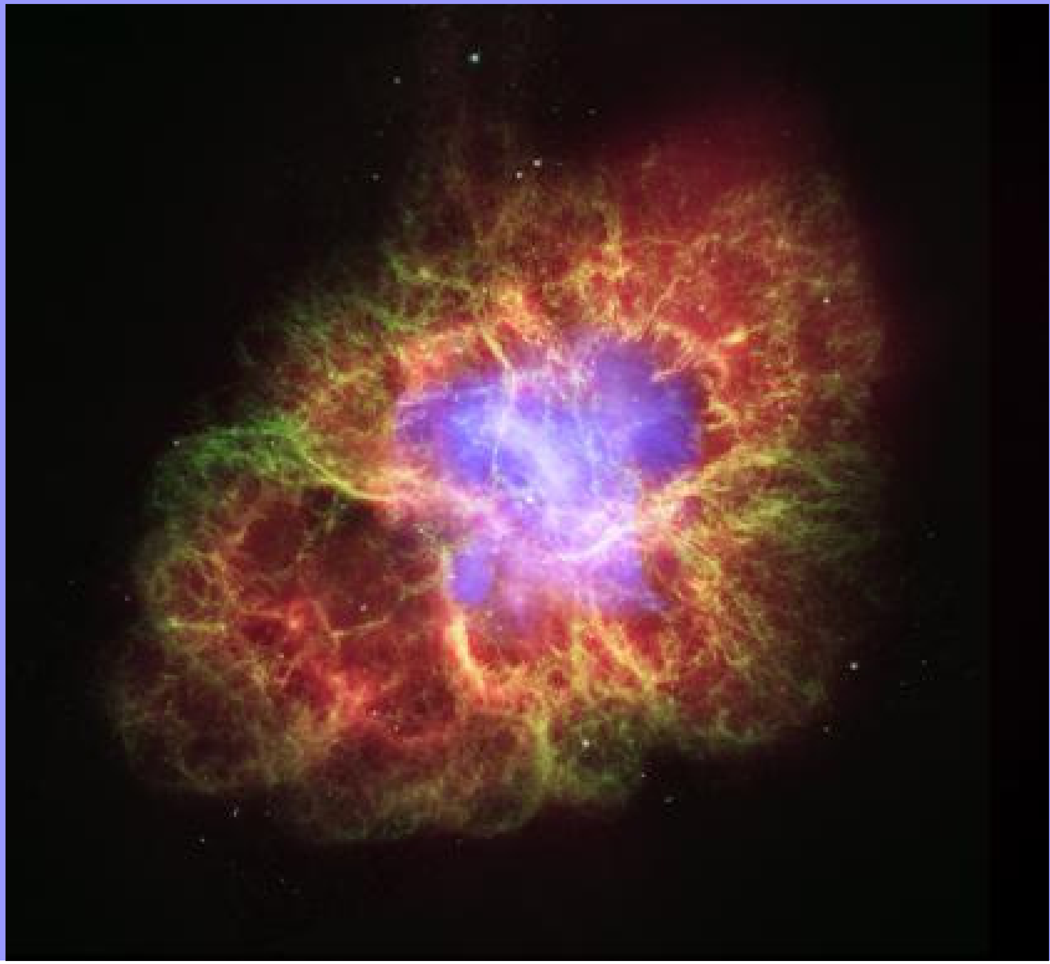
Observing Cosmic Superfluidity in Glitches of the Pulsars

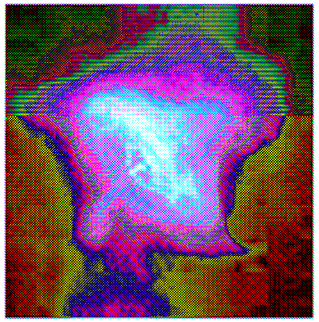
BCS50 Urbana – 13.10.2007

M. Ali Alpar - Sabancı University - Istanbul - Turkey

Current Research supported by the EU Transfer of Knowledge Project ASTRONS and by the Turkish Academy of Sciences



Crab Nebula

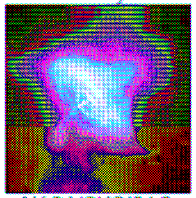


NASA/CXC/SAO

The Crab Nebula is the remnant of a supernova explosion that was seen on Earth in 1054 AD. It is 6000 light years from Earth. At the center of the bright nebula is a rapidly spinning neutron star, or pulsar that emits pulses of radiation 30 times a second.

