On the nature of the radio quiet X-ray neutron star
1E 1207.4-5209

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Abstract. The strange timing property of X-ray pulsar 1E 1207.4-5209 can be explained by the hypothesis that it is a member of an ultra-compact binary system. This paper confronts the ultra-compact assumption with the observed properties of this pulsar. The gravitational potential well of an ultra-compact binary can enlarge the corotation radius and thus make it possible for accreting material to reach the surface of the NS in the low accretion rate case. Thus the generation of the absorption features should be similar to the case of accreting pulsars. The close equality of the energy loss by fast cooling of the postsupernova neutron star and the energy dissipation needed for a wide binary evolving to an ultra-compact binary demonstrates that the ultra-compact binary may be formed in 10-100yr after the second supernova explosion. Moreover, the ultra-compact binary hypothesis can well explain the the absence of optical counterpart and the observed two black body emissions. We suggest a simple method which can test the binary nature directly with XMM-Newton and Chandra observations. We further predict that the temperature of the two black bodies should vary at different pulse periods.

Key words.: pulsars individual (1E 1207.4-5209) stars: neutron–X-rays: stars: binaries

1. Introduction

The X-ray pulsar 1E 1207.4-5209 (hereafter 1E1207) is an very strange object. The X-ray emission with P = 0.4241296s period (Zavlin et al. 2000) indicates that is a neutron star (NS). But there is no radio, no gamma-ray and no optical emission detected. The association with the surrounding supernova remnant (SNR) PKS 1209-51/52 is very likely (Pavlov et al. 2002), however the age of SNR is substantially different from that of the spin-down of the pulsar. The X-ray features show cyclotron absorption, from which the B-field can be obtained. This is very different from the magnetic field (B-field) inferred from the spin-down of the pulsar (Bignami et al. 2003, Zavlin et al. 2004). Moreover, the pulse frequency variation is non-monotonic (Zavlin et al. 2004). These puzzles are difficult to explain by a normal, isolated pulsar.

Can it be an isolated pulsar with an accretion disk? Supernova explosion ejecta may form a disk around it. The disk exerts a torque on the NS and makes it spin down. This model can explain the age and possibly the B-field problem. However, the pulse frequency is non-monotonic, which implies a variable torque, and hence a variable flux density. Moreover, the jump of pulse frequency leads to a high luminosity (∼ 10³⁸erg s⁻¹). But the observed luminosity is stable, around ∼ 10³³erg s⁻¹. Therefore, accretion as the major cause of the pulse frequency variation is not suggested by observations (Zavlin et al. 2004).

If the pulse frequency variation is interpreted as due to one or more glitches, then the amplitude of the glitch of 1E1207 (∆ν > 5µHz) is a factor of 30-60 greater than the typical value observed for glitching radio pulsars, which is unlikely (Zavlin et al. 2004).

Can it be a binary system? The binary hypothesis with orbital period from 0.2yr to 6yr can explain the variation of pulse frequency (Zavlin et al. 2004). However this implies that the variation of the pulse frequency must be periodic, which needs to be confirmed by further observations. On the other hand, the wide binary hypothesis can not explain other puzzles, i.e., age and B-field values. Moreover, repeated optical observations have failed to yield any optical counterpart for the system (De Luca et al. 2004).

Can it be an ultra-compact binary? This model may explain the pulse frequency variation by a long-term orbital effect, not strictly periodic. Moreover, the age puzzle and the B-field puzzle can also be explained (Gong 2005a). This paper confronts the ultra-compact binary model with all available observations.
We demonstrate that the ultra-compact binary system shares a common accretion disk, from which the generation of cyclotron absorption features is naturally expected.

A new scenario for the formation of an ultra-compact binary is proposed, in which an ultra-compact binary can be formed from a wide presupernova binary through energy loss by fast cooling in 10–100 yr.

Why the orbital motion of 1E1207 has not been measured is also analyzed in detail. A simple method to test the binary nature of an ultra-compact binary candidate using XMM-Newton and Chandra data is proposed.

We further predict that the temperatures of the two black bodies should vary at different pulse periods.

2. The search for an orbital period in 1E1207

This section analyzes why the orbital period of 1E1207 can escape different tests, like modulation of flux density, Doppler shift of pulse frequency, and Roemer delay, and how to test the binary nature by XMM-Newton and Chandra data in an alternative way.

