On the nature of the bimodal kick velocity distribution: supernovae and deconfinement

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Abstract

We propose that the bimodal nature of the kick velocity distribution of radio pulsars is connected with the dichotomy between hadronic stars – HSs – (*i.e.* neutron stars with no quark matter content) and quark stars. Bimodality can appear due to different mechanisms of explosion. This leads to the formation of two types of compact stars or due to two different sets of parameters mastering 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 the second energy release, and to the 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 *pro et contra* of these scenarios.

1 Introduction

An important property of neutron stars (NSs) is their spatial velocity distribution (here and below by NS sometimes we will mean both normal NSs and quark stars — QSs — if it does not mislead the reader). At present there are many measurements of radio pulsars (PSRs) proper motions (Brisken et al. 2003 and references therein). Together with distance measurements it leads to determination of transverse velocities, V_t. In the ATNF catalogue (for example Hobbs et al. 2003) there is data on transverse velocities for more than 150 PSRs. Typical spatial velocities of PSRs are about 300-400 km s^{-1} (Lyne, Lorimer 1994, Lorimer et al. 1997). Maximal velocities are higher than 1000 km s^{-1}.

These high velocities are thought to be connected with supernova (SN) explosions which lead to huge energy release (see recent reviews in Lai 2002, Burrows et al. 2003). Understanding of the nature of velocity distribution can give important information about physics of SN.

There were several attempts to reconstruct the initial velocity distribution basing on observed properties of radio pulsars and other NSs (for example NSs in SN remnants — SNR; NSs in close binaries etc.). The most widely accepted at the present time is the distribution obtained by Arzoumanian et al. (2002). It is a bimodal distribution with two maxwellian components. Velocity dispersion, σ, of the first peak is 90 km s^{-1}. The fraction of 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 two-component velocity distribution (however, in their model fraction of the low-velocity component is only about 0.2).

In principle the initial velocity distribution can be multi-component as there are many potential sources for different velocity maxima (binaries of different types, different types of SNae etc.), but relative contribution of many of them should be small (for example, contribution of accretion induced collapse – AIC, or possible compact remnants of faint SNIa etc.). In addition compact objects which never appear as PSRs can have different velocity distribution from PSRs. But here we will concentrate on the following problem: even for observed radio pulsars there is a bimodality with comparable contribution of both peaks. There were many papers in which authors tried to explain this bimodality. We propose a different scenario connected with deconfinement.

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2 The Model

In the following we assume as a fundamental fact: the initial velocity distribution of radio pulsar 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 parameters for which radio pulsars do not exist (for example, too low magnetic field or too long initial periods). Binaries also cannot explain this bimodality: they do not produce enough high-velocity NSs. So, one have to think about some significant dichotomy among normal single (isolated) radio pulsars. Actually, the strongest known dichotomy among compact objects is the dichotomy between NSs and QSs. This is a surprising fact that nobody to our knowledge has discussed in detail the possibility of different kick velocities for these two types of compact objects as an explanation of the bimodality. Only Zhang et al. (2000) briefly noticed in connection with large displacement of SGRs from centers of their SNRs that quark stars can have high kick velocities due to two-step kicks (see also Dar, De Rujula 2000).

