# The Nature of the X-ray Source in SNR RCW 103

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## ABSTRACT

The discovery of the 6.67 hr periodicity in the X-ray source 1E 161348−5055 associated with the supernova remnant RCW 103 has raised interesting suggestions about the nature of the X-ray source. Here we argue that in either accreting neutron star or magnetar model, a supernova fallback disk may be a critical ingredient in theoretical interpretations of 1E 161348−5055. We further emphasize the effect of fallback disks on the evolution of young compact objects in various ways, and suggest that even SS 433 could also be powered by fallback disk accretion process.

*Subject headings:* stars: individual (1E 161348−5055, SS 433) – stars: neutron – supernova remnants – supernovae: individual (RCW 103)– X-rays: stars

## 1. Introduction

The enigmatic radio-quiet central compact objects discovered in supernova remnants (SNRs) have challenged conventional thoughts that most young neutron stars (NSs) evolve in a manner similar to Crab-like pulsars (see Pavlov, Sanwal, & Teter 2004; Kaspi, Roberts, & Harding 2006, for recent reviews). The X-ray source 1E 161348−5055 (hereinafter 1E1613), the prototype of the growing radio-quiet objects in SNRs, was first detected with *Einstein* as a faint, unresolved source located near the center of the SNR RCW 103 (Tuohy & Garmire 1980) with an age of $\sim$ 2000 yr (Nugent 1984) and distance of $\sim$ 3.3 kpc (Caswell et al. 1975). From X-ray observations with *ASCA*, Gotthelf, Petre, & Hwang (1997) found a compact X-ray source inside RCW 103 with the X-ray luminosity $L_{\rm X} \sim 10^{34}$ ergs$^{-1}$ and the black-body temperature about 0.6 keV. Further *ASCA* observation of 1E1613, together with archived *Einstein* and *ROSAT* data showed that this source manifested an order-of magnitude decrease in luminosity over four years (Gotthelf, Petre, & Vasisht 1999), suggesting that this object may be an accreting source rather a cooling NS. But no X-ray pulsations, radio or optical counter part were detected. From *Chandra* observations and archival *ASCA* data, Garmire et al. (2000) reported the $\sim 6$ hr periodicity of its flux. The lightcurve taken by *XMM-Newton* did not show the $\sim 6$ hr periodicity but discovered an eclipse about 3 hr (Becker & Aschenbach 2002). More recent observations with *XMM-Newton* showed a strong, unambiguous periodic modulation at $6.67 \pm 0.03$ hr (De Luca et al. 2006).

The origin of this period could be either an orbital or a spin period. In the former case 1E1613 would be a low-mass X-ray binary (LMXB) which survived the SN event; in the latter, 1E1613 could be an isolated magnetar with magnetic field of order $10^{15}$ G (De Luca et al. 2006). In each possibility the source remains to be peculiar and puzzling. In this *Letter*, we discuss the nature of the X-ray source 1E1613 and its implications for young compact objects, arguing that in both scenarios a fallback disk may be required to account for the observational characteristics of 1E1613. We further propose that fallback disks may play a critical role in the evolution of several kinds of young compact stars including the famous X-ray source SS 433. Throughout this study we assume that both 1E1613 and RCW 103 originated from the same SN event.

## 2. Accreting NS interpretation

The long term flux change suggests that 1E1613 may be an accreting source (Gotthelf, Petre, & Vasisht 1999). The lightcurve observed by *XMM-Newton* shows for the evidence of an eclipse, indicating 1E 1613 as a NS in a binary system (Becker & Aschenbach 2002). The possible companion should be less massive than $0.4\,M_{\odot}$, if it is a normal star, as indicated by optical/IR observations (Pavlov, Sanwal, & Teter 2004; Wang, Kaplan, & Chakrabarty 2007). Thus 1E1613 could be a young NS accreting from a low-mass companion star.

