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On the nature of the bimodal initial velocity distribution of neutron stars

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Abstract. We propose that the bimodal nature of the kick velocity distribution of radio pulsars is connected to the dichotomy between hadronic stars (i.e. neutron stars with no quark matter content) and quark stars. Bimodality can appear due to different mechanisms of explosion which lead to the formation of two types of compact stars or due to two different sets of parameters driving a particular kick mechanism. The low velocity maximum (at ~100 km s^{-1}) is associated with hadronic star formation, whereas the second peak corresponds to quark stars. In the model of delayed collapse of hadronic stars to quark stars (Berezhiani et al. 2003) quark deconfinement leads to a second energy release, and to a second kick, in addition to the kick imparted to the newly formed hadronic star during the supernova explosion. If the electromagnetic rocket mechanism can give a significant contribution to pulsar kicks, then the high velocity peak can be associated with the shorter initial spin periods of quark stars with respect to hadronic stars. We discuss these scenarios.

Key words. stars: neutron – stars: evolution – stars: pulsars: general

1. Introduction

An important property of the compact stars usually called *neutron stars* (NSs) is their spatial velocity distribution. At present there are many measurements of radio pulsar (PSRs) proper motions (Brisken et al. 2003, and references therein). These measurements, together with distance measurements, lead to the determination of pulsar spatial velocities. In the ATNF catalogue (see for example Hobbs et al. 2003) there is data on transverse velocities for 137 PSRs (including millisecond etc.). Typical velocities of PSRs are about 300–400 km s^{-1} (Lyne & Lorimer 1994; Lorimer et al. 1997). The largest inferred velocities are higher than 1000 km s^{-1}.

Such high pulsar velocities are thought to be associated with supernova (SN) explosions. It is believed that a newly born neutron star receives a considerable "kick" during, or shortly after, the SN explosion (see reviews in Lai 2003; Burrows et al. 2003). Understanding of the nature of pulsar velocity distribution can give important information about the physics of SN.

There have been various attempts to reconstruct the initial velocity distribution starting from the observed properties of radio pulsars and other NSs (for example NSs in SN remnants – SNR; NSs in close binaries etc.). At the present time the most widely accepted velocity distribution is the one obtained by Arzoumanian et al. (2002). It is a bimodal distribution with two Maxwellian components (see Fig. 1). The velocity dispersion, σ, of the first peak is 90 km s^{-1}. The fraction of compact objects in the first peak is about 0.4 ± 0.2. The second peak corresponds to $\sigma = 500$ km s^{-1}. Recent results by Brisken et al. (2003) also support a two-component velocity distribution (however, in their model the fraction of the low-velocity component is just 0.2).

In principle the initial velocity distribution can be multicomponent as there are many potential sources for different velocity maxima (binaries of different types, different types of SNae etc.), but the relative contribution of many of them should be small (for example, the contribution of accretion induced collapse (AIC) or possible compact remnants of faint SNIa etc.). In addition compact stars, which never appear as PSRs, can have a velocity distribution different from PSRs. In the present paper, we will concentrate on the spatial velocity distribution for radio pulsars deduced from observational data, and we will try to give a physical interpretation of the origin of its bimodal shape.

There have been several discussions connected with this bimodality or with different possible components of the kick velocity distriburion. For example Colpi & Wasserman (2002) suggested a modification of the Imshennik (1992) SN mechanism (see also Imshennik & Nadezhin 1992) to explain the high-velocity part of the distribution. This mechanism (as noted

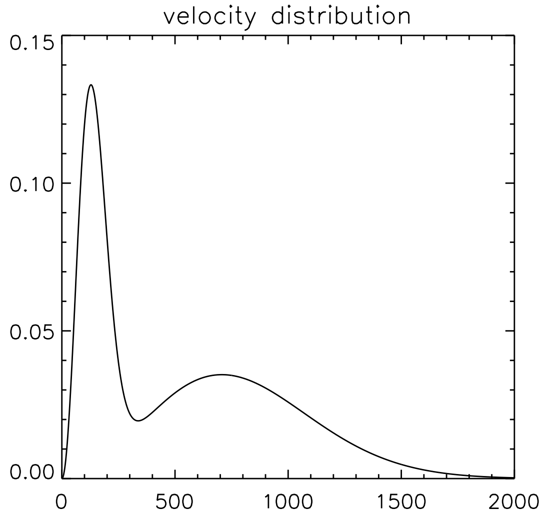

Fig. 1. The initial velocity distribution with two Maxwellians (Arzoumanian et al. 2002). The low velocity part includes 40% of all objects, the maximum corresponds to 127 km s^{-1}. The high velocity part has maximum at 707 km s^{-1}.