In the case of a circular orbit, the phase delays caused by the motion of the pulsar are sinusoidal.

The signal received by a telescope can be described by

\[ f(u) = A \cos \left( \frac{2\pi t}{P} + \phi_{\text{spin}} + \Phi_{\text{orb}} \cos \left( \frac{2\pi t}{P_b} + \phi_{\text{orb}} \right) \right), \]  

(1)

where \( A \) and \( \phi_{\text{spin}} \) are the amplitude and phase of the pulsation, \( \Phi_{\text{orb}} \equiv 2\pi x/P \) and \( \phi_{\text{orb}} \) are amplitude and phase of the orbital modulation, and \( P, P_b \) and \( x \) are pulse period, orbital period, and projected semi-major axis respectively. The binary nature of 1E1207 can be tested in four different ways.

(1) As in radio pulsars, the binary nature can be tested by the Roemer time delay, which is the propagation time in the orbit. However, the short orbital period \( P_b \) corresponds to the small projected semi-major axis, \( x \) (\( x \equiv a_s \sin i/c \sim 3\text{ms} \)), which is comparable or even smaller than the timing resolution of XMM-Newton, \( \sim 6\text{ms} \). Thus the binary nature of 1E1207 cannot be tested directly by the time of arrivals (Gong 2005a).

(2) If 1E1207 is in an ultra-compact binary system, then the measured photon time series should show evidence for orbital modulation. However, this has not been measured. The reason is that the largest modulation which corresponds to the pulsation has an amplitude of about 6% (De Luca et al. 2004). Consequently, the amplitude of the orbital modulation, which is two to three orders of magnitude smaller (\( \Phi_{\text{orb}} \sim 10^{-2} - 10^{-3} \)) than 6%, cannot be observed, as shown in Eq. (1).

(3) The Fourier response of the fundamental spin harmonic corresponding to the signal of Eq. (1) is given by Ransom et al. (2003). Since the amplitude and the separation of the sideband are both dependent of \( \Phi_{\text{orb}} \), which are small for ultra-compact binaries (due to \( x \sim 10^{-2} - 10^{-3} \)), the side bands due to orbital motion are very difficult to resolve from the noise. Thus also this method is not suitable in searching ultra-compact binaries with orbital periods of a few minutes.

(4) The last possibility is measuring the variation of pulse frequency, i.e., analyzing \( \nu \) in the whole time span (typically \( \tau \sim 100\text{ks} \)). This is efficient for binary pulsars with wide orbits, in which \( P_0 \sim \tau \) or \( P_0 > \tau \). If the orbital period is of a few minutes, then \( P_0 < \tau \) and the measured \( \nu \) is affected only by the long-term orbital effect,

\[ \Delta \nu = \frac{xk\nu \pi (1 - e^2/4)}{P_b} + o\left( \frac{P_0}{\tau} \right). \]  

(2)

The second term in the right hand side of Eq. (2) is \( P_b/\tau \) (\( \sim 10^{-3} - 10^{-4} \)) times smaller than the first and can be neglected. The \( \Delta \nu \) of Eq. (2) depends on the orbital elements, \( a, i \) (which are contained in \( x \)), \( e \) and \( P_b \), which are long-periodic terms due to spin-orbit coupling (Gong 2005b). However, these long-periodic terms are not exactly periodic, implying that the variation of \( \nu \) is also not periodic. This may be responsible for the side band on the probability density distribution of \( \nu \) (Zavlin et al. 2004).

Consequently, analyzing \( \nu \) in the whole observational time span can only reflect the long-periodic property of an ultra-compact binary system (at time scales \( \sim 10^4 P_b \)), but not the short-period effect (at time scales \( \sim P_b \)).

Thus, it is the small value of the orbital period of an ultra-compact binary that prevents the measurement of the orbital motion of 1E1207 directly. However, the two NSs in an ultra-compact binary have large orbital velocities, \( \sim 10^6 \text{km s}^{-1} \), which means that the Doppler shifts can be as large as \( v/c \sim 10^{-2} - 10^{-3} \). Using the large Doppler shifts it is still possible to extract the orbital period of 1E1207 directly.