The LMXB interpretation meets many difficulties. One of them is the very low birthrate of LMXBs. It is well known that LMXBs are extremely rare objects, with a birthrate of $\lesssim 10^{-6}{-}10^{-7}\,\mathrm{yr}^{-1}$. The birthrate of 1E1613 as an LMXB would be even lower due to the very low initial mass of its companion - the progenitor binary is very likely to either merge during the previous common envelope evolution (Justham, Rappaport, & Podsiadlowski 2006), or be disrupted during the SN explosion (Brandt & Podsiadlowski 1995). This makes the probability to find an LMXB like 1E1613 inside a SNR extremely low. Moreover, if 1E1613 is indeed an LMXB, it is difficult to explain why there is few association between SNRs and intermediate- or high-mass X-ray binaries (HMXBs) in the Galaxy, which are more likely to form and to be observed. Only a single SNR-HMXB association (SS433 and the SNR W50, Geldzahler, Pauls, & Salter 1980) is known in the Galaxy (see discussion below).

Even if the LMXB can survive the common envelope evolution and the SN explosion, it will take at least $\sim 10^8 - 10^9$ yr for orbital decay so that Roche-lobe overflow from the companion starts (the companion star of mass $\sim 0.4\,M_\odot$ will take a time longer than the age of the Galaxy by nuclear evolution to fill the Roche-lobe). This timescale is in sharp contrast with the young age ($\sim$ 2000 yr) of the SNR RCW 103. De Luca et al. (2006) suggest that the LMXB may have a significant orbital eccentricity (due to the SN kick) and hence orbital modulation in the captured mass by the NS from the companion's wind. We note that the stellar wind mass loss rate for a $\lesssim 0.4\,M_\odot$ dwarf is as low as $\sim 10^{-15}\,M_\odot\,\mathrm{yr}^{-1}$, and obviously cannot power the X-ray luminosity ($\sim 10^{33} - 10^{35}\,\mathrm{ergs}^{-1}$) of 1E1613. Thus the wind from the donor star, if really relevant to the flux modulation, should be induced by X-ray irradiation from the NS. X-ray irradiation can affect stars of mass $< 1.5\,M_\odot$ under certain circumstances by ionizing the hydrogen at the base of the irradiated surface layer and disrupting the surface convection zone (Podsiadlowski 1991). According to Pfahl, Rappaport, & Podsiadlowski (2003), the maximum orbital period for which X-ray irradiation is important is

$$P_{\mathrm{orb,max}} \sim 70\,\mathrm{days}(\frac{\epsilon \dot{M}_{-8}}{S_{\mathrm{c},11}})^{3/4}, \tag{1}$$

where $\dot{M}_{-8}$ is the accretion rate onto the NS in units of $10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$, $S_{\mathrm{c},11}$ is the critical X-ray flux for hydrogen ionization in units of $10^{11}\,\mathrm{ergs}^{-1}\mathrm{cm}^{-2}$, and $\epsilon < 1$ is a factor that takes into account the geometry of the accretion disk and the star, the albedo of the star, and the fraction of X-rays that penetrate below the stellar photosphere (Hameury et al. 1993). Take $L_{\mathrm{X}} \sim 10^{34}\,\mathrm{ergs}^{-1}$ for 1E1613, Eq. (1) yields $P_{\mathrm{orb,max}} < 1.7$ hr, still smaller than the 6.67 hr period. However, if the orbit is highly eccentric, intensive winds might be excited by X-ray irradiation at periastron. Nevertheless, if future observations confirm the existence of the binary companion, it will have important impact on the current theories of NS formation.

In our opinion, perhaps it is more natural to assume that 1E1613 is a NS accreting from the fallback disk rather a low-mass companion. Current stellar evolution models predict that during the core collapse of massive stars, a considerable amount of the stellar material will fall back onto the compact, collapsed remnants (NSs or BHs), usually in the form of an accretion disk (e.g. Woosley 1993). This point of view is supported by the discovery of a remnant disk around the anomalous X-ray pulsar 4U 0142+61 (Wang, Chakrabarty, & Kaplan 2006). In this case one does not need to care about the age contrast in the low-mass donor and young SNR in the LMXB scenario. The lifetime of the fallback disks is around $10^4 - 10^5$ yr. During this time the mass supply may be sufficient to power the observed X-ray luminosity (Chattterjee, Hernquist, & Narayan 2000). The flux outbursts and dips in the light curve could be due to disk instabilities and occultations by disc structures, respectively (De Luca et al. 2006). The 6.67 hr periodicity might be related to the precession of the NS with a hot spot (Heyl & Hernquist 2002) or the disk itself (Katz 1973).

