

Kick velocity

Why do neutron stars move so rapidly?

Stars vs. Neutron Stars



Pulsar velocity distribution

Normal stars have velocities ~10-30 km/s.



Already in 70s it became clear that PSRs have high spatial velocities (>>10 km/s).

A breakthrough happened in 1994 when Lyne and Lorimer in a seminal paper in Nature showed that velocities are even higher than it was thought before – hundreds km/s.

Note, that the observed distribution is much different from the initial one. To derive the later it is necessary to calculate a model.

ATNF catalogue

SN explosions should not be symmetric!

E_{total}~3 10⁵³ erg Most of energy is carried away by neutrinos.

~Few % asymmetry in energy release can produce a strong kick up to 1000 km/s.

Main kick mechanisms

Asymmetric mass ejection (Shklovsky 1970)
Asymmetric neutrino emission (Chugai 1984)

Asymmetric mass ejection includes three mechanisms:

- gravitational pull due to asymmetric matter
- asymmetric neutrino emission due to matter distribution
- asymmetric matter jets (Khokhlov et al. 1999)

Leonid Ozernoy in 1965 discussed asymmetry of SN explosions in the context of GW radiation.

SN and kick explosion mechanisms

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

For neutrino emission: $V_{kick} = \epsilon E_{tot}/Mc \sim 1000 \text{ km/s} (\epsilon/0.1) (E_{tot}/10^{53} \text{ erg})$. Also it depends on the magnetic field.

Kick modeling

Recently, new results on the origin of NS and BH kicks have been obtained:

- Neutrino-triggered asymmetric magnetorotational mechanism arXiv:1110.1041
- Hydrodynamic Origin of Neutron Star Kicks arXiv: 1112.3342
- Three-dimensional neutrino-driven supernovae arXiv:1210.8148
- BH kicks arXiv:1203.3077

A review on SNae properties and explosion mechanisms: arXiv:1210.4921

To kick or not to kick?

Up to mid-90s it was not clear if kicks are absolutely necessary.

- Tademaru (rocket) mechanism
- Binary disruption (Blaaw mechanism)
- Core fragmentation (Berezinski et al., Imshennik)





Asymmetric dipole

However, some discoveries directly point to necessity of natal kicks.

Direct evidence

- 1. High-velocity NSs and binaries
- 2. Spin inclination in binaries and geodetic precession



Orbit inclination relative to a normal star equator can be measure due to:

- orbital precession due to spin-orbit interaction (Kaspi et al. 1996)
- circumstellar disc inclination (Prokhorov, Postnov 1997)



Guitar nebula, B2224+65

The most spectacular 3D velocity measurements for NSs are related to nebulae around these objects.

The transversal velocity can be measured by proper motion observations of radio pulsars and other neutron stars

For binaries large velocities are measured (Cir X-1: Johnston et al. 1999).

Double pulsar PSR J0737-3039

Pulsar A's spin is tilted from the orbital angular momentum by no more than 14 degrees at 95% confidence; pulsar B's -- by 130 ± 1 degrees at 99.7% confidence.



This spin-spin misalignment requires that the origin of most of B's present-day spin is connected to the supernova that formed pulsar B. The spin could be thought of as originating from the off-center nature of the kick. 1104.5001

See also 1302.2914 about probably near-zero for the pulsar A.

Many kick velocity distributions are proposed



Three popular models:

- Arzoumanian, Chernoff, Cordes (2002)
- Hobbs et al. (2005)
- Faucher-Giguer and Kaspi (2006)

Note the difference: We observe present day velocities with selection and evolutionary effects, but we are interested in the velocity at birth!

(Faucher-Giguer, Kaspi 2006)

Bimodal distribution



Arzoumanian et al. 2002

Scheck et al. 2006

Hydrodynamical models



2D simulations

Acceleration of a NS is mainly due to gravitational pull of the anisotropic ejecta



Scheck et al.

See 3D calculations in 1010.0167

NS kick models



Spin-kick alignment resulting from a neutrino-driven explosion launched from a phase of strong spiral-SASI activity.

While the explosion starts by equatorial expansion, the final NS kick is determined by the slower mass ejection in the polar directions.

The NS is accelerated by the gravitational attraction of the mass in these more slowly expanding, dense regions.

In the cartoon the NS is pulled more strongly towards the northern direction and therefore opposite to the (southern) hemisphere where the explosion is more powerful.

Spin-velocity alignment



[Ng & Romani]

Spatial velocity and spin axis are nearly coincident. *Nearly* is important: there is some misalignment.

The best studied cases: Crab and Vela



Crab and Vela are not the only cases, but are the best studied ones. Spin-velocity correlation (in direction) is reported for many radio pulsar. For some of them pulsar wind nebula observations are used, for some only direction of proper motion and polarization properties can be used.