However, a large Doppler shift of 1E1207 can only be found at \( \sim P_b/2 \) time scale, or around 1 minute. If one measures \( \nu \) at the time scale of 1 minute directly, then the signal to noise ratio is far too small.

A simple solution to the problem uses the large Doppler shift and the length of time span (\( \tau >> P_b \)) simultaneously. One can split the time span evenly into a number of segments, and each segment corresponds to a time span of \( \sim P_b/2 \). Then fold the odd segments, which may correspond to one shift (say blue); and fold separately the even segments, which may correspond to the other shift (red). Thus the orbital period can be tested by comparing the shifts in the two groups of folding.

Assume that the total time span of an observation is \( \tau \sim 100\text{ks} \), and that the folding starts at \( t_0 = 70\text{ks} \). Thus, the total of folding time is \( \tau - t_0 \), which can be divided into (for simplicity) 6 segments, No 1,2,3...6, and each segment corresponds to a sub-time scale of \( \tau_i = N \cdot P = 42.4\text{ks} \) (\( N = 100 \) denotes the number of pulses, recall \( P = 0.42\text{s} \) is the pulse period). Then we can fold the two groups of odd and even segments separately. In such a case, the total time span of an observation is \( \tau = t_0 + 67\text{ks} \).

Having the two groups of folding, one can test the binary nature in two ways.
(a) Using the method of Zavlin et al. (2004), the $\nu$ and $\dot{\nu}$ values of the two groups of folding can be obtained. Due to the orbital motion, $\nu$ may be greater than a reference central frequency, $\nu_{\text{ref}}$; and $\dot{\nu} > 0$ in the folding corresponding to blue shift, whereas in the folding corresponding to red shift $\nu$ may less than $\nu_{\text{ref}}$ and $\dot{\nu} < 0$.

(b) Since the Doppler shift can be as large as $\Delta \nu / \nu \approx 1\%$, then the $\nu$ of the blue folding is larger than that of red folding by about $1\%$. Thus, one can find one more pulsation in the blue folding than that in red folding in the given time scale, $P_0/2$, when the number of pulsations in the interval $P_0/2$ is about 100.

Notice that, in the performance of the two above tests one can change the length of each segment, $\tau_1$ (through changing $N$), which corresponds to the orbital period of the binary, and the initial time, $t_0$, of the segments which corresponds to the initial orbital phase of the binary, in order to obtain the maximum effect of (a) and (b).

It is conceivable that the measured pulse profile of 1E1207 may have been broadened by the orbital Doppler shift. By excluding this effect, more precise pulse profiles are expected.

3. Accretion disk of an ultra-compact binary

In this section we demonstrate that the accretion disk of an ultra-compact binary is different from that of other compact systems in two aspects.

One is the corotation radius, $r_c$, which is enlarged by the potential well of the ultra-compact binary. Thus the accretion regime can be reached even in the low accretion rate case.

The other is the inner radius of the disk, which is larger than the separation of the two compact stars, so that the two compact stars share one common accretion disk.

The accretion can proceed in two regimes, Frank et al. (1983) and Zavlin et al. (2004), depending on the relation between the corotation radius, $r_c$ and the magnetospheric radius, $r_m$. The former is given by,

$$ r_c = (Gm_1)^{1/3}(2\pi \nu)^{-2/3} = 0.1 \times 10^9 \text{ cm}, \quad (3) $$

(where $\nu = 2.36 \text{ Hz}$ is the spin frequency, $m_1$ is the mass of the NS) and the latter is given by,

$$ r_m \sim 0.5(8Gm_1)^{-1/7}\mu^4/7\dot{m}^{-2/7} \approx 0.9 \times 10^9 \mu_{14}^{4/7} \dot{m}_{-9}^{-2/7} \text{ cm}, \quad (4) $$

where $\dot{m} = 10^{14} \dot{m}_{14} \text{ g s}^{-1}$ is the accretion rate, $\mu = 10^{30} \mu_{30}$ is the magnetic moment, and the NS mass is assumed, $m_1 = 1.4m_\odot$.

If the accretion rate is high enough, $r_c > r_m$, the accretion matter can overcome the centrifugal barrier and reach the NS surface. In this case the torque exerted on the magnetosphere spins the NS up. When $r_c < r_m$, the centrifugal force at $r = r_m$ exceeds the gravitational force, so that accretion on to the NS surface is inhibited.