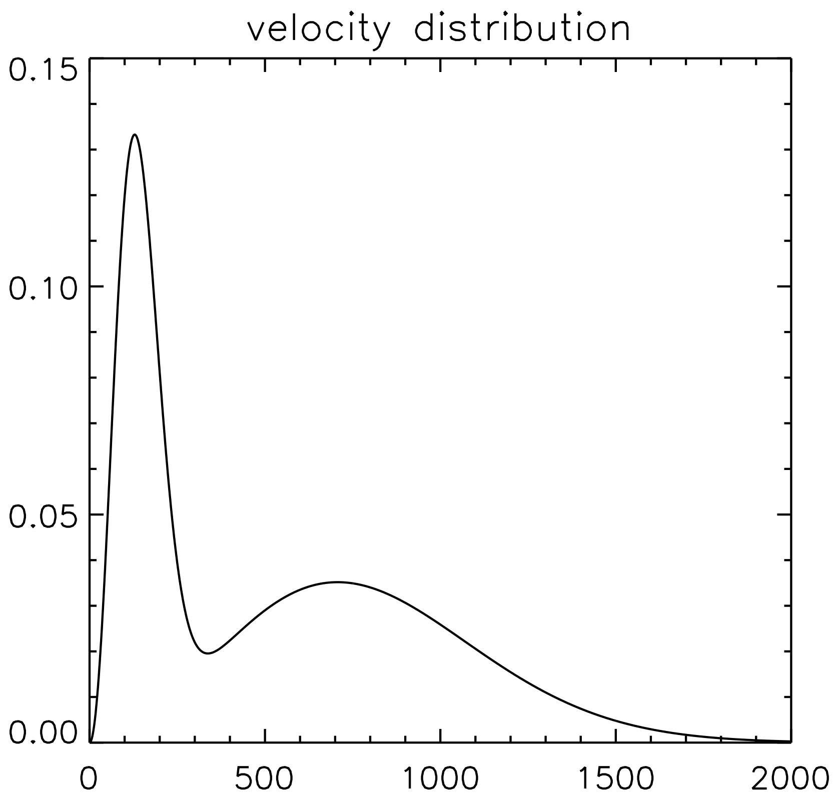

Figure 1: Modelled initial velocity distribution with two Maxwellians (Arzoumanian et al. 2002). The low velocity part includes 40% of all objects. Maximum corresponds to $\sim$130 km s^{-1}. The high velocity part has maximum at $\sim$710 km s^{-1}.

Since early 70-s theoreticians are discussing the possibility of existence of quark (strange) stars (the first paper on QSs was published in 1965 by Ivanenko and Kurdgelaidze, see a review in Xu 2002 and some recent results and discussion from a more observational point of view in Thoma et al. 2003).

If both normal NSs and QSs exist in nature in comparable amount, then we can expect dichotomy of many properties of observed compact objects. In fact, even if QSs are so-called hybrid stars and in many senses are very similar to normal NSs, their initial properties can be different as far as the process of their birth can have pecularities. A dichotomy between NSs and QSs can be connected with the initial mass distribution of compact objects (see Timmes et al. 1996). A quark (or a hybrid) star can form in a delayed collapse (see Berezhiani et al. 2003) or in a direct

Table 1: Kick mechanisms

Mechanism	Time scale	V_{max}, km s^{-1}	Alignment (spin and V)	Main recent refs.
Hydrodynamical	0.1 s	$\sim(100-500)$	random	Lai et al. (2001), Scheck et al. (2004)
ν-driven	$\sim$ few s	$\sim 50\ B_{15}$	parallel	Lai et al. (2001)
Electromagnetic rocket	long	$1400\ R_{10}^2\, P_{ms}^{-2}$	parallel	Lai et al. (2001), Huang et al. (2003)
Binary disruption (without add. kick)	$<< P_{orb}$	~ 1000	perpendicular	Iben, Tutukov (1996)
NS instability	few ms	~ 1000	perpendicular	Colpi, Wasserman (2002), Imshennik, Ryazhskaja (2004)
Magnetorotational	$0.2-1$ s	~ 300 (up to 1000)	quasirandom (closer to parallel)	Moiseenko et al. 2003, Ardeljan et al. (2004)

collapse with an additional energy release (see for example Hong et al. 2001).

At first let us discuss the delayed collapse. The delayed collapse from a metastable hadron phase can happen due to a fall-back (i.e. after a short time since SN explosion; what the fall-back does is just decrease of the waiting time before transition) or due to accretion in a binary. (As far 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 as far as the outcome of NSs from binary systems is rather small to constitute $\sim$1/2 of the total PSR population.) Anyway an additional energy input can form a bimodal distribution of many parameters of objects which we usually call just NSs.

We suggest that the process of the delayed deconfinement can lead to the second kick of a compact object. So, the low velocity part of distribution is mainly formed by normal NSs which experienced one explosion. The high velocity part is mostly composed of QSs which received the second kick due to the deconfinement.

