Nature of the compact X-ray source in supernova remnant RCW103 and related problems

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Abstract. I discuss the nature of the compact X-ray source in the center of the supernova remnant RCW 103. Several models, based on the accretion onto a compact object are analyzed. I show that it is more likely that the central X-ray source is an accreting neutron star than an accreting black hole. I also argue that models of a disrupted binary system consisting of an old accreting neutron star and a new one observed as a 69-ms pulsar are most favored.

Keywords: neutron stars, supernova remnants

1. Introduction

Among all astrophysical objects neutron stars (NSs) and black holes (BHs) attract most attention of physicists. Now we know more than 1000 NSs as radio pulsars and more than 100 NSs emitting X- or/and γ-rays. The Galactic population of these objects is much larger: about $10^8 - 10^9$.

It is generally accepted that NSs and BHs are the products of supernova (SN) explosions. In most cases a supernova remnant (SNR) appears after a *formidable* explosion of a massive star (with $M > 10 - 35 M_{\odot}$). Although sometimes a young NS is observed inside a SNR as a radio pulsar (e.g., Crab, Vela, etc.) or as a X-ray source, in most cases no compact object is found inside a SNR, or an accidental coincidence of the radio pulsar and the SNR is very likely (e.g., (Kaspi, 1998); (Frail, 1997)).

It is possible, that about 50% of NSs are born with low magnetic fields, so they never appear as radio pulsars and spend most of their lives on the Ejector and Propeller stages. These NSs with low magnetic fields can not spin-down significantly even during the Hubble time. For high-velocity NSs the characteristic Ejector period is higher, and NSs spend most of their lives as Ejectors.

Recently, Gotthelf et al. described a compact X-ray source in the center of SNR RCW 103 with the X-ray luminosity $L_x \sim 10^{34}\,\mathrm{erg\,s^{-1}}$ (for the distance 3.3 kpc) and the black-body temperature about 0.6 keV. The source flux has varied since previous observations (Petre and Gotthelf, 1999). The nature of the central compact source is unclear. No radio or optical compact counterpart was observed. Also a 69-ms X-ray and radio pulsar with a characteristic age about 8 kyr was discovered 7' from the center of the remnant (Kaspi, 1998), but the reality of the association of the pulsar with the SNR is unclear (Dickel and Carter, 1999).

Here I discuss possible models of that compact central source and its possible connections with the 69-ms pulsar (see some preliminary results in (Popov, 1998a)).

2. What is inside the RCW 103?

Gotthelf et al. 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 analyze thus only models with compact objects, isolated or with a compact companion (most probably the binary system was destroyed after the second explosion, when the 69-ms pulsar was formed).

The main challenge for the models of accretion of the surrounding material onto isolated compact object is to answer the question of where a NS or a BH finds enough matter to accrete. I don't discuss it here, assuming that the material is available in the surrounding medium (see, for example, (Page et al., 1999)).

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 satellites such as $ROSAT$, $ASCA$ etc. (Heckler and Kolb, 1996). To achieve high X-ray luminosity, a compact object must move with a low velocity relative the ISM:

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

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:

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

During the SN explosions a compact object can obtain an additional kick velocity. At the present time the distribution of the kick velocity is not known well enough (e.g., (Lipunov et al., 1996)). Although observations of radio pulsars favor high kick velocities about $300-500\,\mathrm{km\,s^{-1}}$ (Lyne and Lorimer, 1994). We mark here, that if the 69-ms pulsar is a new born NS, and the central source is the older object, it is not surprising, that the 69-ms pulsar is farther from the center of the SNR. Because the new born NS received a high kick velocity and the old one only saved its orbital velocity, because the system survived in the first explosion. X-ray radiation of the new born NS of course doesn't have the accretion nature.

To explain the observed X-ray luminosity of the compact object in the center of RCW 103 the accretion rate, $\dot{M}$, should be about $10^{14}\,\mathrm{g\,s^{-1}}$.

