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Isolated Neutron Stars

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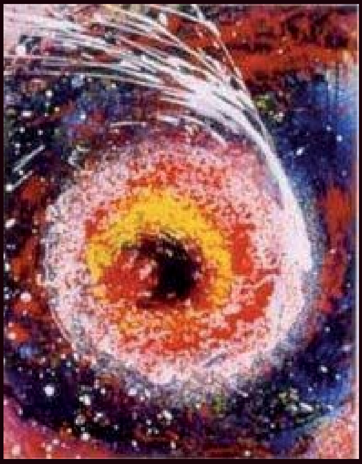
Abstract. Several aspects related to astrophysics of isolated neutron stars are discussed. We start with an introduction into the "new zoo" of young isolated neutron stars. In addition to classical radio pulsars, now we know several species (soft gamma-ray repeators, anomalous X-ray pulsars, central compact objects in supernova remnants, close-by cooling neutron stars - aka "Magnificent seven", - RRATs, and some others). All these types are briefly discussed. In the second lecture a description of magneto-rotational evolution of neutron stars is given. Finally, in the third lecture we discuss population synthesis of isolated neutron stars. In some details we discuss population synthesis of young isolated radio pulsars and young close-by cooling neutron stars.

Lecture 1
Isolated Neutron Stars. Intro.

Sergei Popov (SAI MSU)

Dubna "**Dense Matter In Heavy Ion Collisions and Astrophysics**", July 2008

Artistic view



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Prediction ...

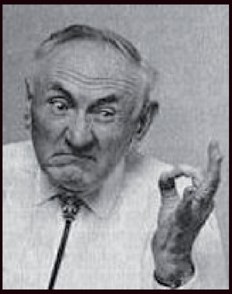
Neutron stars have been predicted in 30s:

L.D. Landau: Star-nuclei (1932) + anecdote

Baade and Zwicky:
neutron stars and supernovae (1934)

(Landau)

(Baade)



(Zwicky)

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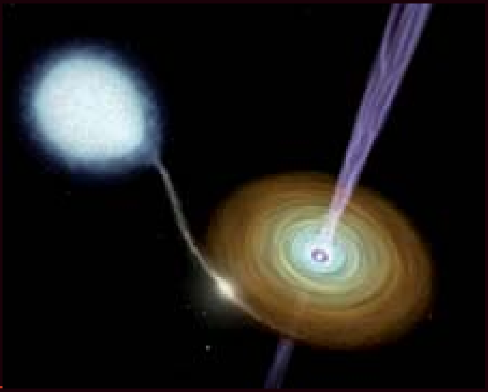
Good old classics

For years two main types of NSs have been discussed: radio pulsars and accreting NSs in close binary systems

The pulsar in the Crab nebula



A binary system

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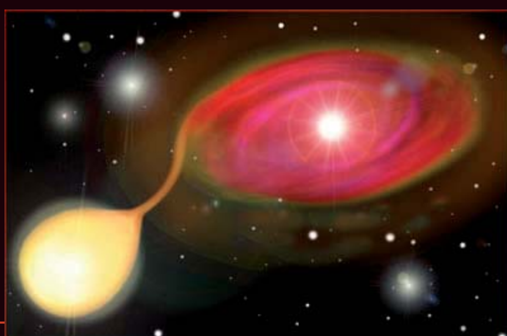
The old zoo of neutron stars

In 60s the first X-ray sources have been discovered.

They were neutron stars in close binary systems, BUT ...
.... they were «not recognized»....



Now we know hundreds of X-ray binaries with neutron stars in the Milky Way and in other galaxies.

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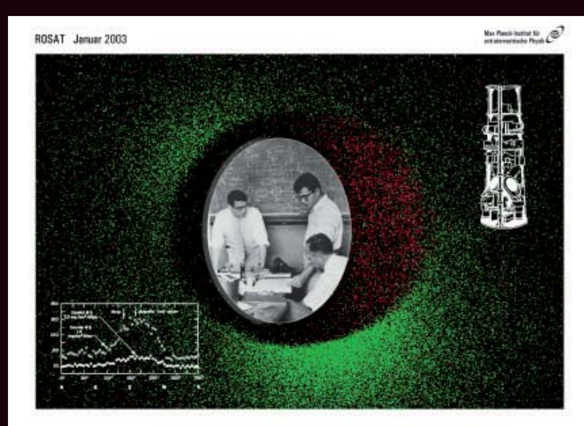
Rocket experiments
Sco X-1

Giacconi, Gursky, Hendel

1962

In 2002 R. Giacconi was awarded with the Nobel prize.



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Discovery !!!!

1967: Jocelyn Bell. Radio pulsars.

Seredipitous discovery.

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The pulsar in the Crab nebula

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The new zoo of neutron stars

During last >10 years
it became clear that neutron stars
can be born very different.
In particular, absolutely
non-similar to the Crab pulsar.

- o Compact central X-ray sources in supernova remnants.
- o Anomalous X-ray pulsars
- o Soft gamma repeaters
- o The Magnificent Seven
- o Unidentified EGRET sources
- o Transient radio sources (RRATs)
- o Calvera ….

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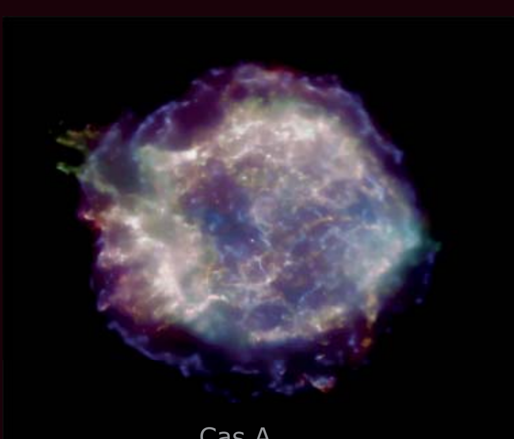
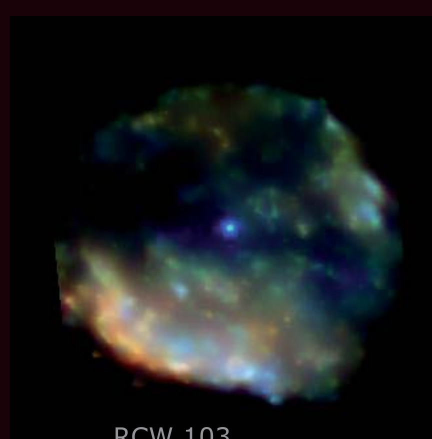
Compact central X-ray sources in supernova remnants





Problem: small emitting area

6.7 hour period
(de Luca et al. 2006, 0803.1373)

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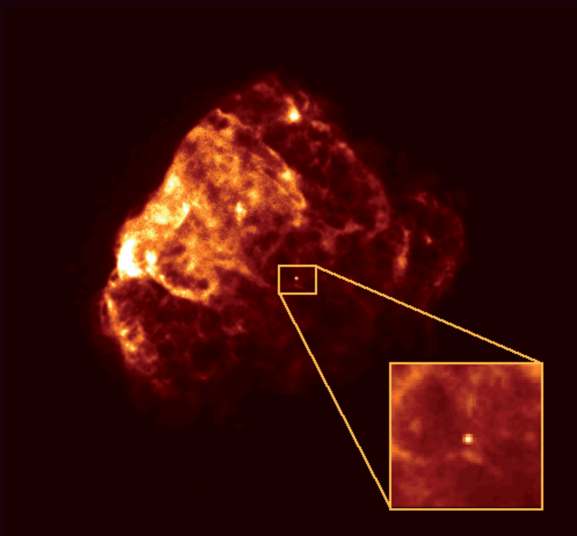
Puppis A



One of the most famous central compact X-ray sources in supernova remnants.

Age about 3700 years.

Probably the progenitor was a very massive star (mass about 30 solar).

V_{kick}=1500 km/s
Winkler, Petre 2006 (astro-ph/0608205)

See a review on these objects in arxiv:0712.2209

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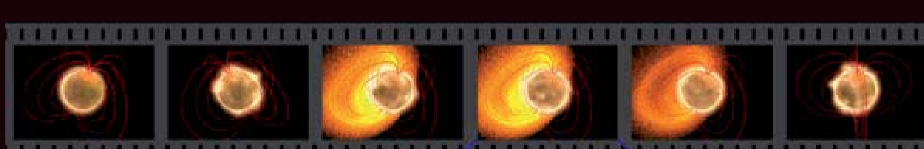
Magnetars

- $dE/dt > dE_{rot}/dt$
- By definition: The energy of the magnetic field is released
- P-Pdot
- Direct measurements of the field (Ibrahim et al.)

Magnetic fields 10^{14}–10^{15} G



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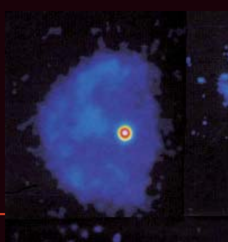
Known magnetars

SGRs

- 0526-66
- 1627-41
- 1806-20
- 1900+14
- +candidates



(CTB 109)

AXPs

- CXO 010043.1-72
- 4U 0142+61
- 1E 1048.1-5937
- CXOU J164710.3-
- 1 RXS J170849-40
- XTE J1810-197
- 1E 1841-045
- AX J1844-0258
- 1E 2259+586
- +candidates and transients

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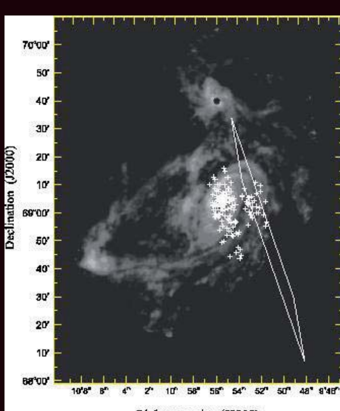
SGRs: monitoring and extraG



SRG detectors can contribute to observations of SGRs.

Now there are few other candidates (Mazets et al., Frederiks et al., Golenetskii et al., Ofek et al, Crider ....), including one in the direction of M31 (Mazets et al. arxiv:0712.1502).

[D. Frederiks et al. astro-ph/0609544]

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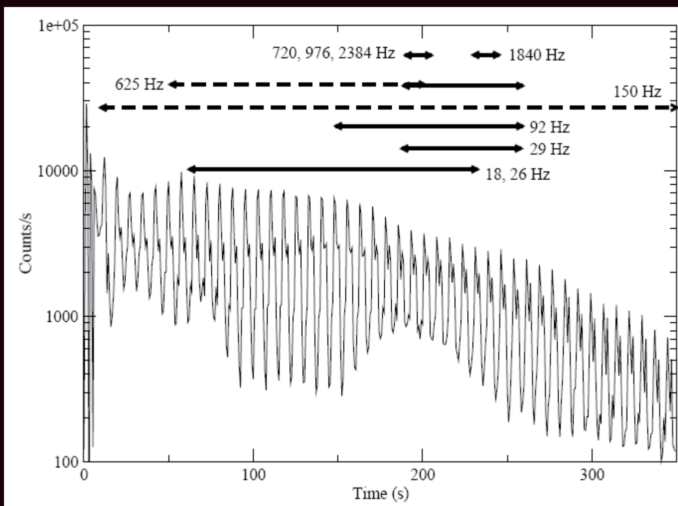
QPOs after giant flares



A kind of quasi periodic oscillations have been found in tail of two events (aug. 1998, dec. 2004). They are supposed to be torsional oscillations of NSs, however, it is not clear, yet.

(Israel et al. 2005 astro-ph/0505255, Watts and Strohmayer 2005 astro-ph/0608463)

See a recent review in aXiv: 0710.2475

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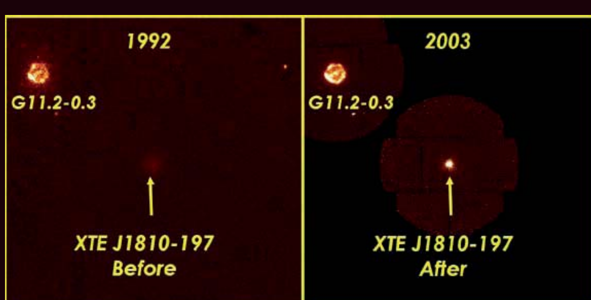
Transient radio emission from AXP



Radio emission was detected from XTE 1810-197 during its active state.

One another magnetar was reported to be detected at low frequencies in Pushchino, however, this result has to be checked.