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

The second possibility for a QS to obtain a larger kick is the following. Higher velocities obtained due to deconfinement could be a result of shorter initial periods if electromagnetic rocket mechanism is operating (Harrison, Tademaru 1975). In this scenario the maximum velocity can be calculated as follows (Lai et al. 2001):

$$V_{max} \sim 1400 R_{10}^2 P_{ms}^{-2}\,\mathrm{kms}^{-1}. \tag{1}$$

Radii of QSs are typially 1.5-2 times lower than radii of NSs. If P of QSs are 4-5 times shorter then we can expect velocities 5-6 times larger. That is what is necessary to explain the difference between two peaks in the initial velocity distribution.

In the model of the delayed collapse it is difficult to increase a spin frequency by a factor of 4 in the process of a NS contraction into a QS (unless there is some additional spin-up due to kick). However, if a QS is formed on an early stage (i.e. without delay), then the difference in initial periods between QSs and NSs can be significant, as far as NSs are believed to suffer different instabilities which lead to spin-down, while QSs, for example, are not subject to the r-mode instability (Madsen 1998). Typical initial periods of NSs are about 20 ms and longer. With such periods the electromagnetic rocket mechanism is not effective. If QSs has typical radii about 7 km and are born with typical periods about 1 ms then they can form a peak around 700 km s^{-1}. Woosley et al. (2002) note that compact objects are expected to be born with periods $\sim$ 1 ms, and only due to the r-mode instability or similar processes NSs are expected to slow down to $>$ 20 ms.

In principle, if the 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 (see for example a paper by Huang and Wu 2003). But at the moment there is no data on the exact shape. Maxwellian distribution is just a reasonable hypothesis used by Arzoumanian et al. (2002). Reconstruction of the initial velocity distribution (especially on the high end) basing on the radio pulsar proper motion data cannot distinguish between Maxwellian and similar shapes.

3 Discussion

3.1 Problems of the scenarios

One problem for a delayed collapse is connected to the survival of close binaries where compact objects accreted significant amount of mass which could lead to deconfinement. Otherwise it is necessary to claim, that all observed accreting NSs in LMXB are normal NSs yet, not QSs which suffered deconfinement in their interiors (or that in the case of binaries deconfinement does not lead to large recoil). However, even with a strong kick there is non negligible probabilty of binary survival. Cir X-1 which has high spatial velocity (see discussion in Lai et al. 2001) can be an example. (Compact objects in HMXBs with moderate kicks discussed by Podsiadlowski et al. (2003) also should be normal NSs accroding to our scenario.)

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). In that case runaway binaries can form.

Another problem comes from the millisecond PSR (mPSR) velocity distribution. These objects are assumed to originate in LMXBs 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 it was shown by Lyne et al. (1998) average velocity of mPSR is rather low: ~ 130 km s^{-1}. And it is consistent with investigations of binary evolution. After the first SN explosion most of survived binaries correspond to the low velocity part of kick velocity distribution. I.e. in our scenario it means that nearly all NSs in LMXBs have to be NSs, not QSs since 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 deconfinement is proved to be in contradiction with observations of mPSRs and LMXBs, then it is a serious problem for the whole scenario of delayed deconfinement due to accretion in binaries as it is diffucult to understand symmetry of an energy release of $\sim 10^{53}$ erg s^{-1} from a compact object which is not a black hole. However, conditions for the second collapse can be different in a binary and in a fall-back. In the first case 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 explosions.

The rocket scenario also has some problems. The main 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 explan PSRs with $V > 1000$ km s^{-1}.

3.2 Glitches and internal structure

Starting from the most early discussions on the astrophysical manifestations of QSs (see for example Alcock et al. 1986) it was noted that glitches could be a problem for the QS hypothesis (see a recent discussion on glitches in QSs in Horvath 2004). We were able to find in the literature data on glitches from 34 PSRs. For 9 of these objects in the ATNF catalogue (Hobbs et al. 2003) transverse velocities are available. (See the table. Data mainly from Krawczyk et al. 2003, Lyne et al. 2000, Wang et al. 2000 and ATNF catalogue; also we add several estimates from Kaspi (1998) marking them with [k]; in bold we show more probable ones, according to Kaspi with Kaspi's coefficient equal to 3 or smaller and bolded in here table.) We note, that data for PSRs B1930+22 and B1727-33 is very uncertain.