Some set of PSRs with known spin-velocity orientation

		2D Pulsars		
B0628-28	318	+61/-64	5 ± 4	
B0740-28	259	+190/-149	7 ± 5	
B0823+26	189	+55/-34	21 ± 7	
B0835-41	170	± 30	13 ± 11	
B0919+06	506	± 80	32 ± 17	
B1133+16	639	+38/-35	22 ± 2	
B1325-43	597	±254	31 ± 22	
B1426-66	150	+40/-24	5 ± 9	
B1449-64	219	+55/-18	1 ± 3	
B1508+55	1082	+103/-90	23 ± 7	
B1642-03	160	+34/-32	26 ± 5	
B1800-21	347	+48/-57	7 ± 8	
B1842+14	512	+51/-50	5 ± 15	
B1929+10	173	+4/-5	16 ± 2	
B2045-16	304	+39/-38	3 ± 6	
IC 443	250	± 50	45 ± 10	
at -		3D Pulsars		
J0205+6449	838	±251	21 ± 10	
B0531+21	140	± 8	26 ± 3	
J0537-6910	634	± 50	3 ± 5	
J0538+2817	407	+116/-74	12 ± 4	
B0540-69	1300	± 612	34 ± 33	
B0833-45	61	± 2	10 ± 2	
B1706-44	645	±194	35 ± 10	
J1833-1034	125	± 30	16 ± 15	
B1951+32	273	± 11	18 ± 5	

[Ng & Romani 2007]

Recent data on radio pulsars



J name	B name	log[age] (yr)	V_T km s ⁻¹	PA_v (\circ)	PA ₀ (0)	Ψ (0)
J0452-1759	B0450-18	6.2	185	72(23)	47(3)	25(23)
J0659+1414	B0656+14	5.0	65	93.1(4)	-86(2)	-1(5)
J0738-4042	B0736-40	6.6	180	313(5)	-21(2)	-26(5)
J0837+0610	B0834+06	6.5	170	2(5)	18(5)	-16(7)
J0837-4135	B0835-41	6.5	360	187(6)	-84(5)	-89(8)
J1604-4909	B1600-49	6.7	510	268(6)	-17(3)	-75(7)
J1735-0724	B1732-07	6.7	570	355(3)	55(5)	-60(6)
J1801-2451	B1757-24	4.2	300	270	-55(5)	-35(5)
J1820-0427	B1818-04	6.2	190	338(17)	42(3)	-64(17)
J1850+1335	B1848+13	6.6	300	237(16)	-45(3)	-78(16)
J1915+1009	B1913+10	5.6	280	174(15)	85(3)	89(15)
J1937+2544	B1935+25	6.7	210	220(9)	-9(5)	49(10)
J2048-1616	B2045-16	6.5	330	92(2)	-13(5)	-75(6)
J2330-2005	B2327-20	6.7	180	86(2)	21(10)	65(10)

Johnston et al. (2007)

The tendency is clear, but it is only a tendency.

Rankin (2007)

New data and discussion in 1502.05270





Kick can be confined in some angle around the spin axis. Typical cones must be <~10° (see, for example, Kuranov et al. 2009).



Kick mechanism can be operative for a long time (many spin periods), so that its influence is average. Typical duration must be 1-10 sec.

Kicks in binary evolution







Influence of kicks on binaries

Kicks can both – destroy and **save** – binaries!



Parameters of binaries after kicks

Kicks significantly influence binary parameters (for example, eccentricity distribution). This is specially important for systems which survived the second explosion (NS+NS).

There are examples, when a NS rotates "in a wrong direction", i.e. its orbital motion is in the direction opposite to the spin of the second companion.

For detailed description see Postnov, Yungelson (astro-ph/0701059) pp. 18-22.



e-supernovae with low kicks

In 80s it was proposed by Nomoto, Miyaji et al. that in some cases a SN explosion can happen due to electron capture by ²⁴Mg and ²⁰Ne (no iron core is formed).

It was noticed (Pfahl et al. 2002, Podsiadlowski et al. 2004; van den Heuvel 2004, 2007) that among Be/X-ray binaries there is a group of systems with small eccentricities. But they suffered one SN explosion and there was no Roche-lobe overflow. This means that kicks in these systems were low. The same is true for some of NS+NS binaries.

The proposed mechanism is related to e^{-} -capture SN.

Such explosions can appear not only in binary systems, but in binaries they can be more frequent. Among isolated stars about 4% (up to ~20%!) of SN can be of this type (Poelarends et al. 2008). [It is not clear if they appear among normal PSRs.]

Why kick is low? Uncertain. Low core mass, rapid explosion, low mass ejection...



Evolution of e-capture SN progenitors



Critical core mass 1.367 solar masses.

For initial stellar masses >11 solar neon is ignited, and later on a Fe-core is formed.



Pulsars with low velocities



3C58. Low kick velocity. Projected velocity 30-40 km/s Some NSs demonstrate low spatial velocities. Obviously, this is due to low kicks.



Kicks as fingerprints

Think about young highly magnetized NSs of different types:

- ➤ SGR
- > AXP
- ➤ RRATs
- Magnificent Seven

Are they relatives?