(Camilo et al. astro-ph/0605429)

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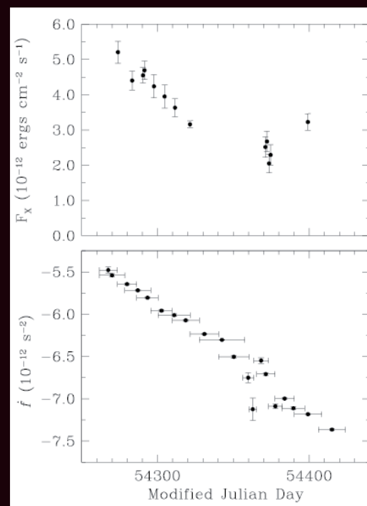
Another AXP detected in radio

1E 1547.0-5408
P= 2 sec
SNR G327.24-0.13



arxiv:0711.3780, 0802.0494

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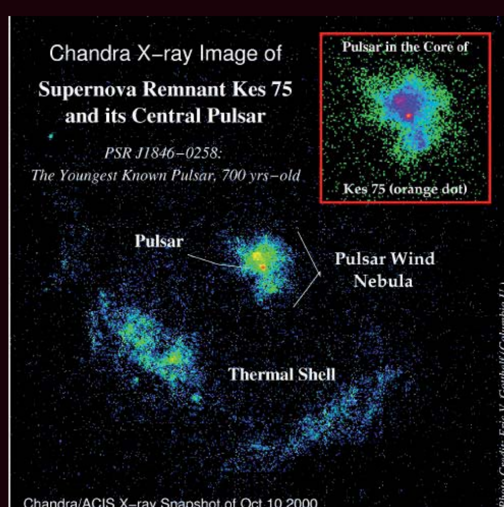
Transient radiopulsar

PSR J1846-0258
P=0.3 sec
B=5 10^{13} G

The pulsar increased
its luminosity in X-rays.
Magnetar-like X-ray bursts.



0802.1242, 0802.1704

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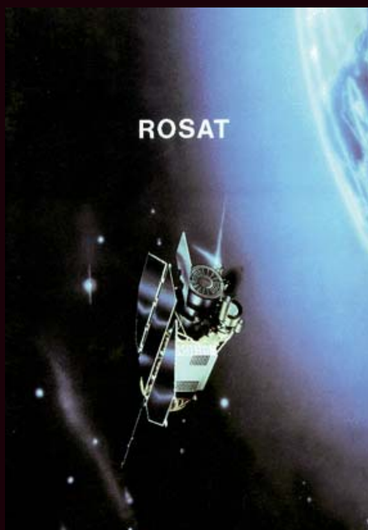
ROSAT



ROentgen SATellite

German satellite
(with participation of US and UK).

Launched 01 June 1990.
The program was successfully ended on 12 Feb 1999.

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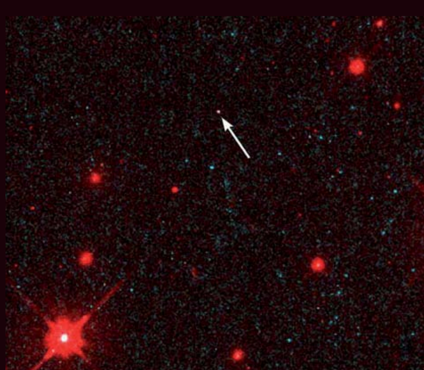
Close-by radioquiet NSs



RX J1856.5-3754

- Discovery: Walter et al. (1996)
- Proper motion and distance: Kaplan et al.
- No pulsations
- Thermal spectrum
- Later on: six brothers

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Magnificent Seven

Name	Period, s
RX 1856	7.05
RX 0720	8.39
RBS 1223	10.31
RBS 1556	6.88?
RX 0806	11.37
RX 0420	3.45
RBS 1774	9.44

Radioquiet (?)
Close-by
Thermal emission
Absorption features
Long periods

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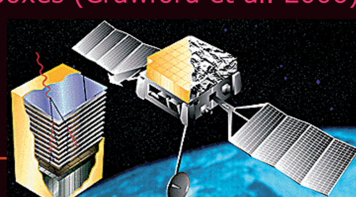
Unidentified EGRET sources

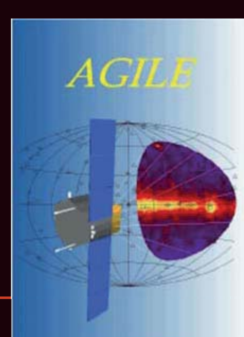
Grenier (2000), Gehrels et al. (2000)
Unidentified sources are divided into several groups.
One of them has sky distribution similar to the Gould Belt objects.

It is suggested that GLAST (and, probably, AGILE)
Can help to solve this problem.

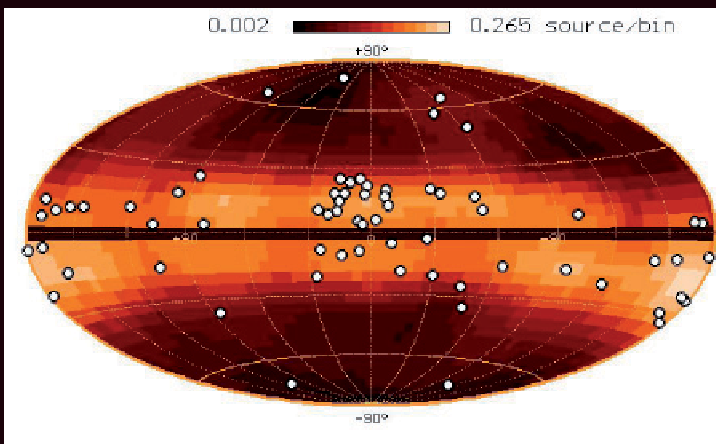
Actively studied subject
(see for example papers by Harding, Gonthier)

No radio pulsars in
56 EGRET error boxes (Crawford et al. 2006)





Pulsars invisible in radio?



(Grenier astro-ph/0011298)

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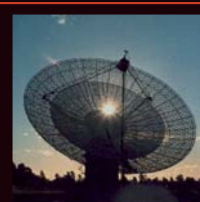
Discovery of radio transients



McLaughlin et al. (2006) discovered a new type of sources– RRATs (Rotating Radio Transients).
For most of the sources periods about few seconds were discovered.
The result was obtained during the Parkes survey of the Galactic plane.

These sources can be related to The Magnificent seven.

Thermal X-rays were observed from one of the RRATs (Reynolds et al. 2006). This one seems to me the youngest.

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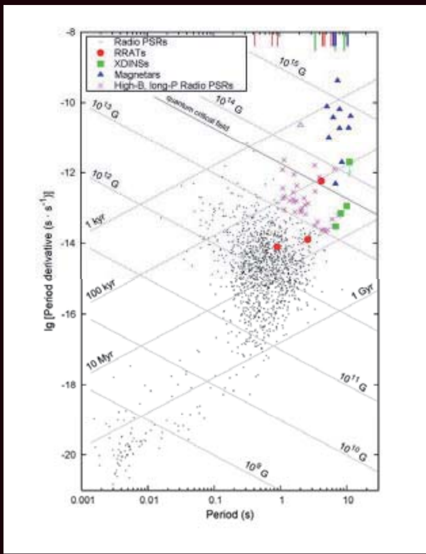
P-Pdot diagram for RRATs



McLaughlin et al. 2006 Nature

Estimates show that there should be about
400 000
Sources of this type in the Galaxy.

Young or old???

Relatives of the Magnificent seven?
(astro-ph/0603258)

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RRATs

- 11 sources detected in the Parkes Multibeam survey (McLaughlin et al 2006)
- Burst duration 2-30 ms, interval 4 min-3 hr
- Periods in the range 0.4-7 s
- Period derivative measured in 3 sources: B ~ 10^{12}-10^{14} G, age ~ 0.1-3 Myr
- RRAT J1819-1458 detected in the X-rays, spectrum soft and thermal, kT ~ 120 eV (Reynolds et al 2006)

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RRATs

- P, B, ages and X-ray properties of RRATs very similar to those of XDINSs
- Estimated number of RRATs ~ 3-5 times that of PSRs
- If $\tau_{RRAT} \approx \tau_{PSR}$, $\beta_{RRAT} \approx$ 3-5 β_{PSR}
- β_{XDINS} > 3 β_{PSR} (Popov et al 2006)
- Are RRATs far away XDINSs ?

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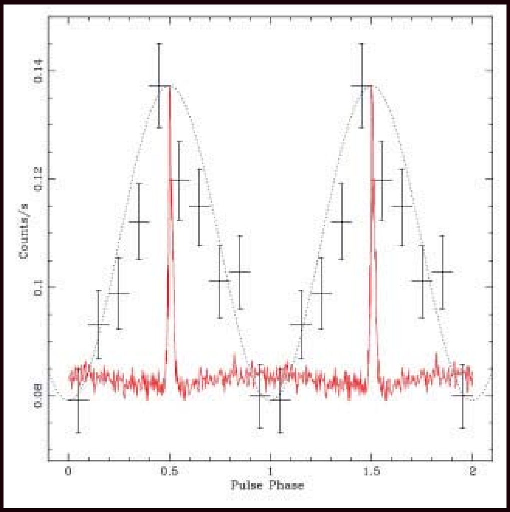
RRATs. Recent data



X-ray pulses overlaped on radio data of RRAT J1819-1458.

(arXiv: 0710.2056, see there also a brief review on these sources)

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Calvera et al.

Recently, Rutledge et al. reported the discovery of an enigmatic NS candidated dubbed *Calvera*.

It can be an evolved (aged) version of Cas A source,
but also it can be a M7-like object, who's progenitor was
a runaway (or, less probably, hypervelocity) star.

No radio emission was found (arxiv:0710.1788).

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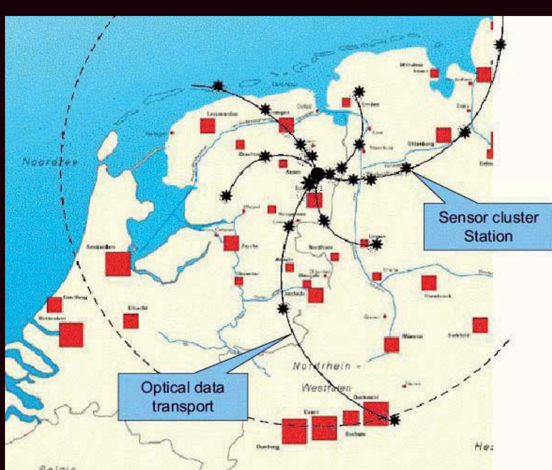
LOFAR



Low Frequency Array (<250 MHz)
Perfect for wide-field observations,
search for transients in radio etc.

See a brief review in arxiv:0710.0675

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Gravitational waves from INSs

INS are expected to be sources of GWs:

- Radio pulsars
- Young magnetars
- ....?

→

- Know periods
- Rapid rotation and strong deformation
- Possible new types sources

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Recent LIGO results for PSRs

1. 0805.4758 **Beating the spin-down limit on gravitational wave emission from the Crab pulsar**

$h_0^{95\%} < 3.5\ 10^{-25}$ $\varepsilon<1.9\ 10^{-4}$ (single template)

2. 0708.3818 **All-sky search for periodic grav. waves in LIGO S4 data**

50-1000 HZ
No evidence. Upper limits on isolated NSs GW emission.
Very weak limits for "dark" sources (<50 pc for $\varepsilon \sim 10^{-6}$)

3. gr-qc/0702039 **Upper limits on gravitational wave emission from 78 PSRs**

$\varepsilon < 10^{-6}$ for PSR J2124−3358
$h<2.6\times10^{-25}$ for PSR J1603−7202

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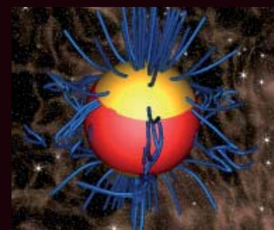
GWs from young magnetars



A newborn magnetar with msec period and toroidal magnetic field B~10^{16} G for few days can be a strong source detectable from the Virgo cluster distance by advanced LIGO.

Birthrate of magnetars in Virgo is about 0.3-1 per year.

Due to strong toroidal magnetic fields young magnetars can have prolate shape with ellipticity $10^{-3} - 10^{-4}$.

Power of the signal goes as ~P^{-6}.

$$\dot{\omega} = -K_d\omega^3 - K_{gw}\omega^5$$

$$\tau_{sd} \equiv \frac{\omega}{2\dot{\omega}} \simeq 10 \;\; P_{i,2}^2 \left(B_{d,14}^2 + 1.15 B_{t,16.3}^4 P_{i,2}^{-2}\right)^{-1} \mathrm{d}$$

$$h \sim 3 \times 10^{-26} d_{20}^{-1} P_2^{-2} B_{t,16.3}^2$$

Instantaneous signal

astro-ph/0702075 Dall'Osso et al.
astro-ph/0511068 Stella et al.