For two-component distribution of Arzoumanian et al. (2002) contribution of the low velocity component dominate up to ~ 300 km s^{-1}, which corresponds to the transverse velocity ~ 250 km s^{-1}. As we see all but two velocity measurments are below this limit. The best known glitchers — Crab and Vela — definitely represent the low-velocity component. The highest-velocity PSR in the list (table 2) — 2224+65 — was reported to have a glitch just once (Shemar, Lyne 1996).

Another proposal, connected with the internal structure of NSs, was made by Larson and Link (1999). They suggested, that in the case of two NSs (namely PSR B1929+10 and 0950+08), for which high temperatures have been estimated, it is necessary to include internal source of heating — superfluid friction. However, later at least temperature estimate for 0959+08 was doubt. But in any case, if the proposal by Larson and Link is valid, it is interesting to note, that both NSs are low velocity objects ($V_t \sim 162.9$ and 36.4 km s^{-1} according to ATNF catalogue). So, they should be normal NSs, and for them this source of energy is available.

Glitches were also detected for AXP 1RXS J170849.0–400910 (Dall'Osso et al. 2003, Kaspi, Gavriil 2003). Note the comment of Zhang et al. (2000) about lower velocities of AXPs in comparison with SGRs, so that AXPs can be normal NSs and SGRs can be QSs.

Table 2: PSRs with glitches

Name	P (s)	$\dot{P}$	Dist (kpc)	Age (Yr)	B (G)	V_t (km/s)	Ref.
B0154+61	2.351	1.8893E-13	1.61	1.97e+05	2.13e+13	*	[1]
B0355+54	0.156	4.3969E-15	2.07	5.64e+05	8.39e+11	136.69	[2,3]
B0525+21	3.745	4.0036E-14	2.28	1.48e+06	1.24e+13	229.05	[2,3]
B0531+21	0.033	4.2276E-13	2.0	1.24e+03	3.78e+12	140.00	[3]
B0833-45	0.089	1.2501E-13	0.29	1.13e+04	3.38e+12	78.54	[3]
J1016-5857	0.107	8.0834E-14	9.31	2.1e+04	2.98e+12	*	[7]
B1046-58	0.124	9.6319E-14	2.98	2.03e+04	3.49e+12	*	[5]
J1105-6107	0.063	1.5826E-14	7.07	6.33e+04	1.01e+12	*	[5]
J1123-6259	0.271	5.2531E-15	7.54	8.19e+05	1.21e+12	*	[5]
B1325-43	0.532	3.0140E-15	2.29	2.80e+06	1.28e+12	587.17	[3]
B1338-62	0.193	2.5311E-13	8.55	1.21e+04	7.08e+12	*	[2,3]
J1437-6146	0.468	6.3304E-15	4.69	1.17e+06	1.74e+12	*	[7]
B1535-56	0.243	4.8493E-15	4.01	7.95e+05	1.10e+12	*	[2,3]
B1610-50	0.231	4.9494E-13	7.24	7.42e+03	1.08e+13	*	[5]
B1641-45	0.455	2.0090E-14	5.3	3.59e+05	3.06e+12	*	[3,3]
B1706-44	0.102	9.2984E-14	1.82	1.75e+04	3.12e+12	<**50** [k]	[2,3]
B1727-33	0.139	8.4829E-14	4.25	2.60e+04	3.48e+12	460 [k]	[2,3]
B1727-47	0.83	1.6363E-13	4.98	8.04e+04	1.18e+13	*	[5]
B1736-29	0.322	7.8798E-15	3.19	6.49e+05	1.61e+12	*	[2,3]
B1737-30	0.606	4.6587E-13	3.28	2.06e+04	1.70e+13	*	[1,3]
B1757-24	0.125	1.2791E-13	4.61	1.55e+04	4.04e+12	78.80	[5]
B1758-03	0.921	3.3101E-15	7.13	4.41e+06	1.77e+12	**200** [k]	[1]
B1758-23	0.415	1.1288E-13	13.49	5.84e+04	6.93e+12	*	[1,2,3]
B1800-21	0.133	1.3410E-13	3.94	1.58e+04	4.28e+12	∼ **0** [k]	[1,2,3]
J1806-2125	0.482	1.2140E-13	10.02	6.5e+04	7.74e+12	*	[4]
B 1822-09	0.789	5.2285E-14	1.00	2.33e+05	6.42e+12	74.96	[6]
B1823-13	0.101	7.5061E-14	4.12	2.14e+04	2.79e+12	∼ **0** [k]	[2,3]
B1830-08	0.085	9.1707E-15	5.67	1.47e+05	8.95e+11	200 [k]	[2,3]
B1859+07	0.643	2.2872E-15	5.49	4.46e+06	1.23e+12	*	[2,3]
B1907-03	0.504	2.1873E-15	10.25	3.66e+06	1.06e+12	*	[1]
B1917+00	1.272	7.6698E-15	3.32	2.63e+06	3.16e+12	35.2	[1]
B1930+22	0.144	5.7572E-14	9.8	3.98e+04	2.92e+12	750 [k]	[1]
B2224+65	0.682	9.6592E-15	2.00	1.12e+06	2.60e+12	1725.71	[2,3]
B2255+58	0.368	5.7529E-15	6.40	1.01e+06	1.47e+12	*	[1]

