On the nature of the compact X-ray source inside RCW 103

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Abstract

I discuss the nature of the compact X-ray source inside the supernova remnant RCW 103. Several models, based on the accretion onto a compact object such as a neutron star or a black hole (isolated or binary), are analyzed. I show that it is more likely that the X-ray source is an accreting neutron star than an accreting black hole. I also argue that models of a binary system with an old accreting neutron star are most favored.

1 Introduction

It is generally accepted that most of neutron stars (NSs) and black holes (BHs) are the products of supernova (SN) explosions (although there is also a possibility of a "quiet collapse"). In some cases a supernova remnant (SNR) appears after a *formidable* explosion of a massive star. Although a young NS is often observed inside a SNR as a radio pulsar (e.g., Crab, Vela, etc.), in most cases no compact object is found inside a SNR, or an accidential coincidence of the radio pulsar and the SNR is very likely (e.g., Kaspi 1996; Frail 1997).

Recently, Gotthelf et al. (1997) found a compact X-ray source inside the SNR RCW 103 with the X-ray luminosity $L_x \sim 10^{34}\, erg/s$ (for the distance $3.3\, kpc$) and the black-body temperature about $0.6\, keV$. The nature of the compact source is unclear. No radio or optical compact counterpart was observed. Here, I discuss possible models of that compact source.

2 What is inside the RCW 103?

Gotthelf et al. (1997) discussed why the source cannot be a cooling NS, a plerion, or a binary with a normal companion. The reader is referred to their paper for the details. In the present analysis I assume that the X-ray luminosity of the source is produced due to accretion of the surrounding material onto a compact object (a NS or a BH). I analyse thus only models with compact objects, isolated or with compact companions. Massive normal companions are excluded by optical observations. If the companion is a low-mass star, it is difficult to explain the X-ray luminosity as high as observed in the RCW 103 because in low-mass systems accretion usually occurs after the Roche lobe is overflowed with higher luminosities.

The main challenge for the models of accretion of the surrounding material is to answer the question of where the compact object finds enough matter to accrete. I don't discuss it here, assuming that the material is available in the surrounding medium.

2.1 Accreting isolated young black hole or accreting old black hole in pair with a young compact object

An isolated BH accreting the interstellar medium can be, in principle, observed by X-ray satellities such as $ROSAT$, $ASCA$ etc (Heckler & Kolb 1996). Using the fact that neither radio pulsar nor X-ray pulsations are actually observed in the case of RCW 103, one can argue that after the SN explosion a BH is formed more likely than a NS. We then can explain why a compact X-ray source inside a SNR without a radio pulsar are rare: the BHs are born by the most massive stars, and so BHs are an order of magnitude less abundant than the NSs.

To achieve high X-ray luminosity, a compact object must move with a relatively low velocity (the Bondi's formula):

$$\dot{M} = 2\pi \left(\frac{(GM)^2 \rho}{(V_s^2 + V^2)^{3/2}} \right), \tag{1}$$

where V_s is the speed of sound, V is the velocity of the compact object with respect to the ambient medium, $M-$ the mass of the accreting star and ρ is the density of the accreting material. One can introduce the effective velocity, V_{eff}, and rewrite eq. (1) as follows:

$$\dot{M} = 2\pi \left(\frac{(GM)^2 \rho}{V_{eff}^3} \right).$$

The effective velocity cannot be much lower than $10\,km/s$, which corresponds to the sound speed in the ISM with the temperature of $\sim 10^4\,K$. I will therefore use this value of the velocity, $10\,km/s$, because the luminosity is high for an isolated object, and with the lower velocity much higher density of the surrounding medium is required.

During the SN explosions a compact object can obtain an additional kick velocity. The value and the distribution of the kick velocity is not known well enough (e.g., Lipunov et al. 1996). Although observations of radio pulsars favour high kick velocities about $300 - 500\,km/s$ (Lyne & Lorimer 1994), alternative scenarios in which the velocity increases after the SN explodes are possible (Kaspi 1996; Frail 1997). The most popular scenarios usually predict the mean kick velocities to be much higher than $10\,km/s$.

To explain the observed X-ray luminosity of the compact object inside RCW 103 the accretion rate, $\dot{M}$, should be about $10^{14}\,g/s$ (assuming that one gramm of accreted material produces $10^{20} erg$). For all models that consider accretion onto an isolated compact object, the density required to obtain $L_x \sim 10^{34}\, erg/s$ is as high as $10^{-22}\, g/cm^3$.

One can then estimate the size of the emmiting region, using observed luminosity and temperature:

$$L = 4\pi \cdot R_{emm}^2 \sigma T^4$$

For observed values of L_x and T this equation gives $R_{emm} \sim 0.9\, km$. For BHs such a low value of R_{emm} is very unlikely because the gravitational radius is about $R_G \sim 3\, km\, (M/M_\odot)$. Also, the efficiency of spherically symmetric accretion onto a BH is very low resulting in a significantly higher density required to achieve the same luminosity. This is probably the main argument against isolated accreting black hole as a model for the RCW 103.