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Detectability by advanced LIGO

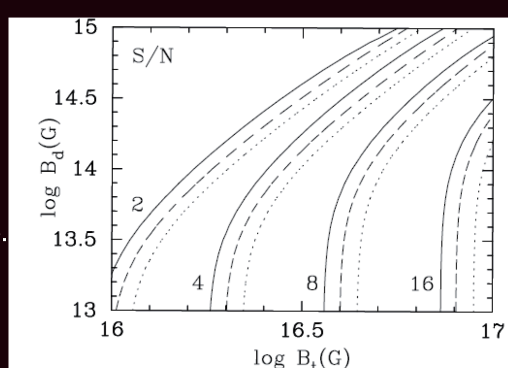
$$h_c = hN^{1/2}, \text{ where } N \simeq \tau_{sd}/P_i$$

The signal is observable for several periods

$$h_c \simeq 6 \times 10^{-22} \frac{B_{t,16.3}^2}{d_{20} P_{i,2}^{3/2} \left(B_{d,14}^2 + 1.15 B_{t,16.3}^4 P_{i,2}^{-2}\right)^{\frac{1}{2}}}$$

So, the signal lasts for several days after a magnetar's birth

It is possible to get very optimistic predictions for advanced LIGO. However, mining the data for a signal with uknown parameters from unknown place in the sky is very complicated. Computational costs are very large.



astro-ph/0702075 Dall'Osso et al.

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Magnetar parameters

Estimating GW emission form magnetars it is necessary to make assumptions avout ellipticity. It is not that easy.

0712.2162 Pons et al.
Relativistic models of magnetars: structure and deformations

This authors estimate that for B~10^{15} G ellipticity is expected ~10^{-6} – 10^{-5}
In extreme cases (low-mass NSs) it can go up to 10^{-3}
Crustal field are very important.

0806.2794 Regimbau, Mandic
Astrophysical sources of stochastic GW background

Magnetars produce strong (in comparison with expected cosmological signal) background around 1 kHz (depends on initil spin of magnetars).

Next generation of interferometers will give important results on NSs.

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Population synthesis of close-by NS and GWs

Palomba [astro-ph/0503046]

The author assumes that some fraction of NSs are born with low magnetic fields, so that GW losses dominate in spin-down.

The author predicts that few NSs can be detected by Virgo
(for not too small fraction of low-field NSs),
and tens – by advanced Virgo.

Expected distances (for Virgo) are 100-300 pc, and frequences about 200-600 Hz.

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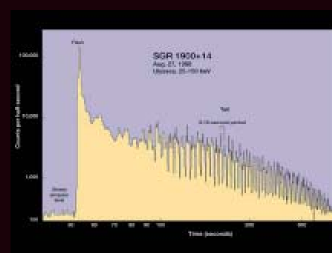
Conclusion

- There are several types of sources: CCOs, M7,
  SGRs, AXPs, RRATs ...
- Magnetars (?)
- Significant fraction of all newborn NSs
- Unsolved problems:
  1. Are there links?
  2. Reasons for diversity



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Main reviews

•NS basics:	physics/0503245
	astro-ph/0405262
•SGRs & AXPs:	astro-ph/0406133
•CCOs:	astro-ph/0311526
	0712.2209
•Quark stars:	astro-ph/0608360
•The Magnificent Seven:	astro-ph/0502457
	astro-ph/0609066
	0801.1143
•RRATs:	astro-ph/0511587
•Cooling of NSs:	astro-ph/0508056
	astro-ph/0402143
• NS structure	astro-ph/0608360
• NS interiors	arXiv: 0705.2708
• Magnetic field of NSs	arXiv: 0802.2227
	0711.3650
• EoS	astro-ph/0612440
• NS atmospheres	astro-ph/0206025

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Lecture 2
Spin evolution of NSs

Sergei Popov (SAI MSU)

Dubna "**Dense Matter In Heavy Ion Collisions and Astrophysics**", July 2008

Hard life of neutron stars

There are about 6 10^9 persons on Earth. How many do you know?
There are about 1 10^9 NSs in the Galaxy. How many do we know? Why?

We know PSRs, SGRs, AXPs, CCOs, M7, RRATs, ... They are young.

Dialogue of two magnetars:

-We are not getting younger, man....
-Yeh, at first you lose spin, then – magnetic field, and then you just cool down...
- ...and nobody cares about you any more ....

Evolution is important!!!

2

Evolution of neutron stars

Thermal

Magneto-rotational

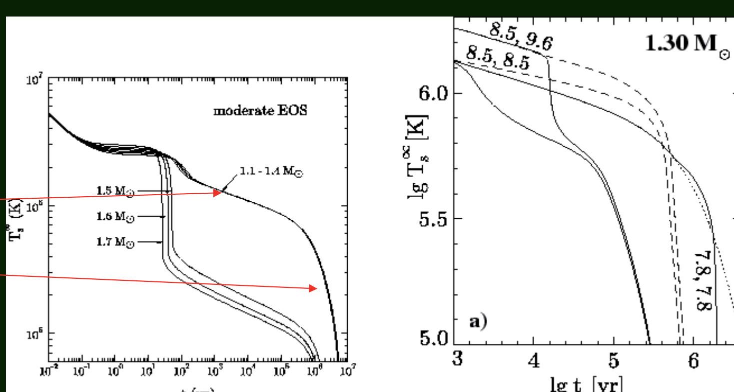
Observational appearence of a NS can depend on:
- Temperature
- Period
- Magnetic field
- Velocity

3

Evolution of NSs: temperature

Neutrino cooling stage

Photon cooling stage



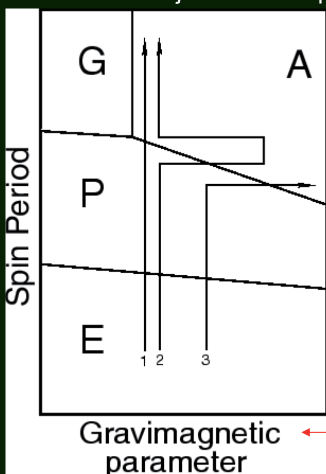
[Yakovlev et al. (1999) Physics Uspekhi]

First papers on the thermal evolution appeared already in early 60s, i.e. before the discovery of radio pulsars.

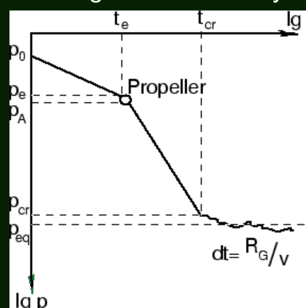
4

Evolution of neutron stars: rotation + magnetic field

Ejector → Propeller → Accretor → Georotator



1 – spin down
2 – passage through a molecular cloud
3 – magnetic field decay

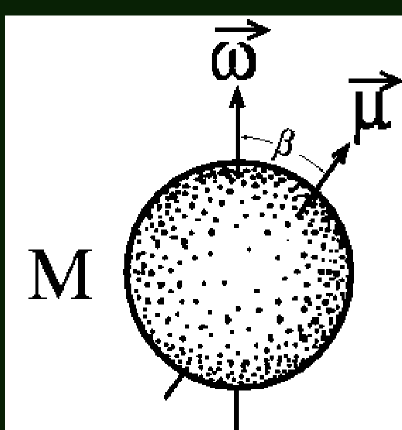


Mdot/μ²

astro-ph/0101031

See the book by Lipunov (1987, 1992)

Magnetic rotator



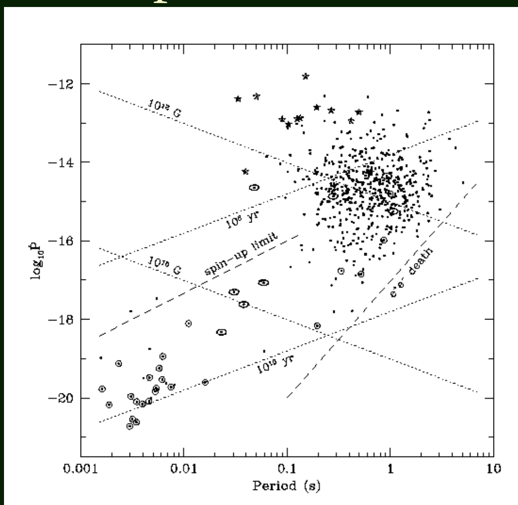
Observational appearences of NSs
(if we are not speaking about cooling)
are mainly determined by P, Pdot, V, B,
(probably the inclination angle χ),
and properties of the surrounding medium.
B is not evolving significantly in most cases,
so it is important to discuss spin evolution.

Together with changes in B (and χ)
one can speak about

magneto-rotational evolution

We are going to discuss the main stages
of this evolution, namely:
Ejector, Propeller, Accretor, and *Georotator*
following the classification by Lipunov

Magneto-rotational evolution of radio pulsars



For radio pulsar magneto-rotational evolution is usually illustrated in the P-Pdot diagram.
However, we are interested also in the evolution after this stage.

$$L_m = \frac{2}{3}\frac{\mu^2\omega^4}{c^3}\sin^2\beta = \kappa_t \frac{\mu^2}{R_l^3}\omega\,,$$

$$B \sim 3.2 \times 10^{19}\,(PdP/dt)^{1/2}\ \mathrm{G}.$$

Spin-down.
Rotational energy is released.
The exact mechanism is still unknown.

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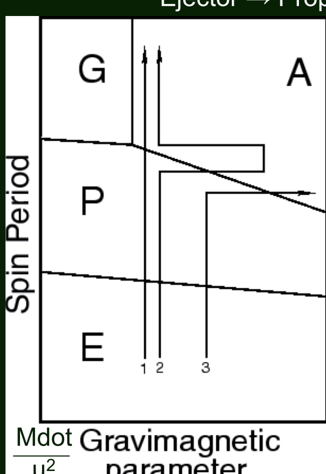
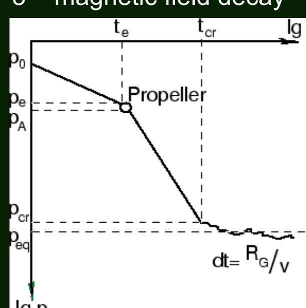
Magneto-rotational evolution of NSs

Ejector → Propeller → Accretor → Georotator



1 – spin down
2 – passage through a molecular cloud
3 – magnetic field decay



astro-ph/0101031

See the book by Lipunov (1987, 1992)

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Critical radii -I

Transitions between different evolutionary stages can be treated in terms of critical radii

- Ejector stage. Radius of the light cylinder. $R_l = c/\omega$.
  Shvartsman radius. R_{sh}.
- Propeller stage. Corotation radius. R_{co}
- Accretor stage. Magnetospheric (Alfven) radius. R_A
- Georotator stage. Magnetospheric (Alfven) radius. R_A

As observational appearence is related to interaction with the surrounding medium the radius of *gravitational capture* is always important. $R_G = 2GM/V^2$.

Schwarzshild radii is typicall unimportant.

$$r_g = \frac{2GM}{c^2} \approx 2.95 \frac{M}{M_{SUN}} \text{ km}$$

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Critical radii-II

1. Shvartsman radius
   It is determined by relativistic particles wind

$$R_{\rm Sh} = \left(\frac{8\kappa_t \mu^2 G^2 M^2 \omega^4}{\dot{M}_c v_\infty^5 c^4}\right)^{1/2}, \qquad R_{\rm Sh} > R_G$$

2. Corotation radius $\omega R_{\rm St} < \sqrt{GM_x/R_{\rm St}}$.

$$R_c = (GM_x/\omega^2)^{1/3} \sim 2.8 \times 10^8 m_x^{1/3} (P/1\ \text{s})^{2/3} \text{ cm}$$

3. Alfven radius $P_m(R_{\rm st}) = P_a(R_{\rm st})$

$$R_A = \begin{cases} \left(\dfrac{2\mu^2 G^2 M^2}{\dot{M}_c v_\infty^5}\right)^{1/6}, & R_A > R_G \\ \left(\dfrac{\mu^2}{2\dot{M}_c\sqrt{2GM}}\right)^{2/7}, & R_A \le R_G \end{cases}$$

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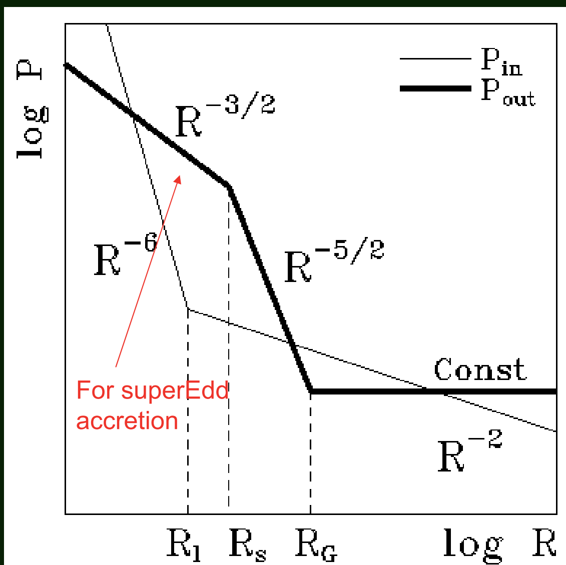
Pressure



$$P_m = \begin{cases} \dfrac{\mu^2}{8\pi R^6}, & R \le R_l \\ \dfrac{L_m}{4\pi R^2 c}, & R > R_l \end{cases}$$

$$L_m = \kappa_t \frac{\mu^2}{R_l^3}\omega$$

We can define a stopping radius R_{st}, at which external and internal pressures are equal.