By Eq. (3) and Eq. (4), we have $r_c < r_m$, which corresponds to a propeller regime in the case of an accretion disk around an isolated pulsar. Transforming to the accretion regime, $r_c > r_m$, needs to substantially increase the $\dot{m}$ and hence X-ray luminosity. This is not supported by observations. Thus the variation of spin frequency is not likely to be due to accretion.

On the other hand, the pulse frequency variation can be interpreted as the dynamic effect of an ultra-compact binary (Gong 2005a). If this is true, then the question is: how does the accretion disk interact with the ultra-compact binary, and what is the difference between a disk in such case and that of normal X-ray binaries. The potential of a binary system is given,

$$ \Phi_R(r) = -\frac{GM_1}{|r-r_1|} - \frac{GM_2}{|r-r_2|} - \frac{1}{2}(\omega_0 \times r)^2, \quad (5) $$

where $r_1$ and $r_2$ are position vectors of the centers of the two stars, $r$ is the position of a field point from the common center of mass, and $\omega_0 = 2\pi/P_0$ is the angular velocity of the binary system. The Roche lobe radius, $R_L$, is given (Frank et al. 1983)

$$ \frac{R_L}{a} = [0.38 - 0.2 \log(m_2/m_1)], \quad 0.05 < \frac{m_2}{m_1} < 2. \quad (6) $$

In the case $m_2/m_1 \approx 1$ and $P_0 = 1\text{ min}$, we have $R_L = 0.38a = 0.8 \times 10^6 \text{ cm}$. Eq. (6) gives a magnetosphere radius, $r_m \sim 0.9 \times 10^6 \text{ cm}$, $r_m > R_L$, which implies that a disk inside the Roche lobe of 1E1207 (say primary for convenience) is impossible. In such a case, the only possibility is that the inner edge radius of the disk is larger than the separation of the two compact stars.

For a given angular momentum, a circular orbit has the minimum energy, so dissipation in the orbiting gas will tend to circularize the motion. If the inner edge of the disk is approximately circular, then the Roche potential of Eq. (5), can be denoted by an equivalent potential, $\Phi \equiv -GM/r$ ($M = m_1 + m_2$),

$$ \Phi \equiv -\frac{GM}{r} \approx \Phi_R. \quad (7) $$

Then we have,

$$ \frac{|\Phi - \Phi_R|}{|\Phi|} < \frac{1}{10}, \quad r > 5a, \quad (8) $$

where $5a \approx 1 \times 10^{10} \text{ cm}$. In the case of Eq. (5), the gravitational force exerted on the inner edge of the disk equals approximately that of a star with mass $M$.

Therefore, 1E1207 and its companion may share an accretion disk, from which material can fall onto both compact stars. The compact system is thus different from a normal X-ray binary, which is characterized by a much larger separation of the two stars and whose disk is in the Roche lobe of the primary.

The potential well of a pulsar in a binary system, given by Eq. (6), is deeper than that of an isolated pulsar. Consequently, a pulsar in an ultra-compact binary system has a larger corotation radius, $r_c$, than that of an isolated pulsar.
To obtain the effective corotation radius, it is sufficient to calculate it in the simple case when \( r, r_1 \) and \( r_2 \) are aligned.

Assuming \( \Phi(r) = -Gm_1/r \), the effective radius, \( r_{\text{eff}} \), can be obtained. When \( P_1 = 1 \) min and \( P_2 = 3.3 \) min, we have \( r_{\text{eff}} \approx 4r \) and \( r_{\text{eff}} \approx 7r_c \), respectively. Thus the potential of Eq. 3 corresponds to a larger corotation radius, and hence, even in the low accretion rate case, i.e., \( \dot{m} \sim 10^{-11} \) g s\(^{-1}\), it is still possible that the relation \( r_c > r_m \) be satisfied, and the pulsar is in the accretion regime. On the contrary, if 1E1207 were to be an isolated pulsar, the pulsar is in the accretion regime. On the contrary, if 1E1207 were to be an isolated pulsar, the pulsar is in the accretion regime. On the contrary, if 1E1207 were to be an isolated pulsar, the pulsar is in the accretion regime.