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 $R_{emm} \sim 1\,\mathrm{km}$. For BHs such a low value of R_{emm} is very unlikely because the gravitational radius is about $R_G \sim 3\,\mathrm{km}\,(M/M_\odot)$, and most of the present BH-candidates have masses about $7-10 M_\odot$. This is probably the main argument against isolated accreting BH as a model for the RCW 103. 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. The same arguments can be used against models with a binary system (probably disrupted): BH+NS (NS was born in the recent SN explosion – a 69-ms pulsar).

2.2. Young isolated accreting neutron star

In the past few years isolated accreting NSs have become a subject of great interest especially due to the observations with the *ROSAT* satellite.

There are four main possible stages for a NS in a low-density plasma: 1). Ejector (a radio pulsar is an example of Ejector); 2). Propeller; 3). Accretor; and 4). Georotator ((Lipunov and Popov, 1995); (Konenkov and 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 on the Accretor stage, then its period is longer than the so-called Accretor period, P_A:

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

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

For the RCW 103 I use the following values: $\dot{M} = 10^{14}\,\mathrm{g\,s^{-1}}$, $M = 1.4\,M_\odot$, $R_{NS} = 10^6\,\mathrm{cm}$ which give:

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

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

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

where V_t is the turbulent velocity (all velocities are in units of $10\,\mathrm{km\,s^{-1}}$); $M_{1.4}$ is the mass of the NS in units of $1.4\,M_{\odot}$, B_{12} is the magnetic field of the NS in unites $10^{12}\,\mathrm{G}$ and R_{NS} is the radius of the NS in units of $10^6\,\mathrm{cm}$.

We then obtain:

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

It is obvious 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 the magnetic field could not decay significantly (Konenkov and Popov, 1997). The flux of the source is not constant (Petre and Gotthelf, 1999), so the idea of cooling NS can be rejected. 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 in the disrupted system)

Binary compact objects are quite 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 NS requires unusual initial parameters. However, there is a chance that we observe a binary system (or a disrupted binary), where one component is an old NS and the other component was formed in a recent SN explosion and appears (for disrupted system) as a 69-ms pulsar.

In that case, the parameters determined by eqs.(3), (5) are not unusual: old NS can have low magnetic fields and long periods (Lipunov and Popov, 1995). Due to the fact that Gotthelf et al. 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: $B < 10^6\,\mathrm{G}$) or that the period is very long ($p > 10^4\,\mathrm{s}$), which is possible for old NSs with "normal" magnetic fields (Lipunov and Popov, 1995): $P \approx 500\,\mathrm{s}$. The last opportunity is, probably, better, as the emmiting area is not large $\approx 1\,\mathrm{km}^2$.

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 (Nazin et al., 1998). 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 $60\,\mathrm{km\,s^{-1}}$) end their evolution as a binary system NS+NS. The second NS is $\sim$ 1 Myr younger. During $\sim$ 1 Myr the magnetic field can decrease up to 1/100 of the initial value with a significant spin-down (Konenkov and 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}).

The 69-ms X-ray pulsing source and it's radio pulsar counterpart that were discovered near RCW 103 (Kaspi, 1998) can be a new-born radio pulsar. So, it means that the binary system was disrupted after the second explosion. It means that in the first explosion the kick velocity was small (about $50\,\mathrm{km\,s^{-1}}$ in the opposite case the system could be disrupted after the first explosion and the older NS could leave the SNR before the second explosion, but if the orbit was significantly eccentric, the kick velocity in the first explosion could be high too) and in the second explosion it was as high as $750 - 800\,\mathrm{km\,s^{-1}}$ for the same initial parameters as in the previous example.

Of course other variants of the initial parameters are possible, and I showed this one just as a simple example.

3. Conclusions

To conclude, I argued that the most likely model for the central compact X-ray source of RCW 103 is that of an accreting old NS in a disrupted binary system with a young compact object (the 69-ms pulsar) born in the recent SN explosion that produced the observed supernova remnant (some ideas about a disrupted binary in RCW 103 were also discussed in the article (Torii et al., 1998)). Such systems are rare, but natural products of the binary evolution. Scenarios with a single compact objects or with accreting BH are less probable.

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