The stage is determined by relation of this radius to other critial radii.

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Classification

Abbreviation	Type	Characteristic radii relation	Accretion rate	Observational appearances
E	Ejector	$R_{st} > R_G$ $R_{st} > R_l$	$\dot{M}_c \le \dot{M}_{cr}$	Radiopulsars, Soft γ-ray repeaters, Cyg X-3? LSI+61 303?
P	Propeller	$R_c < R_{st}$ $R_{st} \le R_G$ $R_{st} \le R_l$	$\dot{M}_c \le \dot{M}_{cr}$	X-ray transients? Rapid burster? γ-bursters??? Magnetic Ap-stars
A	Accretor	$R_{st} \le R_G$ $R_{st} \le R_l$	$\dot{M}_c \le \dot{M}_{cr}$	X-ray pulsars, bursters, cataclysmic variables, intermediate polars
G	Georotator	$R_G < R_{st}$ $R_{st} \le R_c$	$\dot{M}_c \le \dot{M}_{cr}$	Earth, Jupiter
M	Magnetor	$R_{st} > a$ $R_c > a$???	$\dot{M}_c \le \dot{M}_{cr}$	AM Her, polars

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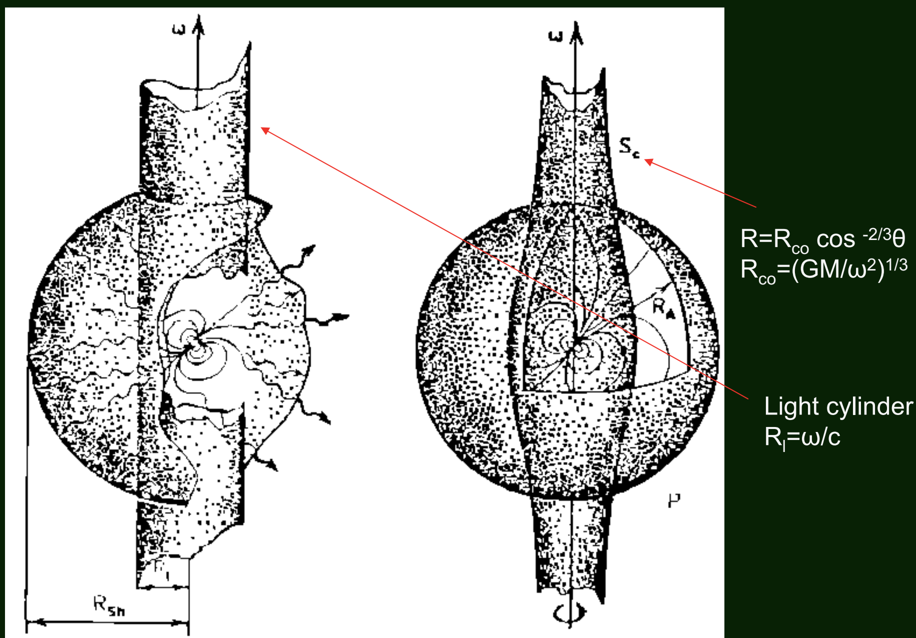

Ejector **Propeller**

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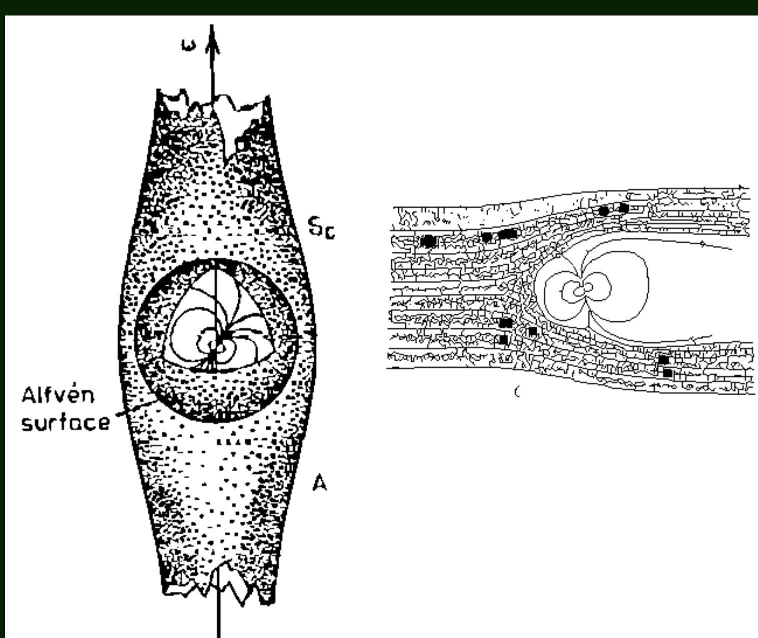

Accretor **Georotator**

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Unified approach to spin-down

One can find it comfortable to represent the spin-down moment by such a formula $-\kappa_t \frac{\mu^2}{R_t^3}$

k_t and R_t are different for different stages.
k_t can be also frequency dependent.

Parameter	Regime					
	E, SE	P, SP	A	SA	G	M
$\dot{M}$	0	0	$\dot{M}_c$	$\dot{M}_c(R_A/R_s)$	0	$\dot{M}_c$
κ_t	~2/3	$\lesssim$1/3	~1/3	~1/3	~1/3	~1/3
R_t	R_l	R_m	R_c	R_c	R_A	a

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Spin-up/down at the stage of accretion

$$\frac{dI\omega}{dt} = \dot{M} k_{su} - \kappa_t \frac{\mu^2}{R_t^3}$$

$$k_{su} = \begin{cases} (GM_x R_d)^{1/2}, & \text{Keplerian disk accretion,} \\ \eta_t \Omega R_G^2, & \text{wind accretion in a binary,} \\ \sim 0, & \text{a single magnetic rotator.} \end{cases}$$

For a single rotator (i.e. an isolated NS) spin-up can be possible due to turbulence in the interstellar medium.

In the case of isolated accreting NS one can estimate the accretion rate as: $\dot{M}_c = 4\pi R_G^2 \rho_\infty v_\infty$

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Equilibrium period

$$\dot{M} k_{su} = -\kappa_t \frac{\mu^2}{R_t^3}$$

The hypothesis of equilibrium can be used to determine properties of a NS.

The corotation radius is decreasing as a NS is spinning up.
So, before equilibrium is reached the transition to the propeller stage can happen.

Looking at this formula (and remembering that for Accretors $R_t=R_{co}$) it is easy to understand why millisecond PSRs have small magnetic field.
Spin-up can not be very large (Eddington rate).
So, to have small spin periods (and so small corotation radii), it is necessary to have small magnetic fields.
High magnetic field NS can not be spun-up to millisecond periods.

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Critical periods for isolated NSs

$$P_E(E \rightarrow P) \simeq 10\, \mu_{30}^{1/2}\, n^{-1/4}\, v_{10}^{1/2}\ \mathrm{s}$$

Transition from Ejector to Propeller (supersonic)

$$t_E \simeq 10^9\, \mu_{30}^{-1}\, n^{-1/2}\, v_{10}\ \mathrm{yr}$$

Duration of the ejector stage

$$P_A(P \rightarrow A) \simeq 420\, \mu_{30}^{6/7}\, n^{-3/7}\, v_{10}^{9/7}\ \mathrm{s}$$

Transition from supersonic Propeller to subsonic Propeller or Accretor

$$P_{eq} = 2.6 \times 10^3\, v_{(t)10}^{-2/3}\, \mu_{30}^{2/3}\, n^{-2/3}\, v_{10}^{13/3}\ \mathrm{s}$$

A kind of equilibrium period for the case of accretion from turbulent medium

$$v < 410\, n^{1/10}\, \mu_{30}^{-1/5}\ \mathrm{km\, s^{-1}}$$

Condition for the Georotator formation (instead of Propeller or Accretor)

(see, for example, astro-ph/9910114)

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Accreting isolated neutron stars

Why are they so important?

- Can show us how old NSs look like
  1. Magnetic field decay
  2. Spin evolution
- Physics of accretion at low rates
- NS velocity distribution
- New probe of NS surface and interiors
- ISM probe

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Expected properties

1. **Accretion rate**

An upper limit can be given by the Bondi formula:
Mdot = π R_G^2 ρ v, $R_G \sim v^{-2}$
Mdot = 10^{11} g/s (v/10 km/s) $^{-3}$ n
L=0.1 Mdot $c^2 \sim 10^{31}$ erg/s

However, accretion can be smaller due to the influence of a magnetosphere of a NS

2. **Periods**

Periods of old accreting NSs are uncertain, because we do not know evolution well enough.

a) $$p_{\rm A} = 2^{5/14}\pi(GM)^{-5/7}(\mu^2/\dot{M})^{3/7} \simeq$$

R_A=R_{co} $$300\,\mu_{30}^{6/7}(v/10\,{\rm km\,s^{-1}})^{9/7}n^{-3/7}\ {\rm s.}$$

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Subsonic propeller

Even after $R_{co}>R_A$ accretion can be inhibited.
This have been noted already in the pioneer papers by Davies et al.

Due to rapid (however, subsonic) rotation a hot envelope is formed around the magnetosphere. So, a new critical period appear.

$$P_{br} \simeq 450\ \mu_{30}^{16/21}\ \dot{M}_{15}^{-5/7}\ m^{-4/21}\ \mathrm{s.}$$

(Ikhsanov astro-ph/0310076)

If this stage is realized (inefficient cooling) then
- accretion starts later
- accretors have longer periods

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Expected properties-2

3. Temperatures

Depend on the magnetic field. The size of polar caps depends on the field and accretion rate: $\sim R\ (R/R_A)^{1/2}$

4. Magnetic fields

Very uncertain, as models of the field decay cannot give any solid predictions

5. Flux variiability.

Due to fluctuations of matter density and turbulent velocity in the ISM it is expected that isolated accretors are variable on a time scale $\sim R_G/v \sim$ days - months

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Still, isolated accretors are expected to be numerous at low fluxes (their total number in the Galaxy is large than the number of coolers of comparable luminosity). They should be hotter than coolers, and have much longer spin periods.

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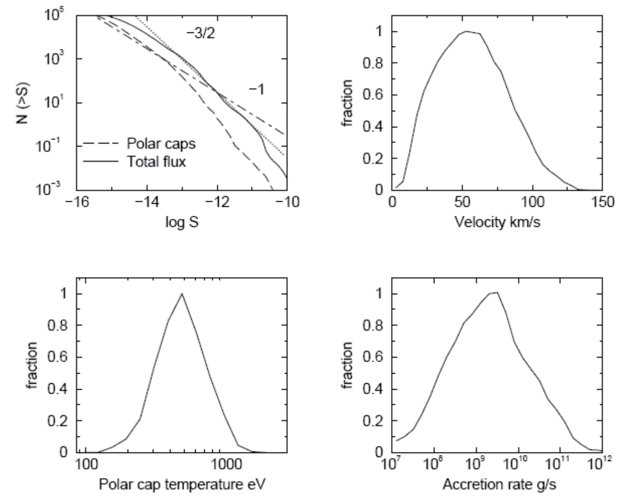
Properties of accretors



In the framework of a simplified model (no subsonic propeller, no field decay, no accretion inhibition, etc.) one can estimate properties of isolated accretors.

Slow, hot, dim, numerous at low fluxes ($<10^{-13}$ erg/cm^2/s)

Reality is more uncertain.

(astro-ph/0009225)

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Where and how to look for

As sources are dim even in X-rays,
and probably are extremely dim in other bands
it is very difficult to find them.

In an optimistic scenario they outnumber cooling NSs at low fluxes.
Probably, for ROSAT they are to dim.
We hope that eROSITA will be able to identify accreting INSs.

Their spatial density at fluxes $\sim 10^{-15}$ erg/cm^2/s is expected to be ~few per sq.degree in directions close to the galactic plane.

It is necessary to have an X-ray survey at ~100-500 eV with good resolution.

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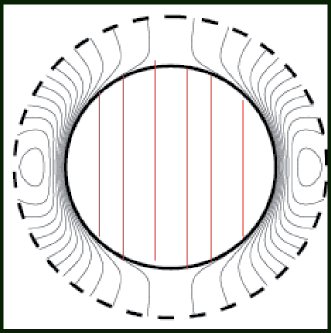
Magnetic field decay

Magnetic fields of NSs are expected to decay due to decay of currents which support them.



Crustal field of core field?

It is easy do decay in the crust.

In the core the filed is in the form of superconducting vortices. They can decay only when they are moved into the crust (during spin-down).

Still, in most of model strong fields decay.