All data from ATNF catalogue (Hobbs et al. 2003) except [k].
References corresponds to papers, where recently glitches from these PSRs were discussed
[1] Krawczyk et al. (2003); [2] Shemar, Lyne (1996); [3] Lyne et al. (2000);
[4] Hobbs et al. (2002); [5] Wang et al. (2000);
[6] Shabanova, Urama (2000); [7] Hobbs et al. (2004).

3.3 Supernovae

At the moment nearly 3000 SNae have been observed. Potentially different types of SN can give different velocity distributions of 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 obsevationaly 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!), but no information about compact objects. For historical SNae we often know a compact object, but it is very difficult to reconstruct the SN type. Then there are SNRs associated with compact objects (see Kaspi, Helfand 2002), but it is also difficult to know for sure the type of SN which produced a given SNR.

Among core-collapse SN fractions 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). SN IIP probably originate from the most low massive stars which can still produce a SNII. SN Ib/c probably are product of binary evolution (or originate from very massive single stars). Compact objects which originate from single stars and compact objects which appeare after disruption of close binaries, should have different velocities simply due to additional orbital velocity. Detailed analysis of this situation was given for example by Iben and Tutukov (1996). They assumed, that no natal kick is added. 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 NSs is small. Oppositely accretion induced collapse (AIC) can produce low velocity NSs, but the contribution is also rather low: $3 \cdot 10^{-3}$ yr^{-1} (Podsiadlowski et al. 2003).

The Crab pulsar is probably associated with SN IIP. In some sense it goes in a line with our scenario, as far as compact objects, formed from low massive stars (i.e. $\sim 10-15\, M_{\odot}$) should be low velocity (i.e. $V_t < 250$ km s^{-1}) normal NSs and their fraction is $\sim 0.3-0.5$.

3.4 Other predictions and speculations

As the fractions of compact objects in the first and in the second components of the *initial* velocity distribution are more or less equal, then the number of *formed* NSs 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 that high. QSs can fill the galactic halo. In the galactic disc there should be not too many old isolated QSs, so for example, old accreting isolated compact objects are expected to be normal NSs. If QSs are fast objects then their fraction in globular clusters should be low as the escape velocity is usually <100 km s^{-1}.

In SNRs closer to the centers we expect to see normal NSs, and QSs with higher average velocities should be more displaced (for the same age). Also it is important to note, that the characteristic age $\tau = P/2\dot{P}$ in the case of delayed deconfinement should not be a good estimate of a real age of a compact object. If there is a delayed deconfinement of a single object, then we can expect (even if the scenario of explanation of bimodality is wrong) young PSRs without pronounced SNR or PSRs inside SNR with different age estimates (a PSR should be younger than its SNR, see also Dar 1999).