by the authors) is not valid for low-velocity NSs as Crab and Vela, for which the spin is nearly aligned with the spatial velocity (see recent data and discussion in Romani 2004). Actually, such a geometrical configuration is not possible in the mechanism discussed by Colpi & Wasserman. Podsiadlowski et al. (2003) proposed the possibility of low kick velocities for a particular type of high-mass X-ray binaries (HMXBs) as a result of mass exchange influence on the stellar evolution.

In the present paper we propose a different scenario dealing with the occurrence of quark deconfinement in the cores of neutron stars, and with the corresponding energy release.

2. The model

In the following we assume that the initial velocity distribution of radio pulsars is at least bimodal, and fractions of stars in the low and high velocity parts of the distribution are more or less equal. This means that among normal radio pulsars there should be at least two different types of objects.

The fact that we are dealing with radio pulsars tells us that to produce different kicks we cannot use ideas which involve physical conditions in which radio pulsars do not exist (for example, too low magnetic fields, or too long initial rotational periods). Binaries also cannot explain this bimodality (they do not produce enough high-velocity NSs if isolated and binary progenitor stars produce PSRs with comparable probabilities). So we come to a conclusion that some significant dichotomy among normal single (isolated) radio pulsars is required.

The strongest theoretically known dichotomy in compact stars is the dichotomy between pure *hadronic stars* (HSs) and *quark stars* (QSs) (see e.g., Glendenning 1996; Bombaci et al. 2004). The physical feature which distinguishes the two families of compact stars is the absence or the presence of deconfined quark matter in the stellar interior. In hadronic stars no fraction of quark matter is present. These stars below the usual stellar crust (Pethick & Ravenhall 1995) have a layer of neutron-rich nuclear matter in beta-equilibrium with electrons and muons, and possibly an inner core containing hyperons (*hyperon stars*) or a condensate of negative kaons in addition to the particles mentioned above. Compact stars which possess a quark matter core, either as a mixed phase of deconfined quarks and hadrons or as a pure quark matter phase, are called *hybrid stars* (HySs). A more exotic alternative to the existence of hybrid stars is the possible existence of self-bound compact stars consisting completely of a deconfined mixture of *up* (u), *down* (d) and *strange* (s) quarks (together with an appropriate number of electrons to guarantee electrical neutrality) satisfying the Bodmer–Witten hypothesis (Bodmer 1971; Witten 1984; see also Terazawa 1979). These compact stars are called *strange stars* (SSs) (Alcock et al. 1986; Haensel et al. 1986). In the following, we will refer to hybrid stars and strange stars collectively as QSs.

Compact stars of each of the two classes (i.e. hadronic stars and quark stars) could be endowed with strong magnetic fields and could manifest their presence in the Universe as pulsars or as compact X-ray sources in binary systems.

Among many differences between HSs and QSs, typical kick velocities for the members of these two families of compact stars can be different too. Nobody to our knowledge has discussed in detail the possibility of having different kick velocities for these two types of compact objects, except a short note by Zhang et al. (2000). These authors briefly mentioned, in connection with larger displacement of soft gamma-repeators (SGRs) in comparison to anomalous X-ray pulsars (AXPs) from the centers of their SNRs, that strange stars can have higher kick velocities due to a two-step kick mechanism.

A quark star can be formed in a delayed collapse (see Berezhiani et al. 2003) or in a direct collapse with additional energy release (see for example Benvenuto & Horvath 1989; Hong et al. 2001). We first discuss the delayed collapse scenario.

It has been recently shown (Berezhiani et al. 2003; Bombaci et al. 2004) that above a threshold value of the gravitational mass pure hadronic stars are metastable to the conversion into quark stars (hereafter the HS→QS conversion). The *mean life time* of a metastable hadronic star is related to the quantum nucleation time to form a drop of quark matter in the stellar center, and dramatically depends on the value of the stellar central pressure. Thus, a metastable hadronic star can have a mean life time which can span many orders of magnitude (Berezhiani et al. 2003; Bombaci et al. 2004). In other words, the HS mean life time could be many orders of magnitude larger than the age of the Universe, or it can be relatively short: from a few hours up to a few years.