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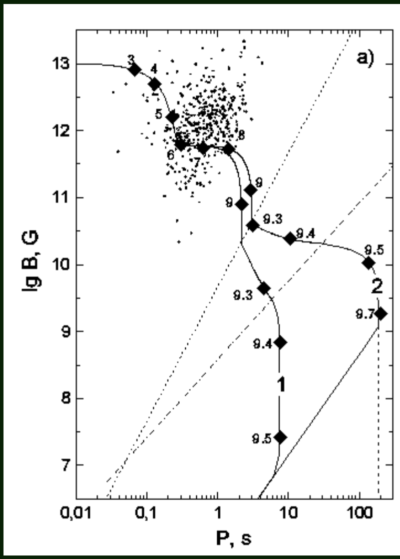
Period evolution with field decay



An evolutionary track of a NS is very different in the case of decaying magnetic field.

The most important feature is slow-down of spin-down. Finally, a NS can nearly freeze at some value of spin period.

Several episodes of relatively rapid field decay can happen.

Number of isolated accretors can be both decreased or increased in different models of field decay. But in any case their average periods become shorter and temperatures lower.

astro-ph/9707318

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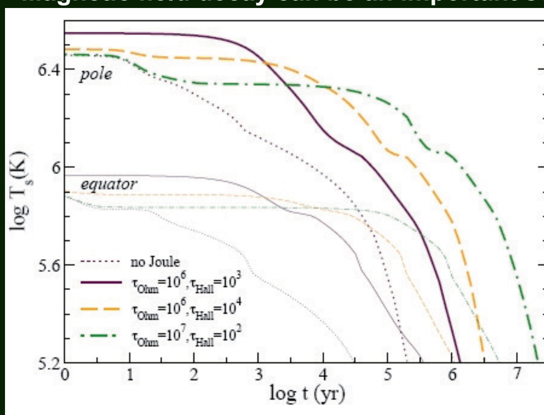
Magnetic field decay vs. thermal evolution

Magnetic field decay can be an important source of NS heating.



Heat is carried by electrons.
It is easier to transport heat along field lines. So, poles are hotter.
(for light elements envelope the situation can be different).

Ohm and Hall decay

$$B = B_0 \frac{\exp(-t/\tau_{\rm Ohm})}{1 + \frac{\tau_{\rm Ohm}}{\tau_{\rm Hall}}(1 - \exp(-t/\tau_{\rm Ohm}))}$$

arxiv:0710.0854 (Aguilera et al.)

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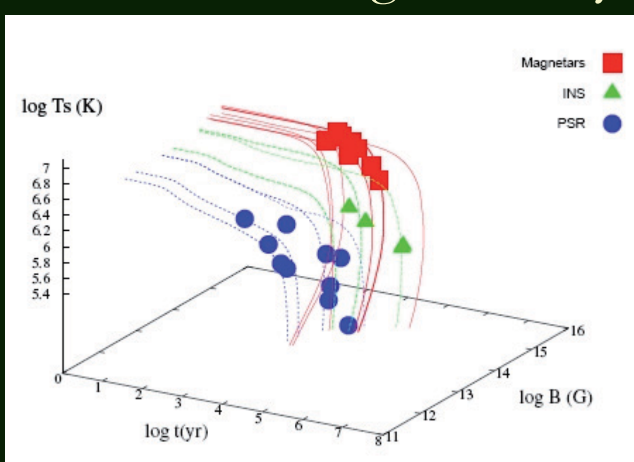
Thermal heating for everybody?



It is important to understand the role of heating by the field decay for different types of INS.
In the model by Pons et al. the effect is more important for NSs with larger initial B.

Note, that the characteristic age estimate (p/2 pdot) are different in the case of decaying field!

arXiv: 0710.4914 (Aguilera et al.)

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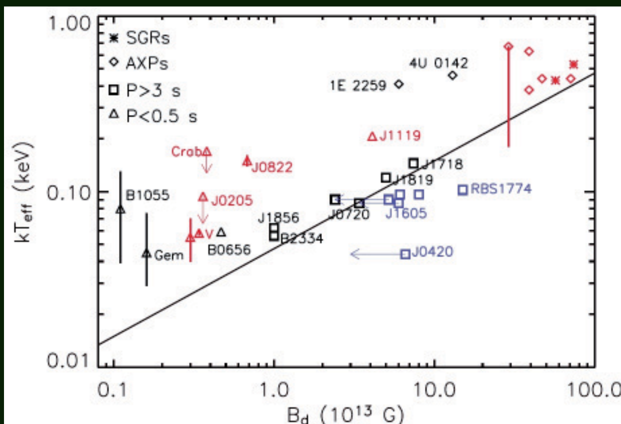
Magnetic field vs. temperature



The line marks balance between heating due to the field decay and cooling. It is expected by the authors (Pons et al.) that a NS evolves downwards till it reaches the line, then the evolution proceeds along the line.

Selection effects are not well studied here.
A kind of population synthesis modeling is welcomed.

(astro-ph/0607583)

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Radio pulsar braking: current losses

The model of pulsar emission is not known, and also the model for spin-down is not known, too. Well-known magneto-dipole formula is just a kind of approximation.

One of competitors is ***longitudinal current losses*** model (Vasily Beskin et al.)

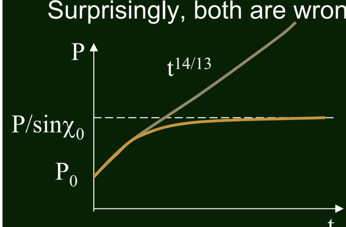
$$\dot{P} = 10^{-15} B_{12}^{10/7} P^{1/14} \cos^{3/2}\chi.$$

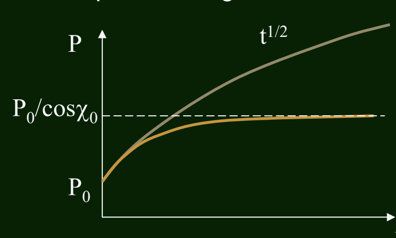
Longitudinal current losses

$$\dot{P} = 0.24 \times 10^{-15} B_{12}^2 P^{-1} \sin^2\chi.$$

Magneto-dipole

Both models predict evolution of the angle between spin and magnetic axis.
Surprisingly, both are wrong!





We are really in trouble with spin-down models for pulsars!

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Radio pulsar braking: braking index

$$n_{\rm br} = \frac{\Omega \ddot{\Omega}}{\dot{\Omega}^2}.$$

Braking index (definition)

$$n_{\rm br} = 3 + 2\cot^2\chi.$$

Magneto-dipole formula

$$n_{\rm br} = 1.93 + 1.5\tan^2\chi.$$

Longitudinal current losses

For well-measured braking indices n<3.
However, for many pulsars they are very large.
This can be simply an observational effect (microglitches, noise, etc.), but it can also be something real.
For example, related to the magnetic field evolution.

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Conclusions

- We have some framework for spin evolution of NSs.
  They are expected to passe several well-defined stages:
  Ejector (including radion pulsar),
  Propeller (probably, with subsonic substage),
  Accretor.
  NSs with large velocities (or fields) after the Ejector stage can appear as Georotators.

- In binaries we observe Ejectors, Propellers and Accretor.
  For isolated NSs – only Ejectors (even, mostly radiopulsars).

- There are still many uncertainties related to the spin evolution:
  1. Spin-down rate and angle evolution for radio pulsars
  2. Subsonic propeller stage for isolated NSs
  3. Inhibition of accretion at low rates
  4. The role of the field decay

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Conclusions-2

- Observations of isolated accreting NSs can help a lot to understand *all* unknown questions of NS spin evolution and low-rate accretion.
- Magnetic field decay can be important also for young NSs, especially for highly magnetized ones, as a source of energy.

So, we have some coherent picture ..... But .....

A lot of funny thing a still waitng for us!

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Papers and books to read

- Lupinov V.M. "**Astrophysics of neutron stars**"
- Lipunov, Postnov, Prokhorov "**The Scenario Machine: Binary Star Population Synthesis**" **Astrophysics and Space Science Reviews (1996)** http://xray.sai.msu.ru/~mystery/articles/review/
- Popov et al. "**The Neutron Star Census**" ApJ 530, 896 (2000)
- Pons, Geppert "**Magnetic field dissipation in neutron star crusts: from magnetars to isolated neutron stars** " astro-ph/0703267
- Ikhsanov "**The origin of long-period X-ray pulsars**" astro-ph/0611442

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Databases on NSs

1. ATNF. Pulsar catalogue
   http://www.atnf.csiro.au/research/pulsar/psrcat/
2. Magnetar database in McGill
   http://www.physics.mcgill.ca/~pulsar/magnetar/main.html
3. Be/X-ray binaries
   http://xray.sai.msu.ru/~raguzova/BeXcat/

1

Lecture 3
Population synthesis

Sergei Popov (SAI MSU)

Dubna “**Dense Matter In Heavy Ion Collisions and Astrophysics**”, July 2008

Population synthesis in astrophysics

A population synthesis is a method of a direct modeling of relatively large populations of weakly interacting objects with non-trivial evolution.
As a rule, the evolution of the objects is followed from their birth up to the present moment.

see astro-ph/0411792
and
Physics-Uspekhi 50, 1123

(УФН 2007 г., N11; http://www.ufn.ru)

3

Why PS is necessary?

1. No direct experiments → computer experiments
2. Long evolutionary time scales
3. Selection effects. We see just a top of an iceberg.
4. Expensive projects for which it is necessary to make predictions

4

Tasks

1. To test and/or to determine initial and evolutionary parameters.
   To do it one has to compare calculated and observed populations.
   This task is related to the main *pecularity* of astronomy:
   we cannot make direct experiments under controlled conditions.

2. To predict properties of unobserved populations.
   Population synthesis is actively used to define programs for future observational projects: satellites, telescopes, etc.

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Two variants

Evolutionary and Empirical

1. Evolutionary PS.
   The evolution is followed from some early stage.
   Typically, an artificial population is formed
   (especially, in Monte Carlo simulations)

2. Empirical PS.
   It is used, for example, to study integral properties
   (spectra) of unresolved populations.
   A library of spectra is used to predict integral properties.

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Examples

1. PS of radiopulsars ←
2. PS of gamma-ray pulsars
3. PS of close-by cooling NSs ←
4. PS of isolated NSs ←
5. PS of close binary systems

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Population synthesis of radio pulsars

The idea was to make an advance population synthesis study of normal radio pulsar to reproduce the data observed in PMBPS and Swinburne. Comparison between actual data and calculations should help to understand better the underlying parameteres and evolution laws.

Only normal (non-millisecond, non-binary, etc.) pulsars are considered.
Note, however, that the role of pulsars originated in close binaries can be important.

Ingredients

- Velocity distribution
- Spatial distribution
- Galactic model
- Initial period distribution
- Initial magnetic field distribution
- Field evolution (and angle)
- Radio luminosity
- Dispersion measure model
- Modeling of surveys

The observed PSR sample is heavily biased. It is necessary to model the process of detection, i.e. to model the same surveys in the synthetic Galaxy. A synthetic PSR is detected if it appears in the area covered by on pf the survey, and if its radio flux exceeds some limit.

2/3 of known PSRs were detected in PBMPS or/and SM (914 and 151).

(following Faucher-Giguere and Kaspi astro-ph/0512585)

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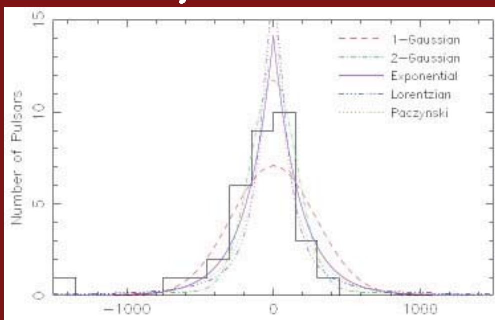
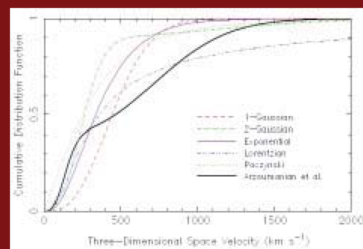
Velocity distribution



Observational data for 34 PSRs.
V_{max}=1340 km/s (PSR B2011+38).