Popov (2007) suggested an interesting idea that 1E1613 could be in a double NS binary system, where the newborn NS which produced the SNR has a remnant disk around it, and the older NS, identified as 1E1613, accretes periodically from that disk when passing close to the companion. The situation here is similar to what happens in Be/X-ray binaries, in which a NS accretes from the disk-like winds from its Be companion star in an eccentric orbit. In the disk truncation model (Okazaki & Negueruela 2001; Okazaki et al. 2002) the X-ray outbursts in Be/X-ray binaries are explained as follows. The NS exerts a negative tidal torque on the viscous decretion disk of the Be star, resulting in the truncation of the disk. The disk matter would then accumulate in the outer rings of the disk until the truncation was overcome by the effects of global one-armed oscillations, disk warping, etc. The subsequent sudden infall of high-density disk matter onto the NS causes type II X-ray outbursts. If the tidal truncation is not very efficient and the disk extends beyond the Roche-lobe of the Be star at periastron, the matter could be accreted onto the NS during the periastron passage, resulting in (quasi-)periodic type I bursts. Calculations by Zhang, Li, & Wang (2004) have shown that the narrower the binary system, the more efficient the truncation, since the truncation efficiency $\propto P_{\rm orb}^{1/3}$. The orbital period (6.67 hr) of 1E1613, which is much smaller than those of Be/X-ray binaries, suggests that the flux variations in 1E1613 may be erratic rather periodic, if caused by the disk truncation effect.

One of the problems for all the accreting NS scenarios is that, to produce an accretion luminosity in the range observed, the NS would have a low magnetic field and/or a slow rotation period, i.e., $P \sim (0.35 - 2.5)B_{10}^{6/7}$ s, where $B_{10}$ is the NS magnetic field in units of $10^{10}$ G, so that the accreting material can overcome the centrifugal barrier (De Luca et al. 2006). Although these values seem to be peculiar if compared with the canonical values ($B \sim 10^{12}$ G and $P \sim 10 - 100$ ms) of young NSs, there is accumulating evidence for some NSs born spinning slowly and with a relatively weak magnetic field (Halpern et al. 2007; Gotthelf & Halpern 2007).

## 3. Magnetar interpretation

De Luca et al. (2006) favor the idea that 1E1613 may be a magnetar rotating at 6.67 hour with $B > 10^{15}$ G, as the X-ray variabilities, luminosity and spectral shape would be naturally explained in the magnetar frame. Even with such field a NS cannot spin down to 6.7 hours via magneto-dipole radiation (MDR) during the lifetime of the SNR. Therefore, a SN fallback disk is required to interact with the NS, providing additional propeller spin-down torque. Calculations by De Luca et al. (2006) show that a disk of $3 \times 10^{-5}\,M_\odot$ would have been enough to slow down, over 2000 years, a $B = 5 \times 10^{15}$ G magnetar to current period, provided that the initial spin period should be $P_{\rm i} \gtrsim 300$ ms. Magnetic field in magnetars is generally thought to be generated by turbulent dynamo, whose strength depends on the star's rotation rate (Duncan & Thompson 1992, see however, Vink & Kuiper 2006). Such a period seems to be too long for magnetars, although its possibility cannot be ruled out.

Additionally, the known magnetars include the anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs), which are rotating at $\sim 5 - 10$ s (Woods & Thompson 2006). If 1E1613 is a magnetar, one needs to explain why its period is much longer than those of AXPs and SGRs.

The mode of interaction between a NS and a surrounding disk is determined by the location of the inner radius $R_{\rm in}$ of the disk with respect to the characteristic radii, the corotation radius $R_{\rm c} = (GMP^2/4\pi^2)^{1/3}$, and the light cylinder radius $R_{\rm L} = cP/2\pi$, where $M$ is the mass of the NS (e.g. Illarionov & Sunyaev 1975; Lipunov 1992). The position of the inner radius of the disk can be estimated by comparing the electromagnetic energy density generated by the NS with the kinetic energy density of the disk. The NS is expected to be in the propeller and ejector (radio pulsar) stage if the inner radius of the disk is beyond the corotation and light cylinder radius, respectively. Since the kinetic energy density in the disk has the dependence $\propto r^{-5/2}$ on the radial distance $r$ from the center of the NS, steeper than the electromagnetic energy density (or radiation pressure) outside the light cylinder ($\propto r^{-2}$), stable equilibrium of the disk outside the light cylinder is not allowed, unless it is beyond the gravitational capture radius (Lipunov 1992).