Multi-wavelength Images: (*Images not to scale)

X-ray



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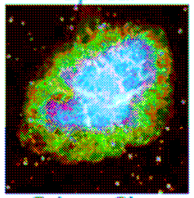
Optical



Palomar Obs.:
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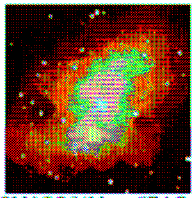
Infrared



2MASS/UMass/IPAC-Caltech/NASA/NSF:
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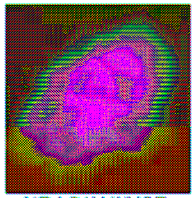
Radio



NRAO/AUI/NSF:
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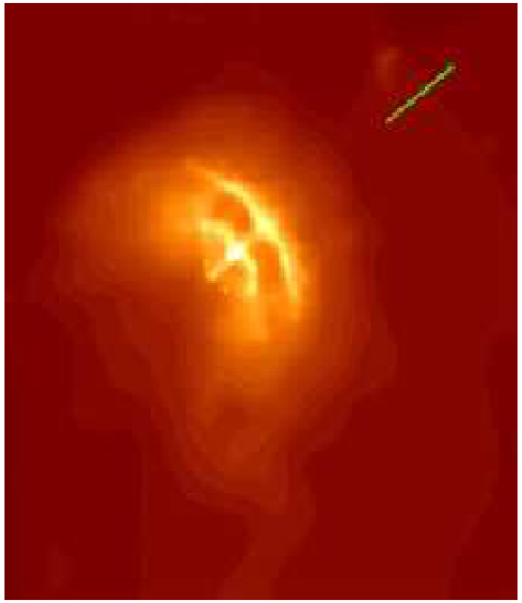
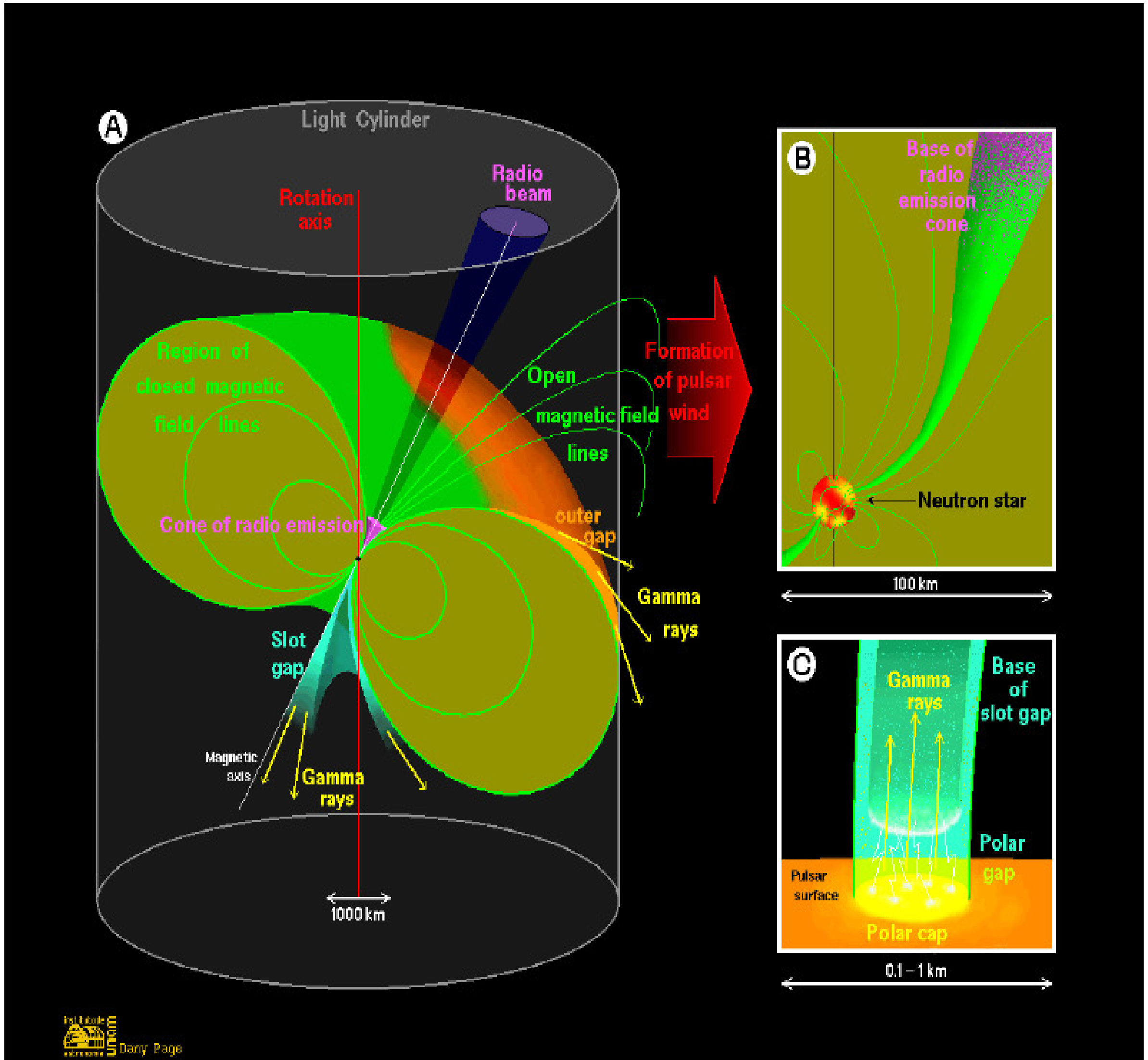
Tif (1.7 MB)
PS (3.6 MB)