The authors checked different velocity distributions: single maxwellian, double maxwellian, loretzian, paczynski mode, and double-side exponential. The last one was takes for the reference model.
Single maxwellian was shown to be inadequate.

$$p(v_l) = \frac{1}{2\langle v_l \rangle} \exp\left(-\frac{|v_l|}{\langle v_l \rangle}\right),$$

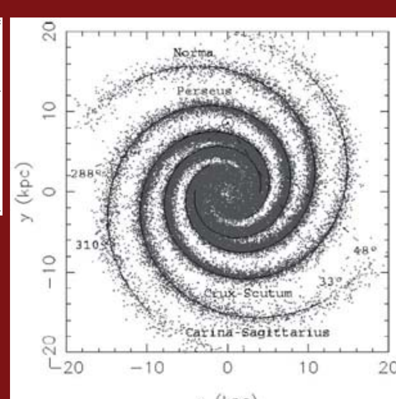
$v_l = D\mu_l \cos b - \Delta v_l$ is the component of the pulsar's transverse velocity parallel to the plane, relative to its LSR, where $\Delta v_l(D, l, b)$ is the contribution to the observed velocity due to differential Galactic rotation and the motion of the Sun relative to its own LSR

Spatial distribution

Initial spatial ditribution of PSRs was calculated in a complicated realistic way.
• exponential dependences (R and Z) were taken into account
• Spiral arms were taken into account
• Decrease of PSR density close to the Galactic center was used

Arm Number	Name	k (rad)	r_0 (kpc)	θ_0 (rad)
1	Norma	4.25	3.48	1.57
2	Carina-Sagittarius	4.25	3.48	4.71
3	Perseus	4.89	4.90	4.09
4	Crux-Scutum	4.89	4.90	0.95

$$\theta(r) = k \ \ln(r/r_0) + \theta_0.$$



However, some details are still missing.
For example, the pattern is assumed to be stable during all time of calculations (i.e. corotating with the Sun).

Galactic potential

The potential was taken from Kuijken and Gilmore (1989):
- disc-halo
- buldge
- nuclei

$$\phi_G(r,z) = \phi_{dh}(r,z) + \phi_b(r) + \phi_n(r),$$

$$\phi_{dh}(r,z) = \frac{-GM_{dh}}{\sqrt{(a_G + \sum_{i=1}^{3} \beta_i \sqrt{z^2 + h_i^2})^2 + b_{dh}^2 + r^2}}$$

$$\phi_{b,n}(r) = \frac{-GM_{b,n}}{\sqrt{b_{b,n}^2 + r^2}}.$$

$$\ddot{\vec{x}} = -\nabla \phi_G,$$

Constant	Disc-Halo (dh)	Bulge (b)	Nucleus (n)
M	1.45×10^{11} $M_\odot$	9.3×10^9 $M_\odot$	1.0×10^{10} $M_\odot$
β_1	0.4		
β_2	0.5		
β_3	0.1		
h_1	0.325 kpc		
h_2	0.090 kpc		
h_3	0.125 kpc		
a_G	2.4 kpc		
b	5.5 kpc	0.25 kpc	1.5 kpc

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Initial spin periods and fields

Spin periods were randomly taken from a normal distribution.
Magnetic fields – also from a normal distribution for log B.

The authors do not treat separately the magnetic field and inclination angle evolution.

Purely magneto-dipole model with n=3 and sin χ=1 is used.
$R_{NS}=10^6$ cm, $I=10^{45}$.

$$P\dot{P} = \left(\frac{8\pi^2 R^6}{3Ic^3}\right) B^2 \sin^2\chi,$$

$P \sim (P_0^2 + K\,t)^{1/2}$

The death-line is taken in the usual form:

$$\frac{B}{P^2} = 0.17 \times 10^{12}\ \mathrm{G\ s^{-2}}$$

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Radio luminosity and beaming

Model I

$$p(L) \propto \begin{cases} L^{\alpha_1} & \text{for } L \in [L_{low}, L_{to}) \\ L^{\alpha_2} & \text{for } L \in [L_{to}, \infty) \\ 0 & \text{otherwise} \end{cases}$$

L_{to} = 2 mJy kpc^2
α_1=-19/15
α_2=-2
L_{low}= 0.1 mJy kpc^2

[Shown to be bad]

Model II

$$\log L = \log\left(L_0 P^{\epsilon_P} \dot{P}_{15}{}^{\epsilon_{\dot{P}}}\right) + L_{corr},$$

$$f(P) = 0.09[\log(P/s) - 1]^2 + 0.03.$$

Average beaming fraction is about 10%

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Optimal model and simulations

Model Parameter	Value
Radial Distribution Model	Yusifov & Küçük
R_1	0.55 kpc
a	1.64
b	4.01
Birth Height Distribution	Exponential
$\langle z_0 \rangle$	50 pc
Birth Velocity Distribution	Exponential
$\langle v_{3D} \rangle$	380 km s^{-1}
Birth Spin Period Distribution	Normal
$\langle P_0 \rangle$	300 ms
σ_{P_0}	150 ms
Magnetic Field Distribution	Log-Normal
$\langle \log(B/G) \rangle$	12.65
$\sigma_{\log B}$	0.55
Luminosity Model	$P - \dot{P}$ Power Paw
L_0	0.18 mJy kpc^2
ϵ_P	−1.5
$\epsilon_{\dot{P}}$	0.5
$\sigma_{L_{corr}}$	0.8

The code is run till the number of "detected" synthetic PSR becomes equal to the actual number of detected PSRs in PBMPS and SM.

For each simulation the "observed" distributions of *b*,*l*, *DM*, S_{1400}, *P*, and *B*, are compared with the real sample.

It came out to be impossible to to apply only statistical tests.
Some human judgement is necessary for interpretation.

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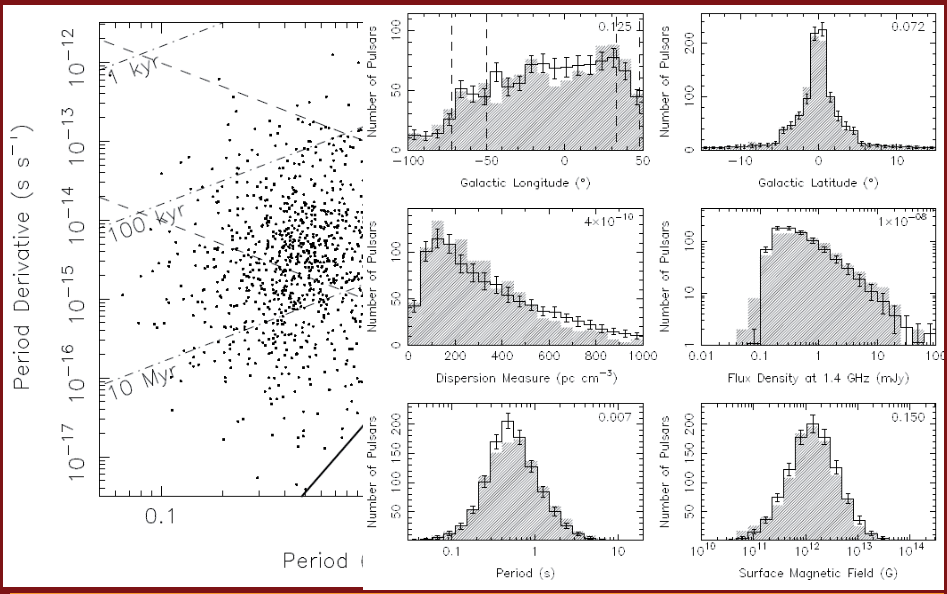
Results



Solid lines – calculation, hatched diagrams - real observations

15

Discussion of the results

1. No significant field decay (or change in the inclination angle) is necessary to explain the data.
2. Results are not very sensitive to braking index distribution
3. Birthrate is 2.8+/-0.1 per century.
   If between 13% and 25% of core collapse SN produce BHs, then there is no necessity to assume a large population of radio quiet NSs.
   120 000 PSRs in the Galaxy

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Population synthesis of gamma-ray PSRs

Ingredients

1. Geometry of radio and gamma beam
2. Period evolution
3. Magnetic field evolution
4. Initial spatial distribuion
5. Initial velocity distribution
6. Radio and gamma spectra
7. Radio and gamma luminosity
8. Properties of gamma detectors
9. Radio surveys to comapre with.

Tasks

1. To test models
2. To make predictions for GLAST and AGILE

(following Gonthier et al astro-ph/0312565)

17

Population of close-by young NSs

- Magnificent seven
- Geminga and 3EG J1853+5918
- Four radio pulsars with thermal emission (B0833-45; B0656+14; B1055-52; B1929+10)
- Seven older radio pulsars, without detected thermal emission.

To understand the origin of these populations and predict future detections it is necessary to use population synthesis.

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Population synthesis: ingredients

- Birth rate of NSs
- Initial spatial distribution
- Spatial velocity (kick)
- Mass spectrum
- Thermal evolution
- Interstellar absorption
- Detector properties

Task:

To build an artificial model of a population of some astrophysical sources and to compare the results of calculations with observations.

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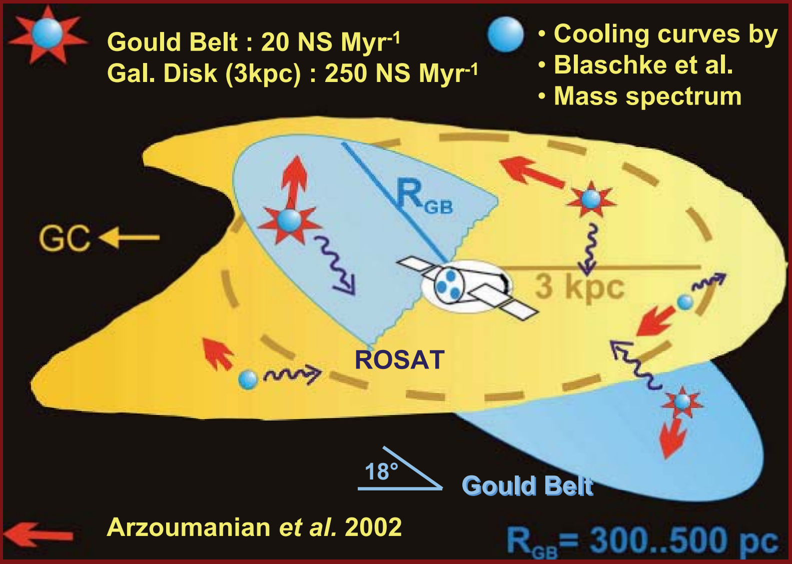
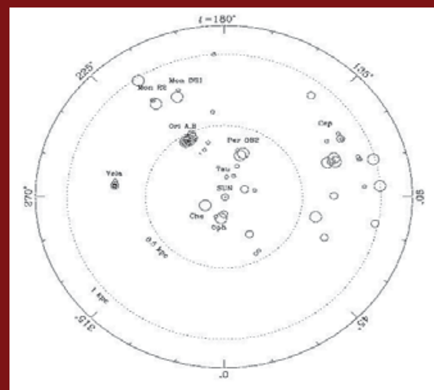
Population synthesis – I.

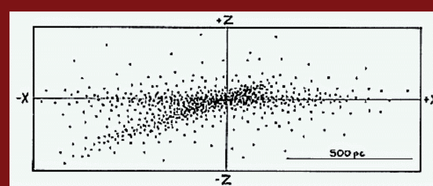


20

The Gould Belt

- Poppel (1997)
- R=300 – 500 pc
- Age 30-50 Myrs
- Center at 150 pc from the Sun
- Inclined respect to the galactic plane at 20 degrees
- 2/3 massive stars in 600 pc belong to the Belt
- 20-30 SN per Myr





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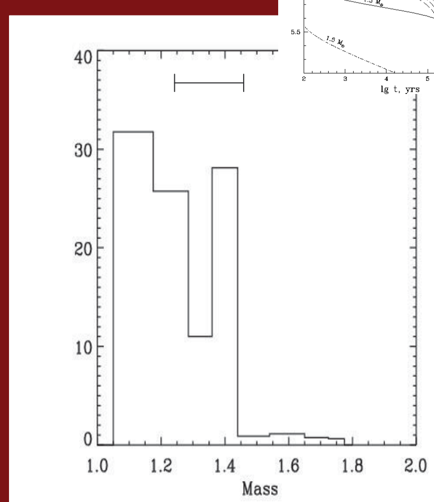
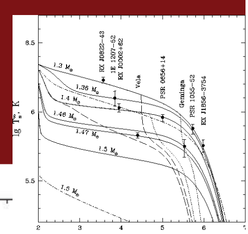
Mass spectrum of NSs

- Mass spectrum of local young NSs can be different from the general one (in the Galaxy)
- Hipparcos data on near-by massive stars
- Progenitor vs NS mass:
  Timmes et al. (1996);
  Woosley et al. (2002)





astro-ph/0305599

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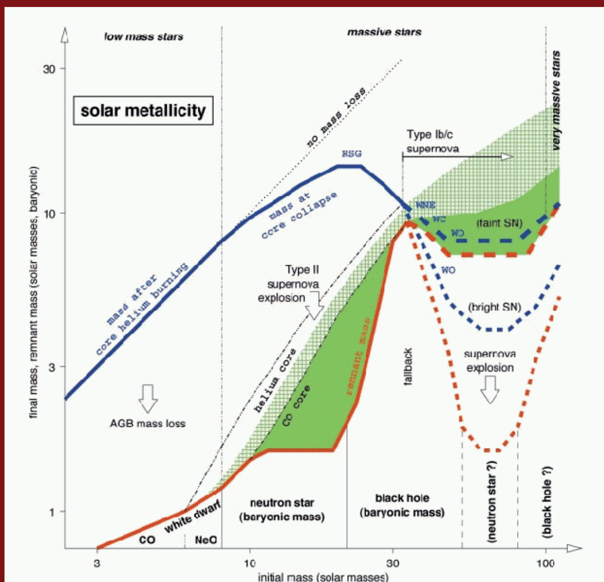
Progenitor mass vs. NS mass



Woosley et al. 2002

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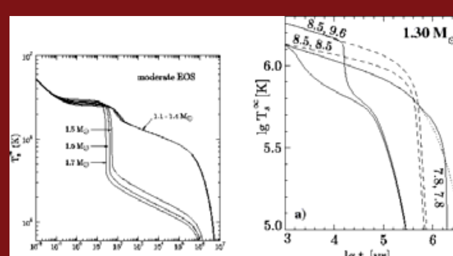
Cooling of NSs

- Direct URCA
- Modified URCA
- Neutrino bremstrahlung
- Superfluidity
- Exotic matter (pions, quarks, hyperons, etc.)