The delayed collapse of a metastable hadronic star to a quark star may be triggered by a fall-back (i.e. relatively soon after the SN explosion forming the HS) or by accretion of matter in a binary system. Both of these processes increase the central stellar density and, consequently, strongly decrease the nucleation time to form the first critical-size drop of quark matter which starts the stellar conversion process. As we suggest that about one half of all PSRs are QSs, then *most* of QSs should be formed due to fall-back or directly in the SN explosion (so that the delay time is significantly shortened), since the outcome of

NSs from binary systems is rather small to constitute ~1/2 of the total PSR population. Anyway, an additional energy release can produce a bimodal distribution of many physical properties of the compact stars which we usually call just NSs.

We suggest that the delayed stellar conversion process of a pure HS to a QS, triggered by quark deconfinement, can give a second kick to the compact star. Thus, the low velocity component of the pulsar velocity distribution receives contributions mainly from "normal" NSs (hadronic stars) which have passed through a single explosion (the SN explosion). The high velocity part is mostly composed of QSs which have received a second kick due to the energy release associated with the stellar conversion process.

Of course, as far as both explosions produce *distributions* of velocities, it is possible to find low velocity QSs which experienced two kicks, and high velocity HSs which received just a single natal kick. Also, among mid- and high-velocity objects there can be a contribution of HSs from massive binaries (Iben & Tutukov 1996).

Kicks can be imparted to compact stars by several different mechanisms (see Table 1). We estimate the additional spatial velocity imparted to a QS formed via the delayed HS→QS conversion process in the case where the kick is the result of two asymmetric neutrino jets. The total energy, $E_{\rm Total}$, liberated in the stellar conversion is about a few 10^{53} erg (Bombaci & Datta 2001; Berezhiani et al. 2003). A fraction η of this energy goes to a ultra-relativistic beamed e^+e^- plasma. The *efficiency factor* η is related to the cross section for the process of neutrino-antineutrino annihilation into e^+e^- pairs. Near the surface of the nascent QS due to general relativity effects the efficiency of the $\nu\bar{\nu} \rightarrow e^+e^-$ process is strongly enhanced with respect to the Newtonian case (Salmonson & Wilson 1999), thus η can be as high as 0.1. To be more conservative let us assume $\eta = 0.01{-}0.1$. Next we assume that the asymmetry between the two jets, κ, can vary from a few percent up to ten(s) percent. So the energy unbalance between the two jets is:

$$\Delta E = \eta\kappa E_{\rm Total} \sim \text{few } 10^{49}{-}10^{51} \text{ erg}$$

for η and κ varying between 0.01 and 0.1. The associated momentum difference is:

$$\Delta P = \Delta E/c.$$

Total moment conservation then requires for the kick velocity:

$$V_{\rm NS}/c = \Delta E/(M_{\rm NS}c^2).$$

So finally we obtain $V_{\rm NS} \approx$ few (1–100) km $\rm s^{-1}$.

A similar hydrodynamical neutrino driven kick mechanism could give the first kick to the HS during the SN explosion (Goldreich et al. 2000).

The second possibility for a QS to obtain a larger kick velocity with respect to an HS is the following. If compact star kicks are produced by the electromagnetic rocket mechanism (Harrison & Tademaru 1975), then the high velocity peak can be connected with a shorter initial stellar rotational period of QSs with respect to that of HSs. Of course, this mechanism is valid both for QSs formed directly in the SN explosions (Benvenuto & Horvath 1989; Hong et al. 2001), and for QSs formed with significant time delay (Berezhiani et al. 2003).