In their calculations De Luca et al. (2006) have adopted the traditional estimates of the radiation pressure from a NS by employing a rotating magnetic dipole in vacuum to generate the electromagnetic fields. Recently Ekşi & Alpar (2005) derived the electromagnetic energy density from the global electromagnetic field solution of Deutsch (1955) for obliquely rotating magnetic dipoles. They showed that the electromagnetic energy density of a rotating dipole makes a rather broad transition for disk existence across the light cylinder for small inclination angles. *Within this model the disk could survive beyond the light cylinder even if the radio pulsar activity turns on.*

To examine to what extent the fallback disks affect the spin evolution of magnetars, we carried out Monte Carlo simulations of the evolution of $10^6$ NSs based on the spin-down model presented in Lipunov (1992, see also Li 2002). As the mass of a fallback disk is not replenished, mass flow rate in the disk declines and the inner radius of the disk moves out. The NS in this case generally passes three evolutionary stages. (1) First is the "ejector" phase, in which the radiative pressure from the NS is sufficient to keep the surrounding plasma away from the light cylinder; the NS evolves as a radio pulsar. Here we assume that once $R_{\rm in}/R_{\rm L} > x_{\rm cr}$, the gaseous disk is disrupted by the radiation pressure, and the NS is spun down only by MDR (here $x_{\rm cr} > 1$ is a parameter depending on the magnetic inclination, and is calculated according to Ekşi & Alpar 2005); if $1 < R_{\rm in}/R_{\rm L} < x_{\rm cr}$, the disk is still stable beyond $R_{\rm L}$, and MDR also works. (2) If $R_{\rm c} < R_{\rm in} < R_{\rm L}$, the "propeller" phase follows, in which the plasma interacts with the neutron star magnetosphere but further accretion is inhibited by the centrifugal barrier, and the disk exerts a propeller spin down torque on the NS. (3) For sufficiently long time of evolution, the NS will enter the "accretor" phase, in which the inner disk radius becomes smaller than the corotation radius and steady accretion of the plasma is allowed.

In our calculations the initial NS magnetic field $B$ is chosen from a log normal distribution of mean 15 and standard deviation 0.4. We assume that all NSs were born with a surrounding supernova fallback disk, the initial masses of which $\log(\Delta M/M_\odot)$ are distributed uniformly between $-6$ and $-2$. Mass flow rate through the disk is assumed to decline in a power law with time, $\dot{M} \propto t^{-1.25}$ (Cannizzo, Lee, & Goodman 1990; Francischelli, Wijers, & Brown 2002). We set the initial spin periods $P_{\rm i}$ and the inclination angle to be distributed uniformly between 2 ms and 50 ms, and between 0° and 90°, respectively. For the propeller torque, we adopt the expression $T_{\rm prop} = \dot{M}R_{\rm in}^2[\Omega_{\rm K}(R_{\rm in}) - \Omega_{\rm s}]$, where $\Omega_{\rm K}(R_{\rm in})$ is the Keplerian angular velocity at $R_{\rm in}$ and $\Omega_{\rm s}$ the angular velocity of the NS (see also Menou et al. 1999). We stop the calculations at a fiducial time of 2500 yr, to be compatible with the age of RCW 103.

In Fig. 1 we plot the histogram of the spin periods for the magnetars. The hatched regions indicate the propeller/accretor (+45°) and ejector (−45°) systems, respectively. It is noted that most ($\sim 99\%$)[1] of the magnetars are in the ejector state, having spin periods of a few seconds. These features are consistent with most of AXPs and SGRs, which occupy the majority of the magnetar family. The spin periods of the propeller/accretors, which consist of $\sim 0.6\%$ of the whole population, have a much broader distribution, peaking around a few of $10^3$ s. 1E1613 may belong to this latter group. In this case, the puzzling initial spin period $P \gtrsim 300$ ms does not appear.