It is worth mentioning that the influence of the B-field of the secondary on the magnetic moment of the primary, \( \mu = Br^3 \), is negligible. Because we do not need to consider the B-field between the two compact stars, and in the region outside of the two stars, the B-field is dominated by each star’s own B-field (since the B-field of the secondary near the surface of the primary is \( B \sim (R_*/a)^3B_2 \approx 10^{-9}B_2 \), with \( R_* \) the radius of the primary, and \( B_2 \) the B-field of the secondary).

Consequently, the ultra-compact binary scenario can lead to a significant increase in the corotation radius of each NS, while causing insignificant changes in their magnetospheric radius.

4. The formation of an ultra-compact binary

The age of 1E1207 should be that of that of SNR hosting it, which is about 3–20 kyr (Roger et al. 1988). But forming an ultra-compact binary through gravitational wave radiation takes a much longer time span. This problem can be solved by a simple scenario. We assume that the presupernova binary is a wide one, which makes it possible for it to survive the second SN explosion, whose remnant we observe. The presupernova binary (still with a wide orbit) loses an enormous amount of energy in 10-100 yr, through fast cooling.

The energy released in the fast cooling corresponds to a pulsar wind of \( (10^{-5}M_\odot - 10^{-6}M_\odot)\text{yr}^{-1} \), which interacts with the SN envelope and reduces the mechanic energy of the binary system rapidly.

On the other hand, the energy released in the fast cooling is approximately the energy that is required for a wide binary to decay to an ultra-compact one. This implies that fast cooling may be the cause of formation an ultra-compact binary system in a relatively short time scale.

NSs are formed at very high temperatures, \( \sim 10^{11} K \), in the imploding cores of supernova explosions. Much of the initial thermal energy is radiated away from the interior of the star by various processes of neutrino emission, leaving a one-day-old NS with an internal temperature of about \( \sim 10^8 - 10^{10} K \) (Becker & Pavlov 2001).

The relationship between surface temperature, \( T_s \) and the core temperature \( T_c \) of a NS is given (Gudmundsson et al. 1983)

\[
T_s = 3.1(g/10^{14} \text{cm} s^{-1})^{1/4}(T_i/10^9)^{0.549} \ K
\]

where \( g \) is the gravitational acceleration at the NS surface.

Having cooled down to \( T_s = 1.5 - 3 \) MK (1 MK = 1 x 10^6 K), the NS surface temperature stays on a plateau for several decades. The cooling can then follow two different scenarios, depending on the still poorly known properties of super-dense matter and on the mass of NS (Page & Applegate 1992).

For a NS with mass, \( m < 1.3 m_\odot \), the cooling is not by direct Urca process (Page & Applegate 1992) and the temperature decreases gradually, down to \( \sim 0.3 - 1 \) MK, by the end of the neutrino cooling era. It then falls down exponentially, becoming lower than \( \sim 0.1 \) MK in \( \sim 10^7 \) yr (Becker & Pavlov 2001).

For NS with mass, \( m \geq 1.35 m_\odot \), the interior of a star cools very rapidly by the direct Urca process. A sharp drop in temperature, down to 0.3-0.5 MK, occurs at an age of \( \sim 10 - 100 \) yr, followed by a more gradual decrease, down to the same \( \sim 0.1 \) MK at \( \sim 10^9 \) yr (Page & Applegate 1992, Lattimer et al. 1991, Becker & Pavlov 2001, Yakovlev & Pethick 2004).

From Eq. (10), the decrease of the surface temperature from \( T_s = 1.5 - 3 \) MK, to 0.3-0.5 MK corresponds to a decrease of core temperature,

\[
\Delta T_i \sim 1 \times 10^9 \ K
\]

This temperature drop corresponds to an energy dissipation of

\[
\Delta E_1 \sim \frac{3}{2}k\Delta T_i\sigma N
\]

where \( N \) denotes the total number of nuclei in a compact star, and \( \sigma \) (\( 0 < \sigma < 1 \)) denotes the ratio of the number of nuclei contained in the core to that of the whole NS.