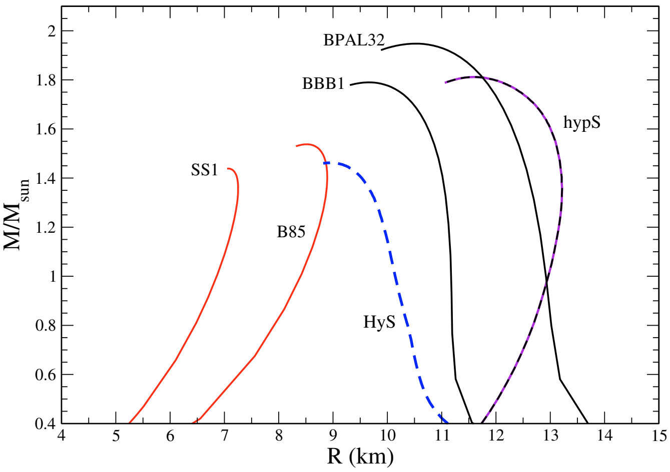

Fig. 2. The mass-radius relation for different types of compact The curves labeled BBB1 (Baldo et al. 1997) and BPAL32 (Prakash et al. 1997) are related to pure nucleonic compact stars (i.e. hadronic stars with the whole core made of β-stable nuclear matter), the curve labeled with hypS – to hyperonic stars (Glendenning 1992). The curve labeled with HyS is relative to a hybrid star (Bombaci et al. 2004). Finally, the two curves SS1 (Dey et al. 1998) and B85 to strange stars. Stellar masses are plotted in unit of the solar mass.

Within the electromagnetic rocket mechanism the maximum stellar velocity can be estimated as (Lai et al. 2001):

$$V_{\rm max} \sim 1400 R_{10}^2 P_{\rm ms}^{-2} \text{ km s}^{-1} \qquad (1)$$

where $P_{\rm ms}$ is the stellar rotational period in milliseconds, and R_{10} is the radius of the star in unit of 10 km.

Radii of QSs are typically 1.5–2 times lower than radii of HSs. This is illustrated in Fig. 2, where we plot the mass-radius relation for different types of compact stars (see figure caption for more details and references to the stellar models). If the initial rotational periods of QSs are 4–5 times shorter than those for HSs, then we can expect spatial velocities 5–6 times larger. Such a difference would be sufficient to explain the difference between the two peaks in the initial velocity distribution.

In the model of the HS→QS conversion, it is difficult to increase the stellar spin frequency by a factor of 4 in the process of HS contraction into a QS, unless there is some additional spin-up due to the kick (see below). However, if a QS is formed during the SN explosion (i.e. without time delay), then the difference in the initial periods between QSs and HSs could be significant. In fact, different types of compact stars can suffer diverse instabilities which lead to spin-down, depending on the stellar composition. For example, strange stars are not subject to the r-mode instability (Madsen 1998). Typical initial periods of "normal" NSs (HSs) are about 20 ms or longer. With such values for the spin period, the electromagnetic rocket mechanism is not effective. If QSs have typical radii of about 7 km and if they are born with typical periods of about 1 ms, then they can form a peak around 700 km $\rm s^{-1}$. Woosley et al. (2002) note that compact stars are expected to be born with periods ~1 ms, and only due to r-mode instability or similar processes they are

Table 1. Kick mechanisms.

Mechanism	Time scale	V_{max}, km s^{-1}	Alignment (spin and V)	Main recent refs.
Hydrodynamical	0.1 s	~(100–200)	random	Lai et al. (2001)
ν-driven	~few s	~50 B_{15}	parallel	Lai et al. (2001)
Electromagnetic rocket	long	1400 $R_{10}^{2}\,P_{\mathrm{ms}}^{-2}$	parallel	Lai et al. (2001), Huang et al. (2003)
Binary disruption (without add. kick)	$\ll P_{\mathrm{orb}}$	~1000	perpendicular	Iben & Tutukov (1996)
NS instability	few ms	~1000	perpendicular	Colpi & Wasserman (2002), Imshennik & Ryazhskaya (2004)
Magnetorotational	0.2 s – min	~300 (up to 1000)	quasirandom	Moiseenko et al. (2003), Ardeljan et al. (2004)

expected to slow down to rotational periods larger than about 20 ms.

As it was discussed in Spruit & Phinney (1998) and in Postnov & Prokhorov (1998) the kick itself can spin-up a newborn NS. So, in several kick mechanisms there is a possibility of higher initial spin frequency for higher initial kicks. Such a situation is in favour of having higher velocities due to the electromagnetic rocket mechanism if (before it starts to be active) the spin period had been decreased by a kick. In that case even a moderate electromagnetic-rocket kick can be important as it would be active for stars with already significant kick. In addition, a non-central first kick can probably lead to dipole displacement which causes more efficient acceleration due to the electromagnetic rocket mechanism.