It is a difficult question, but velocity measurements can give you a hint. Even if fields are decayed, rotation is slowed down, thermal energy is emitted ... if they are relatives – velocity distributions must be identical. Unfortunately, now we do not know the answer.

Magnetar velocity measurements

SGR 1806-20350 +/- 100 km/s arXiv:1210.8151SGR 1900+14130 +/- 30 km/s arXiv:1210.8151PSR J1550-5418280 +/- 130 km/s arXiv:1201.4684XTE J1810-197200 km/s Helfand et al. (2007)

Record velocities

- 1. PSR J1357-6429 1600-2000 km/s arXiv:1206.5149 shown to be wrong
- 2. IGR J11014-6103 2400-2900 km/s arXiv: 1204.2836



CCO velocities

RX J0822-4300 in the Supernova Remnant Puppis A

672 +/- 115 km/s arXiv: 1204.3510



Spinnig-up kicks

Do you play billiard?

Non-central kicks can spin-up a NS. In some cases one can speculate that a new rotation axis is determined mainly by non-central kick.

But then velocity - spin period correlation is expected.

Evolution of isolated NSs and kicks

Evolution of an isolated NS depends on the intensity of its interaction with the ISM. This intensity depends on the relative velocity of a NS and the ISM.



Will a NS start to accrete from the ISM, or will it stay as Ejector, or Propeller, or will in enter another regime strongly depends on the relative velocity of a NS and the ISM.

Galactic potential



Clearly, some NSs are rapid enough to leave the Galaxy.

Z-distribution of PSRs is much wider than the progenitors' one.



Wu et al. 2008

Mass distribution in the Galaxy



Klypin et al. (2002)

"Paczynski" model

Disc+Buldge+Halo Actually, it is Miyamoto, Nagai (1975) model. It is simple and popular in NS motion calculations.



At the very center one has to add the central BH potential

Examples of old NS distribution





In both models N=5 10⁸. Kick: ACC02. Potential: Paczynski 1990

NS formation rate is assumed to be proportional to the square of the ISM density at the birthplace.

Formation rate is proportional to [exp(-z/75 pc) exp(-R/4 kpc)].

astro-ph/0305599

X-ray sources in other galaxies



X-ray sources are shifted from the stellar light distribution. This might be due to kicks, especially in the case of NS binaries.

The effect cannot be explained by sources in globular clusters.



Black hole kicks

Do BHs obtain kicks?

- they are more massive
- horizon is formed
- SN mechanism can be different

If before the horizon formation a "protoNS-like" object is formed, then there should be a kick, but smaller (in km/s) due to larger mass. We do not know isolated BHs, but we know binaries. It is possible to measure velocity.



XTE J1118+480

Knowing just a velocity it is difficult to distinguish kick from dynamical interaction or initially large velocity (for example, a system can be from a globular cluster).

On the mechanism of BH kick see 1306.0007



Kick 45-115 km/s



Willems et al. (2005)

Cyg X-1



For this system the distance is known very precisely. This allows to trace the trajectory back and derive the value of post-SN peculiar velocity.

It is equal to 22-32 km/s. Probably, the BH obtained a moderate kick <77 km/s.



BH binaries in the Galaxy



The situation is not clear when we look at the whole population:

- Distribution for BHs is similar to the one for NS (for kick)
- Modeled distribution for zero kick can explain, roughly, the spatial distribution (against large kick)

Also line-of-site velocities are not high

Nelemans (2004)

Black hole kick velocities



Some BHs receive large kicks at birth. Difficult to explain by scaling from NSs.

H 1705-250



Large kick is not necessary. ~100 km/s is enough.

IC 10 X-1



M_{BH Pro} – progenitor mass before BH formation Low kick <130 km/s.



Velocity of BH and NS X-ray binaries



 $V_{
m pec,min} = \sqrt{2[\Phi(R_0,z) - \Phi(R_0,0)]},$

Some BHs might obtain significant kick.

NS binaries kick distribution is compatible with the one derived from PSRs.



1701.01347

Conclusions

- NSs and (most probably) BHs obtain natal kicks
- For NSs kick velocity can be as large as >1000 km/s
- The direction of the kick and rotation are correlated
- Kicks depend on the SN mechanism
- Kicks influence parameters of binaries
- Kicks influence evolution of isolated NSs



Important papers

- Lai astro-ph/0212140- different kick mechanisms
- ATNF catalogue database including PSR transversal velocities
- Ng & Romani, ApJ 660, 1357 (2007) spin-velocity alignment in PSRs with nebulae
- Johnston et al. MNRAS 381, 1625 (2007) and Rankin ApJ 664, 443 (2007) spin-velocity alignment in dozens of radio pulsars (polarization)
- Postnov, Yungelson astro-ph/0701059 kicks in binaries (pp.18-23)
- Ofek et al. NS spatial distribution. arXiv: 0910.3684