(see a recent review in astro-ph/0508056)

In our study we use a set of cooling curves calculated by Blaschke, Grigorian and Voskresenski (2004) in the frame of the *Nuclear medium cooling model*

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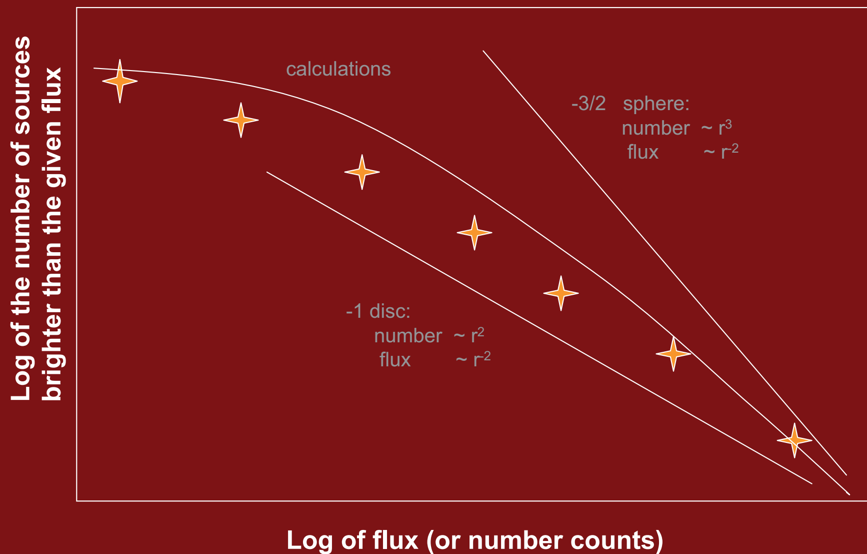
Log N – Log S



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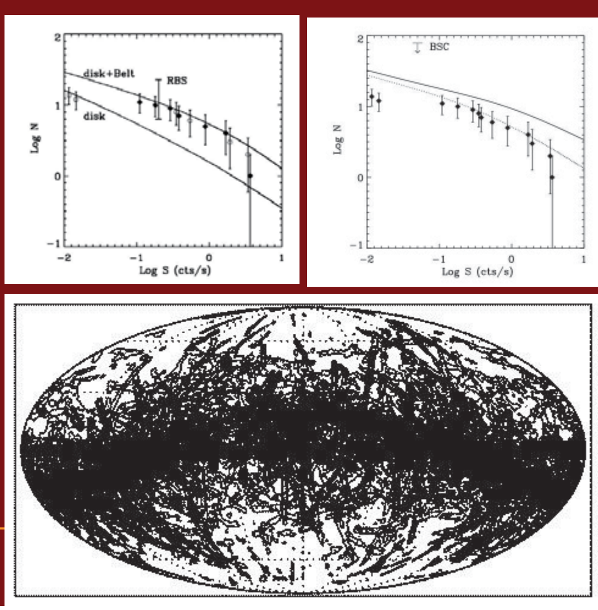
Some results of PS-I:
Log N – Log S and spatial distribution



Log N – Log S for close-by ROSAT NSs can be explained by standard cooling curves taking into account the Gould Belt.

More than ½ are in +/- 12 degrees from the galactic plane.
19% outside +/- 30°
12% outside +/- 40°

(Popov et al. 2005 Ap&SS 299, 117)

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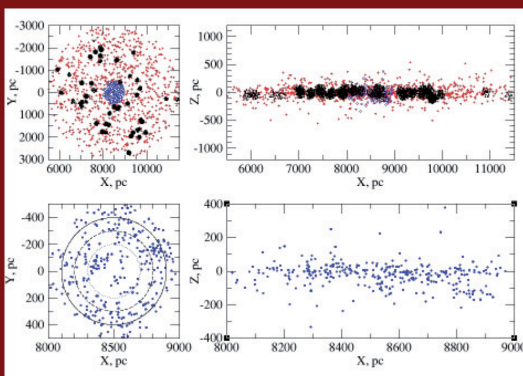
Population synthesis – II. recent improvements

1. Spatial distribution of progenitor stars



a) Hipparcos stars up to 500 pc
[Age: spectral type & cluster age (OB ass)]
b) 49 OB associations: birth rate ~ N_{star}
c) Field stars in the disc up to 3 kpc

We use the same normalization for NS formation rate inside 3 kpc: 270 per Myr.

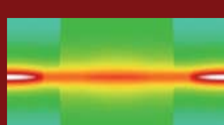
Most of NSs are born in OB associations.

For stars <500 pc we even try to take into account if they belong to OB assoc. with known age.

Population synthesis – II. recent improvements

3. Spatial distribution of ISM (N_H)

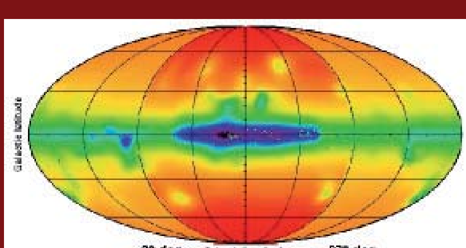
instead of :

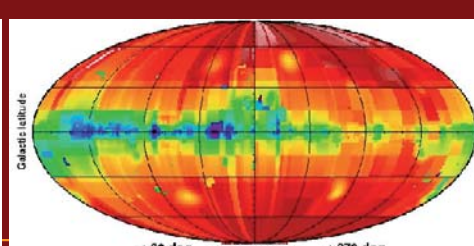


N_H inside 1 kpc

(see astro-ph/0609275 for details)

now :

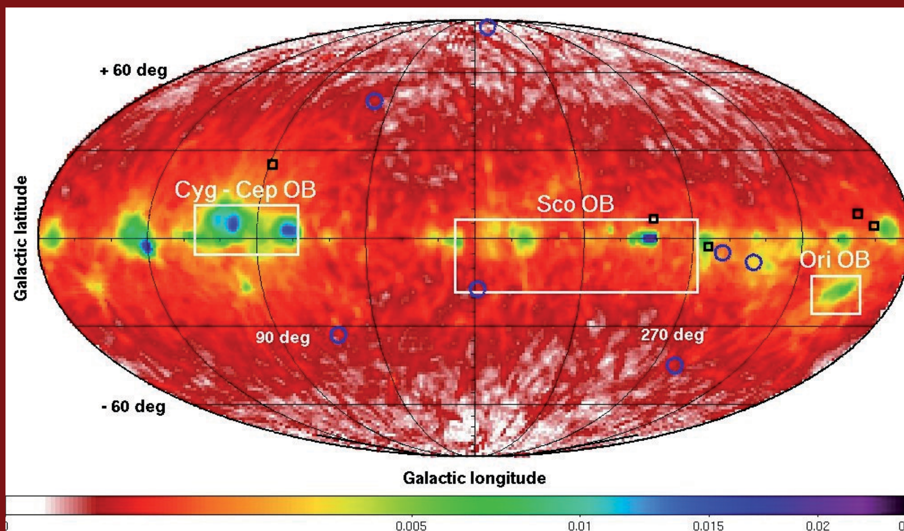




Modification of the old one

Hakkila

50 000 tracks, new ISM model



Predictions for future searches

(Posselt et al. arXiv: 0801.4567)

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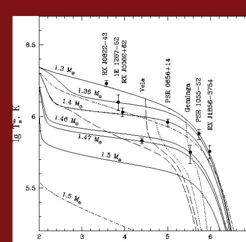
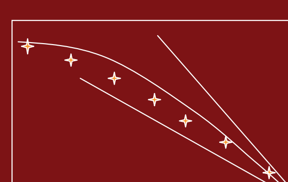
Log N – Log S as an additional test

- Standard test: Age – Temperature
  - Sensitive to ages <10^5 years
  - Uncertain age and temperature
  - Non-uniform sample
- Log N – Log S
  - Sensitive to ages >10^5 years (when applied to close-by NSs)
  - Definite N (number) and S (flux)
  - Uniform sample
- Two test are perfect together!!!



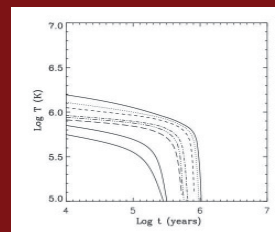


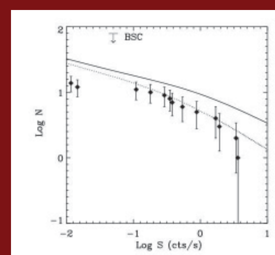
astro-ph/0411618

30

Model I

- Pions.
- Gaps from Takatsuka & Tamagaki (2004)
- T_s-T_{in} from Blaschke, Grigorian, Voskresenky (2004)





Can reproduce observed Log N – Log S

(astro-ph/0411618)

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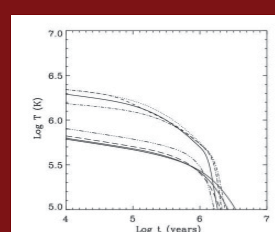
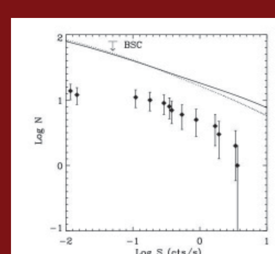
Model II

- No Pions
- Gaps from Yakovlev et al. (2004), $^3P_2$ neutron gap suppressed by 0.1
- T_s-T_{in} from Tsuruta (1979)





Cannot reproduce observed Log N – Log S

32

Sensitivity of Log N – Log S

- Log N – Log S is very sensitive to gaps
- Log N – Log S is not sensitive to the crust if it is applied to relatively old objects (>10^{4-5} yrs)
- Log N – Log S is not very sensitive to presence or absence of pions

We conclude that the two test complement each other

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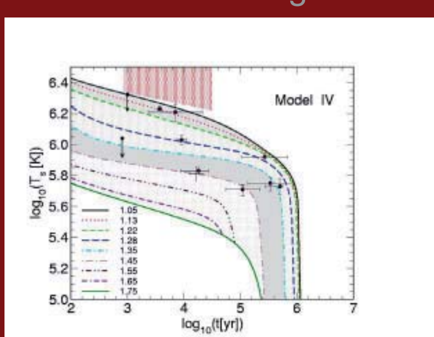
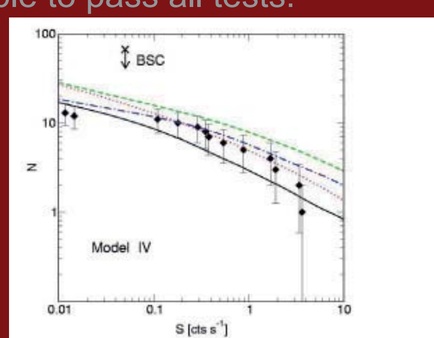
Results for HySs application

Model	Δ_0 [MeV]	α	BC	T – t	Log N – Log S	$M_{typ} \leq 1.5\ M_\odot$	All tests
I	1	10	+	+	○	-	-
II	0.1	0	+	-	+	-	-
III	0.1	2	+	○	+	-	-
IV	5	25	+	+	+	+	+

One model among four was able to pass all tests.





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Isolated neutron star census

Task.