In principle, if an exact shape of the second velocity peak is known then for the electromagnetic rocket mechanism it is possible to reconstruct the form of QSs spin period distribution. But at the moment there is no data on the exact shape. A Maxwellian distribution is just a reasonable hypothesis used by Arzoumanian et al. (2002). Reconstruction of the initial velocity distribution (especially on the high end) based on radio pulsar proper motion data cannot distinguish between Maxwellian and similar shapes.

3. Discussion

3.1. Problems with the scenarios

Here we discuss some possible problems with both scenarios (delayed HS→QS conversion and electromagnetic rocket) for stellar kicks, paying more attention to the former one.

One problem for a delayed HS→QS conversion is connected to the survival of close binaries, where the compact star has accreted a significant amount of matter which could lead to quark deconfinement and subsequent HS→QS conversion. If most of the binaries do not survive the stellar conversion, due to the additional kick imparted to the newformed QSs, it will be necessary to claim that all the observed accreting compact stars in low-mass X-ray binaries (LMXBs) are HSs[1], or it will be necessary to claim that in the case of binaries the HS→QS conversion does not lead to a large recoil. However, even with a strong kick there is a non-negligible probability of binary survival. Cir X-1, which has high spatial velocity (see discussion in Lai et al. 2001), may be an example. Thus, the compact star SAX J1808.4-3658 (a member of a LMXB) could be a strange star as suggested by Li et al. (1999).

We note that in the electromagnetic rocket model, binaries can survive as far as the time of acceleration is long, unless the NS is a magnetar (Lai et al. 2001; Huang et al. 2003). This mechanism can lead to the formation of runaway binaries with QSs.

Another problem comes from the millisecond PSR (mPSR) velocity distribution. These objects are assumed to originate in LMXBs or in intermediate-mass X-ray binaries (IMXBs) where they accreted a significant amount of matter, so in the scenario of Berezhiani et al. (2003), one can expect that most of mPSRs are QSs. As was shown by Lyne et al. (1998), the average velocity of mPSR is rather low: ~130 km s^{-1} (or even lower, see Nicastro et al. 2001). This is consistent with investigations of binary evolution (i.e. no additional kick is necessary). After the SN explosion, most of the surviving binaries correspond to the low velocity part of kick velocity distribution. Thus, in our scenario, most of the compact stars in LMXBs are more likely HSs, not QSs, since the mPSR population does not show any signs of enhanced velocities (there is a higher probability that a QS can stay bound in a HMXB system).

If the idea of the second kick due to the delayed HS→QS conversion is proved to be in contradiction with observations (i.e. no "imprints" of an additional kick on orbital parameters or/and velocity distribution are found), then it is a serious problem for the whole scenario of delayed HS→QS conversion due to accretion in binaries as it is difficult to understand the absolute symmetry of an energy release of ~10^{53} erg s^{-1} from a compact object which is not a black hole. However,

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[1] Compact objects in HMXBs with moderate kicks discussed by Podsiadlowski et al. (2003) also should be normal NSs according to our scenario.

the physical conditions for the second collapse can be different in the case of accretion in a binary and in the case of a fall-back. In the first case the pre-collapsed object is a millisecond NS with low magnetic field ($\sim 10^9$ G). In the second case there is a protoNS with longer spin period and higher magnetic field. This can lead to different asymmetries of explosion.

The rocket scenario also has some problems. The main one is that we need to assume significant displacement of the dipole relative to the spin axis. Otherwise the coefficient in Eq. (1) is much smaller and it is necessary to assume very short periods together with relatively large radii to explain PSRs with $V > 1000$ km s^{-1}.

3.2. Supernovae

At the moment nearly 3000 SNae have been observed. Potentially different types of SNae can give different velocity distributions of the resulting compact objects (if they are formed). So, as it was mentioned above, the initial velocity distribution should have many components. Different components can be associated with different SNae. It is very difficult to check observationally which SNae produce different compact objects. Most of the know SNae are extragalactic and recent – for them there is good data about types (and even data on SN progenitors, see van Dyk et al. 2003), but no information is available about compact objects. For historical SNae (Green & Stephenson 2003) we often know a compact object, but it is very difficult to reconstruct the SN type. There are SNRs associated with compact objects (see Kaspi 2000; Kaspi & Helfand 2002), but it is also difficult to know for sure the type of SN which produced a given SNR.

