrogen atmosphere.

The recent discovery by Torii et al. (1998) of a 60-ms X-ray pulsar (J161730-505505) in the vicinity of SNR RCW 103 complicates the evaluation of the possible models. It has a spin-down age of $8.1 \times 10^3$ yr, several times larger than that of the remnant. Torii et al. (1998) examine the possibility that the X-ray pulsar is associated with the remnant, and find that a kick velocity of $1300d_{3.3}^{-1}s_{-1}^{-1}$ km s$^{-1}$ is required to explain its current position relative to the center of the supernova remnant. Such a large supernova kick velocity is uncommon but has been observed for other pulsars (Lyne & Lorimer 1994). However, when this object is compared with other similar rotation-powered, plerionic pulsars, it is a factor of ten underluminous. We would argue with Gotthelf, Petre & Hwang (1997) that this source is a heavily absorbed background object, possibly a rotation-powered, plerionic pulsar as Torii et al. (1998) suggest but located at a distance $\sim 10$ kpc. A reanalysis of the spectrum studied by Torii et al. (1998) may be able to determine the interstellar column density to J161730-505505 and verify its status as a background source.

Gotthelf, Petre & Hwang (1997) failed to find flux variations at a level of 13% over a wide range of
periods. Although the total flux from a magnetized neutron star may not vary at this level because of gravitational defocussing (e.g. [Heyl & Hernquist 1997]), the magnetic field causes the atmospheric emission to be highly anisotropic (Shibanov et al. 1995; Rajagopal, Romani & Miller 1997), so its apparent lack of variability may indicate that it is only weakly magnetized ($B \sim 10^{11}$ G) or simply that the geometry is not conducive to large flux variations. Observations of this object with AXAF should be able to distinguish between these models by determining the spectral shape of 1E 161348-5055.

We argue that the X-ray source in the supernova remnant RCW 103 is simply the natural end product of stellar evolution through a supernova: an isolated, cooling neutron star.

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Fig. 1.— The cooling evolution calculated analytically for iron and hydrogen envelopes. The results for unmagnetized iron envelopes are taken from Hernquist & Applegate (1984). The upper cross-hatched region shows the fitted blackbody temperature of 1E 161348-5055 and the acceptable range in age from 1,000 to 3,000 years. The lower shaded region depicts the luminosity of the object estimated from observations.
Fig. 2.— Emergent spectra from the power-law atmospheres. The left panel shows the direct calculation, and the right depicts the iterated results. The solid line traces a blackbody spectrum, the dotted line is for a $\gamma = 1$ opacity, the short-dashed line is $\gamma = 2$, and the long-dashed line is $\gamma = 3$. The heavy solid line shows results for a hydrogen atmosphere with $T_{\text{eff}} = 10^{6.5}$ K and $g_s = 2.43 \times 10^{14}$ cm s$^{-2}$ from Zavlin, Pavlov & Shibanov (1996).