The same argument can be used against models with a binary system: BH+BH (BH is born in the recent SN explosion) and BH+NS (NS is born in the recent SN explosion and the pulsar is not observed due, for example, to unfortunate orientation), or against models in which no compact remnant survives after the recent SN explosion of the massive star in a binary system with a BH as a companion.

In the next subsections I present more viable models with accreting NS.

2.2 Accreting isolated young neutron star

In the past few years isolated accreting NSs have become a subject of great interest due to the new observations by the *ROSAT* satellite (Treves & Colpi, 1991; Walter et al. 1996; Haberl et al. 1996). In this subsection I will present an argument that the compact X-ray source in RCW 103 can be an isolated accreting NS and will estimate some properties of that NS.

There are four main possible stages for a NS in a low-density plasma: 1). Ejector (or a radio pulsar); 2). Propeller; 3). Accretor; and 4). Georotator (Lipunov & Popov 1995; Konenkov & Popov 1997). The stage is determined by the accretion rate, $\dot{M}$, the magnetic field of the NS, B, and by the spin period of the NS, p.

If the NS is in the Accretor stage, then its period is longer than the accretor period, P_A:

$$P_A = 2^{5/14} \pi\, (GM)^{-5/7} (\mu^2/\dot{M})^{3/7}\, sec, \tag{2}$$

where $\mu = B \cdot R_{NS}^3$ is magnetic moment of the NS.

For the RCW 103 I use the following values: $\dot{M} = 10^{14}\, g/s$, $M = 1.4\, M_\odot$, $R_{NS} = 10^6\, cm$ which give:

$$B \sim 10^{10} \cdot p^{7/6}\, G. \tag{3}$$

This critical line for this period (eq. 2), P_A, is shown in the Figure 1. The region below the line is allowed for accreting NS.

If material is accreted from the turbulent interstellar medium, a new equilibrium period can occur (Konenkov & Popov 1997):

$$P_{eq} \sim 30\, B_{12}^{2/3} I_{45}^{1/3} \dot{M}_{14}^{-2/3} R_{NS_6}^2 V_{eff_6}^{7/3} V_{t_6}^{-2/3} M_{1.4}^{-4/3}\, sec, \tag{4}$$

where V_t is the turbulent velocity (all velocities are in units of $10\, km/s$); $M_{1.4}$ is the mass of the NS in units of $1.4\, M_\odot$, B_{12} is the magnetic field of the NS in unites $10^{12}\, G$ and R_{NS} is the radius of the NS in units of $10^6\, cm$.

We then obtain:

$$B \sim 8 \cdot 10^9 \cdot p^{3/2}\, G. \tag{5}$$

The corresponding critical line for the equilibrium period (eq. 4) is also shown in the Figure 1.

It is obvious from the Figure 1 that to explain the luminosity of the RCW 103 by an isolated accreting NS, one must assume that the NS was born with extremely low magnetic field or with unusually long spin period. The age of the SNR RCW 103 is about 1000 years (Gotthelf et al., 1997), which means that magnetic field could not decay significantly (Konenkov & Popov 1997). Thus, the model with isolated young accreting NS is not a likely explanation for the data.

2.3 Accreting old neutron star in pair with a young neutron star or a young black hole

Binary compact objects are natural products of binary evolution (Lipunov et al. 1996). One can, therefore, discuss these scenarios as a viable alternative.

In the previous subsection I showed that accretion onto a young isolated neutron star requires unusual initial parameters. However, there is a chance that we observe a binary system, where one component is an old neutron star and the other component (a NS or a BH) was formed in a recent SN explosion (or there was no remnant at all).

In that case, the parameters determined by eqs.(3), (5) are not unusual: old NS can have low magnetic fields and long periods. Due to the fact that Gotthelf et al. (1997) did not find any periodic change of the luminosity, one can argue that the field is too low to produce the observable modulation (the accreting material is not channeled to the polar caps: $B < 10^6\, G$) or that the period is very long ($p > 10^4\, sec$), which is contrary to what is expected (Lipunov & Popov 1995).

The evolutionary scenario for such a system is clear enough (Lipunov et al., 1996). One can easily calculate it using the "Scenario Machine" WWW-facility (**http://xray.sai.msu.su/sciwork/scenario.html**; Nazin et al. 1996). For example, two stars with masses $15\, M_\odot$ and $14\, M_\odot$ on the main sequence with the initial separation $200\,R_\odot$, $R_\odot$ – the solar radius, after 14 Myr (with two SN explosions with low kick velocities: about $60\,km/s$) end their evolution as a binary system NS+NS. The second NS is 1 Myr younger. During 1 Myr the magnetic field can decrease up to 1/100 of the initial value with a significant spin-down (Konenkov & Popov, 1997). The binary NS+NS is relatively wide: $20\,R_\odot$ with an orbital period 5.8^d, so the orbital velocity is not high (the orbital velocity of the accreting NS should be added to V_{eff}).

Young NS can be unobsereved as a radiopulsar due to several reasons. The simplest one is the effect of orientation.

3 Conclusions

To conclude, I argued that the most likely model for the RCW 103 is that of an accreting old NS in a binary system with a young compact object born in the recent SN explosion that produced the observed supernova remnant (or no remnant survived after the explosion). Such systems a rare, but natural products of the binary evolution. Scenarios with single compact objects or with accreting BH are less probable.

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