Core-collapse SN (in spiral galaxies) represent about 70−80% of all SN (Cappellaro & Turatto 2001). Among core-collapse SN the fractions of different supernova types are the following: SN IIP (0.3), SN IIL (0.3), SN IIn (0.02), SN 1987A-like (0.15), SN Ib/c (0.23) (Chevalier 2003, see details in Dahlen & Fransson 1999). We note that the distribution of SNae through types is different for different types of galaxies; it depends on the metallicity and so on the cosmic age. As a consequence, all corresponding distributions (like velocity and mass distributions of compact objects) are not universal. This fact can lead to different fractions of compact objects and different velocity distributions of PSRs in different galaxies.

SN IIP probably originate from the most low massive stars which can still produce a SN II. SN Ib/c probably are the product of binary evolution (or originate from very massive single stars). Obviously compact objects which originate from single (isolated) stars and compact objects which appeared after disruption of a binary should have different velocities simply due to additional orbital velocity. A detailed analysis of this situation was given for example by Iben & Tutukov (1996). They assumed that no natal kick is added (these authors also assumed that PSRs are born only in close binaries, see Tutukov et al 1984). As it is clear from their Fig. 10, massive binaries can give velocities up to 1000 km s^{-1}, but the fraction of these high-velocity objects in the total number of compact objects is small. Oppositely AIC can produce low velocity compact stars, but the contribution is also rather low: 3×10^{-3} yr^{-1} (Podsiadlowski et al. 2003).

The Crab pulsar is probably associated with SN IIP. In some sense it is consistent with our scenario, as compact objects formed from low massive stars (i.e. $\sim 10{-}15\ M_\odot$) should be of low velocity (i.e. $V_\mathrm{t} < 250$ km s^{-1}) HSs and their fraction is $\sim 0.2{-}0.4$. Then the high-velocity component of the velocity distribution should be related to SN IIL and probably to SN Ib/c.

3.3. Predictions and speculations

There are many predictions connected with the proposed scenario, and much more speculation can be done.

Fractions of compact objects in the first and in the second components of the *initial* velocity distribution are more or less equal; then, within our scenario, the number of *formed* HSs and QSs are also nearly equal. On the other hand, high velocity objects quickly leave our Galaxy. So, among *observable* sources the number of QSs should be not very large. QSs can fill the galactic halo.

If QSs are fast objects, then their fraction in globular clusters should be low when the typical escape velocity is <100 km s^{-1}.

Due to the different cooling history of HSs and QSs we can expect a correlation in the temperature-velocity relation for young compact objects, i.e. temperatures (for the same age) of objects from the first and the second peaks of the velocity distribution can be different. However, the cooling history is mass-dependent both for HSs and QSs, so this kind of correlation should not be a clear one.

An interesting problem is the possibility of glitches in QSs. Because internal structure of QSs and HSs are different, it is reasonable to expect that glitches of the two types of compact objects have different properties (see an early discussion in Alcock et al. 1986, and more recent in Horvath 2004). At present up to 100 glitches from about 30 PSRs have been reported (see Shemar & Lyne 1996; Krawczyk et al. 2003, and references therein). For 8 of these objects in the ATNF catalogue (Hobbs et al. 2003) transverse velocities are available. Several glitching PSRs with known velocities can be added from Kaspi (2000). For the two-component distribution of Arzoumanian et al. (2002), contribution of the low velocity component dominates up to ~ 300 km s^{-1}, which corresponds to the transverse velocity $V_\mathrm{t} \sim 250$ km s^{-1}. All but two velocity measurements of glitchers are below this limit. The best known glitchers – Crab and Vela – definitely represent the low-velocity component. The most high-velocity PSR among glitchers – 2224+65 – was reported to have a glitch just once (Shemar & Lyne 1996) and detailed properties of this glitch are unknown.

In SNRs closer to the centers we expect to see HSs, and QSs with higher average velocities should be more displaced (for the same age). (See also Zhang et al. 2000, where the authors briefly discuss this topic in connection with AXPs and SGRs.)