For each proton-electron pair accreted, the potential energy released is \( GM(m_p + m_e)/R_\ast \approx GM(m_p)/R_\ast \), and the thermal energy is \( 2 \times \frac{4}{3}kT \), therefore (Frank et al. 1985),

\[
T_{\text{th}} = GMm_p/3kR_\ast \approx 5.5 \times 10^{11} \ K
\]

where \( R_\ast \sim 1 \times 10^6 \) cm is the radius of NS. Replacing it by \( R_c + a \approx 2 \times 10^6 \) cm (recall \( P_b = 1 \) min corresponds to \( a = 2 \times 10^6 \) cm), we have

\[
T_{\text{th}} = GMm_p/3k(R_\ast + a) \approx 2 \times 10^8 \ K
\]

This temperature means that the energy released by two distant NSs (in a wide binary) decaying to an ultra-compact binary is

\[
\Delta E_2 \sim 3kT_{\text{th}}N
\]

From Eq. (11) and Eq. (13) we see that the two energies, \( \Delta E_1 \) and \( \Delta E_2 \), are equivalent when \( \sigma \approx 0.4 \). This implies
that the energy released in the orbital decay can be consistent with the energy loss predicted by the fast cooling of a postsupernova binary.

The fast cooling (on time scales of 10-100 yr) corresponds to a pulsar wind of \((10^{-5} M_{\odot} - 10^{-6} M_{\odot}) yr^{-1}\), which interacts with the SN envelope (Bednarek 2001, Ikhsanov & Choi 2004) and causes torques reducing both the orbital angular momentum of the binary system and the spin angular momenta of the pulsars. Consequently, the kinetic energy of the binary system is reduced substantially. Thus the binary orbit decays from a wide one to an ultra-compact one, and the spin frequencies of the two NSs also reduce substantially.

The above scenario is analogous to the magnetic dipole radiation resulting in the spin-down of a pulsar, assuming that the energy loss by electro-magnetic emission equals the decrease in mechanical energy corresponding to the spin-down of a NS.

Therefore, an ultra-compact binary can be formed in 10-100yr after SN explosion through fast cooling, and the observed SNR age can still be greater than the time scale of the formation. Thus the problem in the formation of ultra-compact binaries like 1E1207 can be naturally explained.

The best fit two-BB model to the XMMM-Newton data indicates an emitting radius of 3km for the soft component, with a temperature of \(\sim 200eV\) (Bignami et al. 2003).

Since an ultra-compact binary contains two compact stars (separated at \(\sim 2 \times 10^9\)cm), which cannot be resolved at the distance of 2.1kpc, the two BB temperatures (Mereghetti et al. 1999, Vasisht et al. 1997, Zavlin et al. 1998, Bignami et al. 2003) may be radiation from the two compact stars. The two temperatures may be caused by the two cooling NSs. The accretion induced spots may also contribute to the nonuniform temperature distributions on the NS surfaces, reflected in a pulsation of 1E1207 at the 6% level.

Therefore, the two BBs should have different pulse frequencies, corresponding to different pulse periods of the two compact stars. This prediction can be checked by further spectral fitting.

The confrontation of the ultra-compact binary model of 1E1207 with the observations of it can be summarized as follows:

1. An ultra-compact NS-NS binary system would naturally explain the absence of optical counterpart (De Luca et al. 2004). This is now confirmed by deep HST observations, with no object in the Chandra error bar down to \(m_v \sim 27\) (Mignani 2006, private communication).

2. The predicted long-periodic effect in \(\nu\) and \(\dot{\nu}\) can explain the observed variation in pulse frequency, as well as in the age and the B-field discrepancies. Such phenomena can all be attributed to timing properties due to orbital motions.

3. An ultra-compact binary makes it possible to enlarge the corotation radius and hence accretion may supply the plasma density needed for producing the cyclotron lines in 1E1207.

4. The two observed BB temperatures can be interpreted by the cooling temperatures or accretion-induced emissions of the two compact stars.

Moreover, the ultra-compact binary scenario predicts the following measurable effects:

a. The large Doppler shift corresponding to the orbital motion of 1E1207 can be directly measured by the new method proposed above.

b. The variation of pulse frequency is not only non-monotonic, but also non-periodic (the long-periodic spin-orbit coupling effect is not exactly periodic).

c. Two BB temperatures should have different pulse periods.

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