## 4. Discussion

The above arguments suggest that in either accreting NS or magnetar interpretation, a SN fallback disk seems to be favored, to explain the observational characteristics of 1E1613. Especially we show that, in the more reasonable magnetar model, it is possible to model the spin period evolution in 1E1613 with typical values of the input parameters for a mag-

[1]The percentages presented here are subject to the uncertainties in the initial parameters and the spin-down mechanisms adopted, and should not be taken very seriously.

netar. This work emphasizes that fallback disks may considerably influence the formation and evolution of young compact objects evolved from core collapse of massive stars. The existence of fallback disks can be tested by searching for optical/IR emission from the cooler parts of the disk (Perna, Hernquist, & Narayan 2000; Wang, Chakrabarty, & Kaplan 2006). Recently Wang, Kaplan, & Chakrabarty (2007) reported on search for the optical/infrared counterparts to the central compact objects in four young SNRs including RCW 103, but found that there is confusion with several faint stars at the position of 1E1613.

The fallback disk may manifest itself in various ways. Recent X-ray observations show that some young pulsars, such as the Crab and Vela pulsars, may have the jet configuration, which suggests the existence of a disk surrounding the neutron star (Blackman & Perna 2004, and references therein). Such disks can influence the braking indices and timing ages of some young radio pulsars (Menou, Perna, & Hernquist 2001; Marsden, Lingenfelter, & Rothschild 2001; Jiang & Li 2005). A small group of rotating radio transients (RRATs) were recently reported by McLaughlin et al. (2006). These objects are characterized by single, dispersed bursts of radio emission with durations between 2 and 30 ms. Li (2006) suggested that these phenomena could be due to the interaction between the NS magnetosphere and the surrounding SN debris disk. The pattern of radio pulsar emission depends on whether the disk can penetrate the light cylinder and efficiently quench the processes of particle production and acceleration inside the magnetospheric gap; a precessing disk may naturally account for the switch-on/off behavior in PSR B1931+24 (Kramer et al. 2006). Cordes & Shannon (2006) also proposed that the bursty emission by RRATs is due to a disk of circumpulsar asteroids randomly straying into the magnetosphere.

Fallback disk accretion may also play an important role in producing the X-ray emission of some ultraluminous X-ray sources (ULXs) that are possibly associated with SNRs, e.g. IC 342 X-1 (Roberts et al. 2003) and the ULX in the SNR MF 16 in NGC 6946 (Roberts & Colbert 2003). This association seems to rule out mass transfer in binaries as the main energy source, since there is little time for the donor stars (if they exist) to evolve and transfer mass rapidly to the black holes. A much more plausible explanation is that the black hole is accreting from the disk originating from the fallback supernova debris (Li 2003).

In our Galaxy the X-ray source SS 433 is usually thought to appear as an ULX if observed face-on. This bizarre object is an X-ray binary associated with the SNR W50 (see Margon 1984; Fabrika 2004, for reviews). It has a 13 d orbital period and is famous for the presence of its relativistic jets precessing with a periodicity of about 162 d. There is no consensus about the binary component masses and the origin of W50. It might be a stellar windblown bubble produced by the SS 433 jets, as was proposed by Begelman et al. (1980, see however, Zealy et al. 1980). The companion star has been suggested to be a supergiant which is filling its Roche lobe (Hillwig et al. 2004, but see Barnes et al. 2006), thereby producing an extremely high-mass transfer that occurs on thermal time scale with the rate of $\dot{M} \sim 10^{-4}\,M_{\odot}\,{\rm yr}^{-1}$ (King, Taam, & Begelman 2000). This gives rise to a total luminosity of $\sim 10^{40}$ ergs$^{-1}$, although the observed unabsorbed $2-10$ keV X-ray luminosity is $\sim 10^{35}-10^{36}$ ergs$^{-1}$. However, recent *Chandra* observations by Lopez et al. (2006) suggest the radius of the companion to be about one third of the Roche lobe radius. A similar conclusion was also reached by Brinkmann, Kawai, & Matsuoka (1989) with *Ginga* observations. If it is correct, this indicates that the compact object (possibly a black hole) is likely to be accreting through a SN fallback disk rather Roche lobe overflow. Stellar wind accretion is also possible. But it is difficult to account for the high mass accretion rate and the existence of a stable accretion disk. Additional evidence for fallback disk accretion in SS 433 my lie in recent *XMM-Newton* observations by Brinkmann, Kotani, & Kawai (2005). These authors find over-abundances in different elements in the outflowing gas: Si and S by factors of $\sim 2$, Ni by $\sim 8$. This overabundance of heavy elements might be a tracer for the past explosion of the massive progenitor of the compact star, since elemental synthesis of for example Ni in the inner parts of the accretion disk appears unlikely due to the extremely high temperatures required. The fallback disk accretion is the most natural way to convert the SN ejecta containing the synthesized heavy elements into the outgoing jets.