It is unclear if kick is correlated with the initial spin period. Postnov and Prokhorov (1998) argued, that a kick can be a reason of fast initial rotation. Contrary, Spruit and Phinney (1998) gave arguments for longer periods due to a kick. If this point is clarified one can speculate about different initial periods of QSs in comparison with normal NSs.

An outcome of a SN explosion depends on metallicity (Woosley et al. 2002). Masses of an iron core and shells, amount of fall-back, rotation rates etc. are different for stars with different fraction of heavy elements. Metallicity is changing during the lifetime of the Galaxy. Because of that one can expect different fraction of newborn QSs among compact objects at different galactic ages.

As the formation of a QS from a NS is accompanied by the shrinking of the compact object it can lead to increase of the magnetic field and decrease of a spin period. However, details of the process are uncertain. For example, Frail et al. (1994) note that in their set of PSRs high-velocity ones have higher magnetic fields. But results of that paper (mainly the reality of associasions of PSRs and SNRs) were later doubted. Results mentioned in Kaspi, Helfand (2002) are against any correlation between initial spin and velocity (see the table of initial spin periods for 7 PSRs in Migliazzo et al. 2002).

Now it is more or less clear that not all NSs pass the stage of active PSR (or at least this stage is very short for them). In that 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, definitely are low-velocity objects: $V_t < 200$ km s^{-1}.

Table 3: NSs with known initial periods (from Migliazzo et al. 2002)

Name	P, ms	V_t	Ref. for V_t
J0537-6910	< 14	~ 600	Kaspi, Helfand (2002)
B0531+21	19	~ 142	ATNF
B1951+32	27 ± 6	~ 296	ATNF
B0540-69	30 ± 8	—	—
J0205+6449	60	—	—
J1811-1925	62	< 110	Kaspi, Helfand (2002)
J1124-5916	90	—	—

Table 4: Other NSs with known velocities

Name	Type	P	V_t	Ref. for V_t	Comments
B0656+14	Cooler	0.385	~ 155	ATNF	
B1929+10	Cooler	0.227	~ 163	ATNF	marked by Larson, Link (1999) as a candidate for additional heating
B0950+08	Cooler ?	0.253	~ 36	ATNF	marked by Larson, Link (1999) as a candidate for additional heating
Geminga	γ-PSR	0.237	~ 128	ATNF	
J1856.5-3754	Magnificent seven	—	~ 185	Walter, Lattimer (2002)	
J0720.4-3125	Magnificent seven	8.4	$\sim 92 d_{200}$	Motch et al. (2003)	distance is uncertain, 200 pc was assumed
J0437-4715	cooler?	0.006	~ 94	ATNF	marked by Kargaltsev et al. (2003) as a candidate for additional heating

3.5 Correlations

In our opinion it is important to check possible links of properties associated with the internal structure of compact stars with their velocity properties, but not just in a form of correlations: it is important to check in which peak of the distribution a given compact star falls. Correlations can be absent inside each peak of the velocity distribution, but average values for NSs from each of the two peaks can be different. One example was presented above: among glitching PSRs the fraction of high-velocity objects is very low. Glitchers are young objects, so a selection effect due to quick escape of PSRs from observable volume is not very important ($l = 1$ kpc $V_{1000}\ t_{Myr}$). Even oppositely, another effect – that it is more difficult to measure small velocities – can be more important. Few high-velocity glitchers can be explained, for example, as NSs originated from close binaries (about 10% of the total number).

Due to different cooling history of NSs and QSs we can expect a correlation between temperature and velocity for young compact objects. However, cooling history is strongly mass-dependent both for HSs and QSs, so this kind of correlation should not be a clear one.

The fall-back process can bring additional correlations between different properties of compact objects (as it was suggested by Popov et al. 2002), especially this process can play a key role in shortening the time of delay between the SN explosion and the HS$\rightarrow$QS conversion. It would be very interesting to know if average masses of compact objects from the low- and high-velocity parts of the distribution are different or not.

4 Conclusion

The bimodal initial velocity distribution of PSRs can appear due to two different explosion mechanisms or due to two different sets of initial parameters of compact objects. Normal SN are responsible for the low velocity part of the velocity distribution, and the high velocity part is associated with the phase transition of NS interiors to deconfined state, i.e. with QSs.

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