If there is a delayed quark deconfinement in a single compact object, then we can expect (even if the present scenario for the explanation of the bimodality for PSR velocity distribution is not correct) to have "young" PSRs without pronounced SNRs. Due to stellar contraction and (probably) due to an additional kick, such objects can be spun-up and warmed, so they can look like young *neutron stars*. In the case of a short time delay between the SN explosion and the HS→QS conversion (so that a SNR formed after the HS formation is still visible) there can be a discrepancy between the characteristic PSR age ($\tau = \dot{p}/2p$), the SNR age and the kinematic age (displacement of a compact object from the SNR center divided by the transverse velocity).

The outcome of a SN explosion depends on the metallicity (Woosley et al. 2002). The masses of iron cores and oxygen shells, the amount of matter fall-back, the rotation rates etc. are different for stars with different fractions of heavy elements. Metallicity changes during the lifetime of the Galaxy. As a consequence, one can expect different fractions of newborn QSs among compact objects at different galactic ages.

The formation of a QS from an HS is accompanied by the shrinking of the compact object and it can lead to an increase of the stellar magnetic field and to a decrease of the initial spin period. However, the details of this process are uncertain. Frail et al. (1994) note that in their set of PSRs, the high-velocity ones have higher magnetic fields. But the results of that paper (mainly the reality of associations of PSRs and SNRs) were later doubted. Also, the results mentioned in Kaspi & Helfand (2002) are against any correlation between initial spin and velocity (see data on initial spin periods for 7 PSRs in Migliazzo et al. 2002). Among these seven PSRs, the transverse velocities are known in four cases. Only one of them has a transverse velocity which falls into the second (high-velocity) peak of the velocity distribution. This pulsar has the shortest period (even just an upper limit) among those reported in (Migliazzo et al. 2002). We predict that the remaining three with unknown velocities should have $V_{\mathrm{t}} < (250\text{–}300)$ km s^{-1}. In our opinion, it is important to check possible links between properties connected with the internal structure of compact stars and their velocity properties, but not just in the form of correlations: it is important to check in which peak of the distribution a given compact star falls.

Fall-back processes can bring additional correlations between different properties of compact objects (as it was suggested by Popov et al. 2002), especially as far as this process can play a key role in shortening time of the delay between the SN explosion and the HS→QS conversion.

There are reasons to suspect that the magnetic field distribution of compact objects is also bimodal because of a significant number of magnetars. However, the high-field population is at most 10%, not comparable with the high-velocity fraction of PSRs.

Nowadays it is more or less clear that not all *neutron stars* pass through the stage of active PSR (or at least this stage is very short). In this sense, it is interesting to understand if they can be QSs. In connection with the proposed scenario, it is important to note that two of the Magnificent seven (seven ROSAT radioquiet NSs) for which velocities are known, probably are low-velocity objects: $V_{\mathrm{t}} < (200\text{–}250)$ km s^{-1}. However, more precise results will be available soon.

4. Conclusion

The existence of both hadronic and quark stars in comparable amounts can imply a bimodality of many properties of observed compact objects including radio pulsars. In this paper, we discussed the bimodality of the kick velocity distribution of PSRs. Within our scenario, the low-velocity peak of the velocity distribution corresponds to hadronic stars. Quark stars populate the second (high-velocity) part of the distribution.

Such bimodality in the kick velocity distribution can appear due to the following reasons:

- QSs can experience two huge energy release separated well in time. The first one occurs during a "normal" SN explosion, which forms a pure HS. The second occurs during a delayed stellar conversion (triggered by quark deconfinement) which forms a QS. Large second kicks can explain the observed velocity bimodality.
- Even in the case when both types of compact stars (i.e. HSs and QSs) are formed promptly during a SN explosion, the kick mechanism can be more efficient for a QS than for a HS. For example, we discussed in this paper that the electromagnetic rocket kick can be larger for QSs as these objects can be born with spin periods much shorter than those for HSs.

It is of great interest and importance to compare different observational properties of high- and low-velocity compact stars as the difference in the initial kick can have roots in differences in the internal stellar structure. In our opinion, it is useful not just to correlate the stellar spatial velocity with other physical parameters, but to look at differences between two ensembles of compact stars (two components of the velocity distribution). These two components probably are formed by different classes of compact objects (QSs and HSs), and inside each part correlations can be absent, but between the two parts, differences can be significant.

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