In summary, SN fallback disks may account for the observed features of young compact stars through various ways of interaction between the disk and the star. Our results motivate further efforts to detect disks around NSs and BHs in SNRs, and more detailed models of the disk-star interaction.

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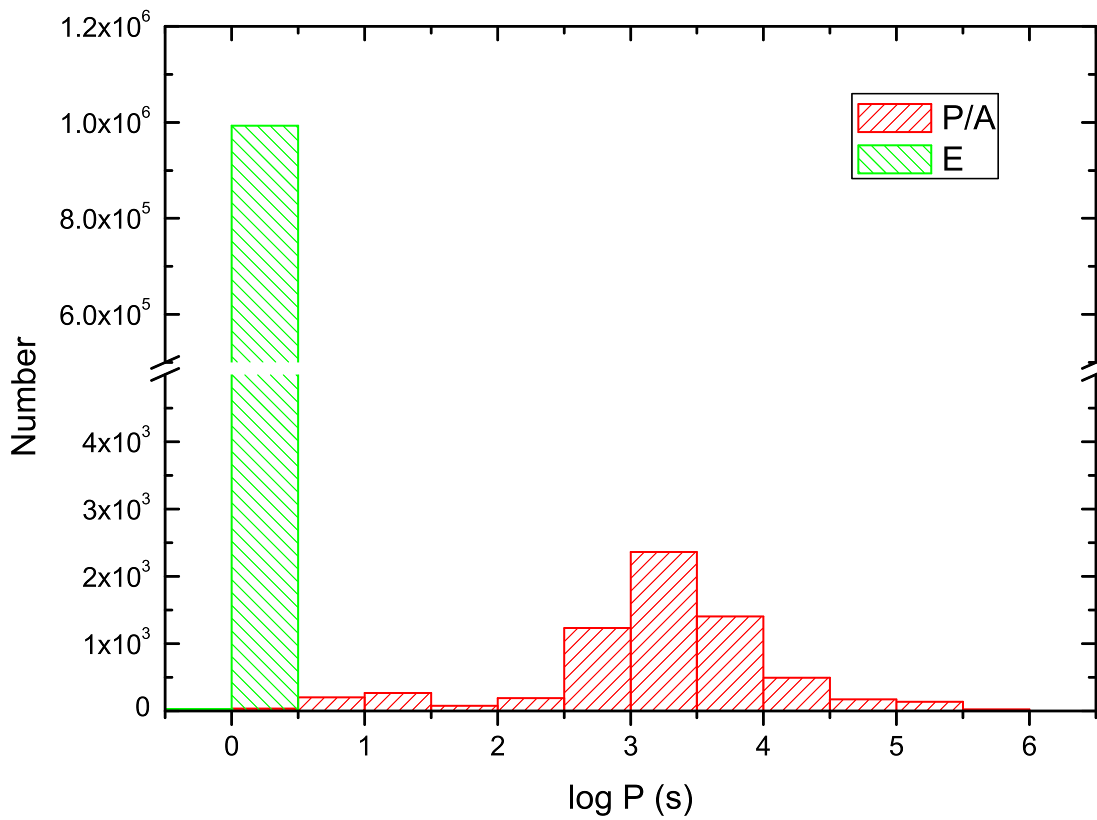


Fig. 1.— Distribution of the spin periods of magnetars at the age of 2500 yr. The hatched regions indicate propeller/accretor (+45°) and ejector (−45°) systems, respectively.