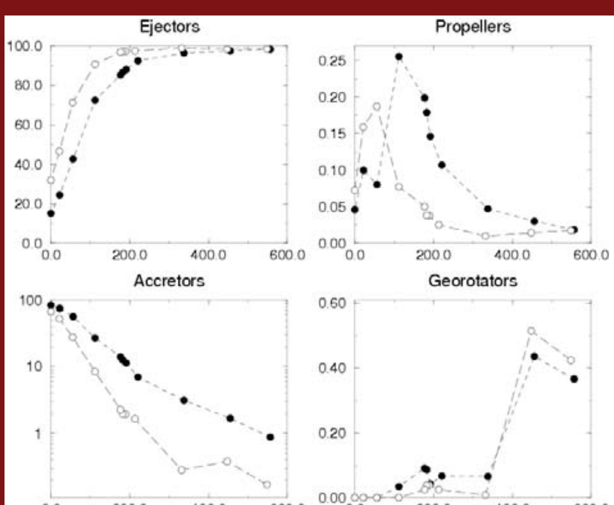
- To calculate distribution of isolated NSs in the Galaxy over evolutionary stages: Ejector, Propeller, Accretor, Georotator
- Predict the number of accretors

Ingredients.

- Galactic potential
- Initial NS spatial distribution
- Kick velocity
- ISM distribution
- Spin initial distribution, evolution and critical periods
- Magnetic field initial distribution and evolution

35

Stages



Rather conservative evolutionary scheme was used.

For example, supersonic propellers have not been considered (Ikhsanov 2006).

astro-ph/9910114

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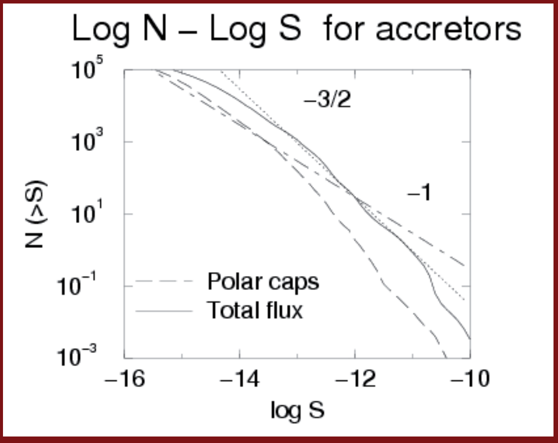
Accreting isolated NSs

At small fluxes $<10^{-13}$ erg/s/cm^2 accretors can become more abundant than coolers. Accretors are expected to be slightly harder: 300-500 eV vs. 50-100 eV. Good targets for eROSITA!



From several hundreds up to several thousands objects at fluxes about few **x** 10^{-14}, but difficult to identify.

Monitoring is important.

Also isolated accretors can be found in the Galactic center (Zane et al. 1996, Deegan, Nayakshin 2006).

astro-ph/0009225

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Population synthesis of binary systems

Interacting binaries are ideal subject for population synthesis studies:

- The are many of them observed
- Observed sources are very different
- However, they come from the same population of progenitors...
- ... who’s evolution is non-trivial, but not too complicated.
- There are many uncertainties in evolution ...
- ... and in initial parameters
- We expect to discover more systems
- ... and more types of systems
- With new satellites it really happens!

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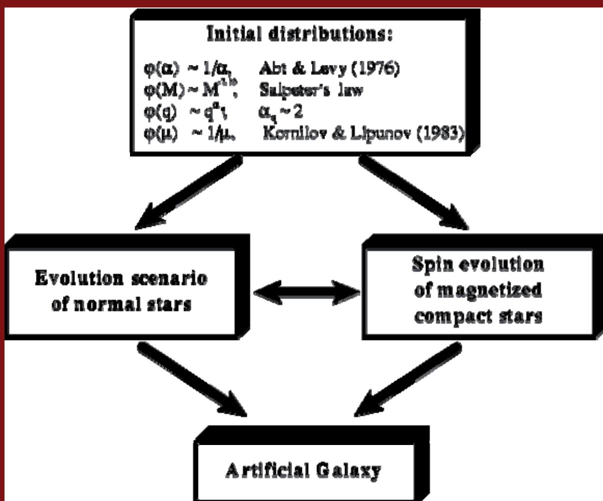
Scenario machine



There are several groups in the world which study evolution of close binaries using population synthesis approach.

Examples of topics

- Estimates of the rate of coalescence of NSs and BHs
- X-ray luminosities of galaxies
- Calculation of mass spectra of NSs in binaries
- Calculations of SN rates
- Calculations of the rate of short GRBs

(Lipunov et al.)

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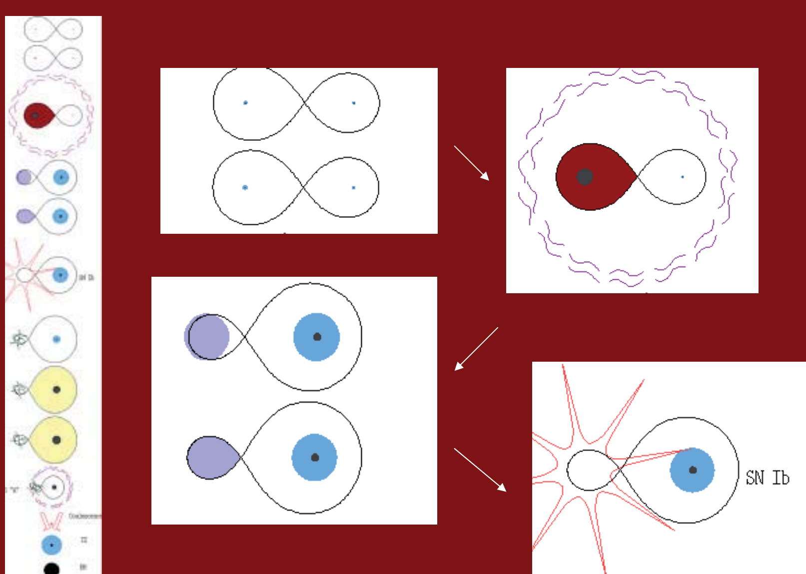
Evolution of close binaries



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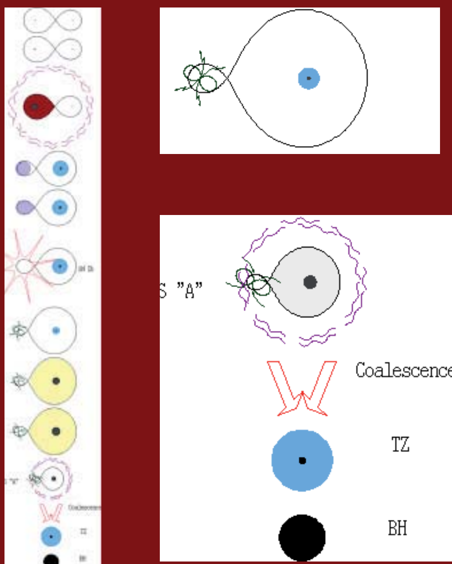
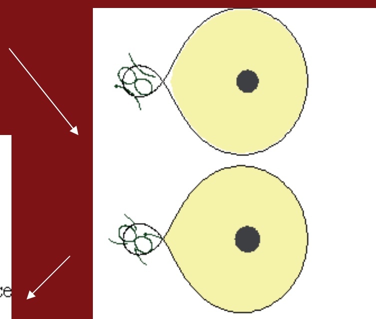




("Scenario Machine" calculations)

http://xray.sai.msu.ru/sciwork/

(«Вокруг света» июль 2008 г. http://vokrugsveta.ru)

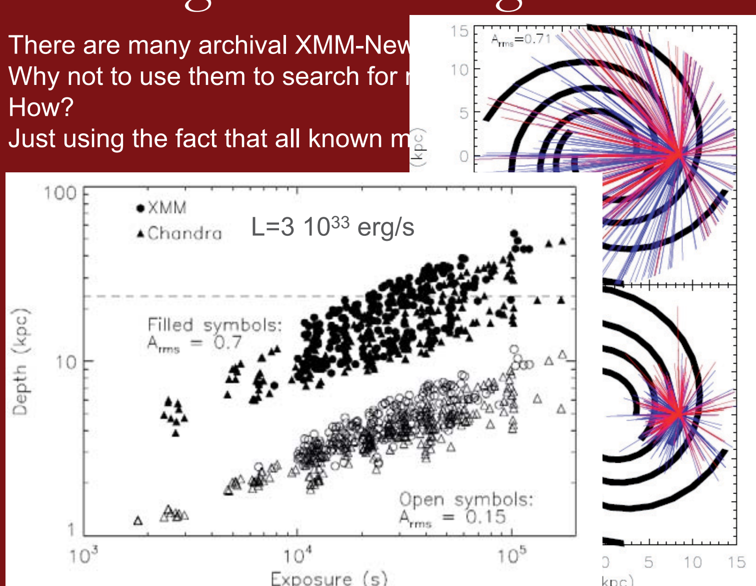
41

Looking for new magnetars

There are many archival XMM-New … ations.
Why not to use them to search for r…
How?
Just using the fact that all known m… narrow range!

…s of the

… magnetars.
…<100 or **<500**.



(0711.0988)

By the way, they also can put contraints on M7-like sources.....

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Looking for new M7-like sources

M7-like objects are very interesting by themselves and are important for studies of NS physics.

Several campains have been made to look for more sources.

- Agueros et al. (astro-ph/0511659)
- Chieregato et al. (astro-ph/0502292)

Looking for blank field soft X-rays sources (extreme f_x/f_{opt} ratio).

Chieregato et al. searched for blank field sources with the ROSAT HRI data (only ~1.8% of the sky, mostly at high galactic latitudes).
Several candidates have been figured out.

Agueros et al. used ROSAT All-sky Survey and SDSS.
Also several candidates have been found.

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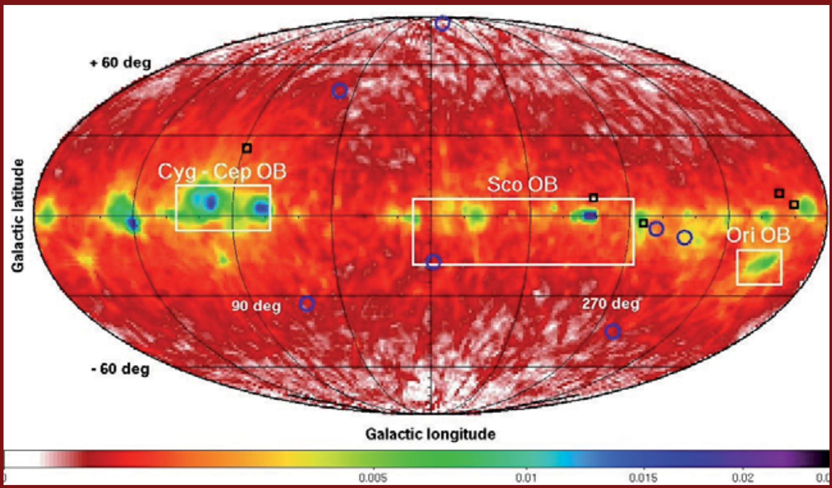
Predictions for future searches and candidates



(Posselt et al. arXiv: 0801.4567)

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Looking for isolated accretors

Many programs aimed to find accreting isolated NSs have been made in 90s (see a review in Treves et al. (2000) PASP 112, 297).
Since then researches became a little bit pessimistic about the subject.
However, with present day abilities and prospects for near future it is important to remember about the pos

For example, looking for new M7-like NS
which are expected to be more abundan
optimistic scenario) at fluxes $<10^{-13}$ erg/c

Recently, Pires and Motch (0710.5192)
in the 2XMMp catalogue. One interestin
Most probably, it is a cooling INS (work

45

Looking for radio pulsar counterparts for EGRET unidentified sources

Recently Crawford et al. (astro-ph/0608225) tried to find dim radio pulsars in 56 relatively small error boxes of EGRET unidentified sources.
Nothing came out.

Then, Keith et al. (0807.2088) made a search at high frequencies for three cases and discovered a new pulsar! Probably, it is important to use high frequencies (~few GHz)

GLAST is in orbit now and everything is working.
Hopefully, soon we'll have more *gamma-ray selected* isolated neutron stars (radio pulsars, coolers, ...).
More population studies will be necessary which take into account all possible types of NSs.

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Conclusions

- Population synthesis is a useful tool in astrophysics
- Many theoretical parameters can be tested only via such modeling
- Many parameters can be determined *only* via PS models
- Actively used to study NSs
- Actively used for predicting future observations and setting on observational programs

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Dorothea Rockburne

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Papers to read

- Popov, Prokhorov "**Population synthesis in Astrophysics**"
  Physics-Uspekhi 50 (11), 1123 (2007)
- Faucher-Giguere, Kaspi "**Birth and evolution of isolated radio pulsars**"
  astro-ph/0512585
- Postnov, Yungelson "The Evolution of Compact Binary Star Systems "
  Living Reviews on Relativity 9, 6 (2006) astro-ph/0701059
- Lipunov et al. "**Description of the Scenario Machine**" arXiv: 0704/1387
- Lipunov, Postnov, Prokhorov "**The Scenario Machine:**
  Binary Star Population Synthesis"
  Astrophysics and Space Science Reviews (1996)
  http://xray.sai.msu.ru/~mystery/articles/review/

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