Vela Pulsar: Chandra Reveals a Compact Nebula Created by a Shooting Neutron Star



NASA/PSU/G.Pavlov et al.
JPEG (88 k) , Tiff (732 k), PS (3.8 MB)

Chandra image of compact nebula around Vela pulsar. The image shows a dramatic bow-like structure at the leading edge of the cloud, or nebula, embedded in the Vela supernova remnant. This bow and the smaller one inside it, are thought to be the near edges of tilted rings of X-ray emission from high-energy particles produced by the central neutron star. Perpendicular to the bows are jets that emanate from the central pulsar, or neutron star. As indicated by the green arrow, the jets point in the same direction as the motion of the pulsar. The swept back appearance of the nebula is due to the motion of the pulsar through the supernova remnant.



Dipole Spindown

$I\,\Omega\, d\Omega/dt = -\,2/3\, \mu^2\, \Omega^4 / c^3$

$d\Omega/dt = -\,k\, \Omega^3$ braking index $n = 3$

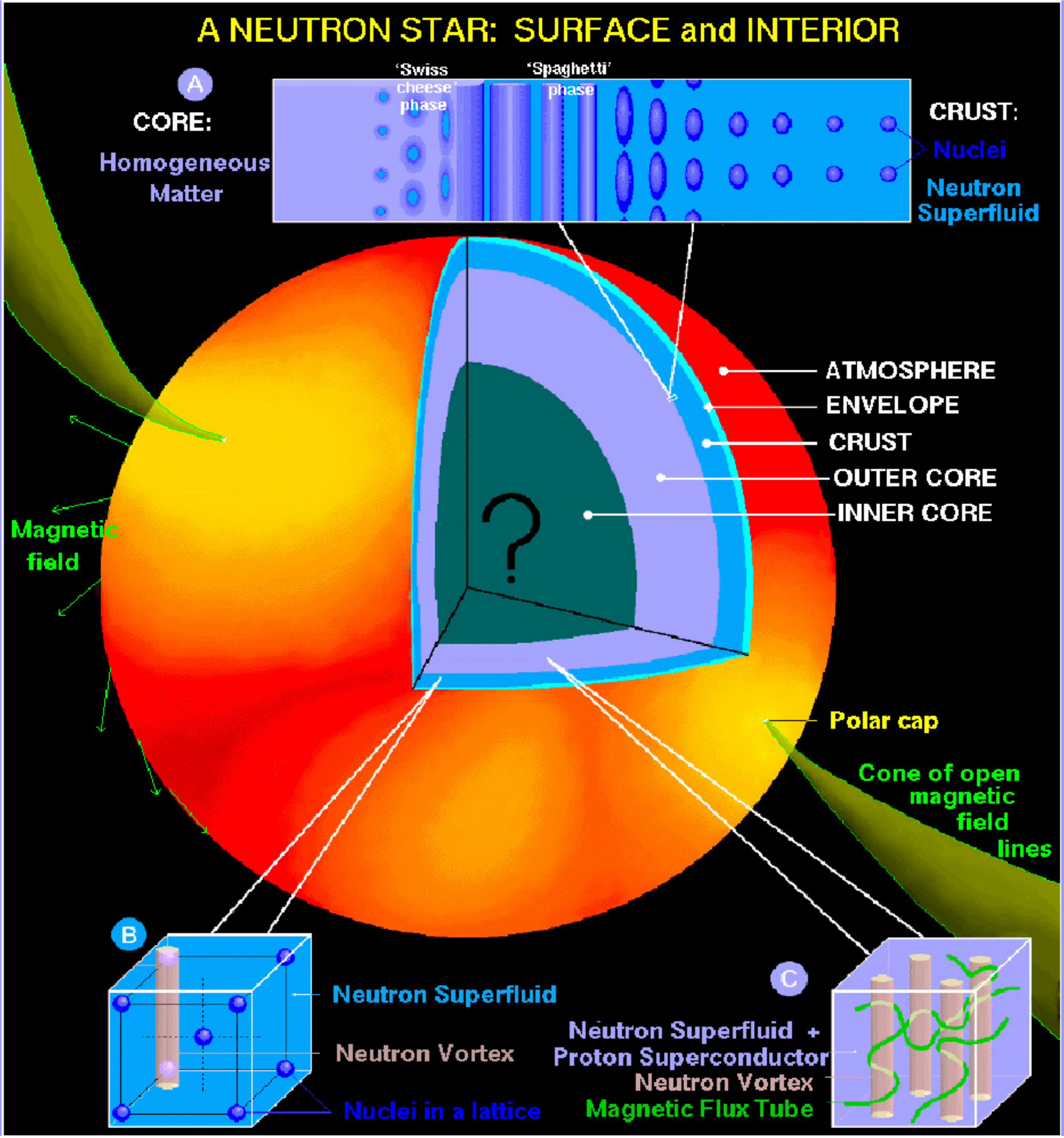
$n \sim 2 – 3$ (a few young pulsars)

To determine the torque requires measurement of the second derivative of Ω - difficult, contaminated by noise.

Compared to neutron stars in X-ray binaries, which spin up or down under noisy accretion torques, radio pulsars exhibit much quieter spindown. This allows the effects of the neutron star's internal dynamics to be observed clearly in pulsar glitches and postglitch spindown.

There is no evidence of change in electromagnetic signatures – no change in external torques concurrent with glitches.

Dany Page et al. http://www.astroscu.unam.mx/neutrones



Dany Page et al.
http://www.astroscu.unam.mx/neutrones

Current observations seem to support stiff equations of state – and rule out exotic neutron stars → A simple model with just a plain neutron superfluid/proton superconductor star: no pion-kaon condensates, quark matter or core solid: central density of the neutron star is less than the transition densities for these exotic phases.

EXO 0748−676 Rules out Soft Equations of State for Neutron Star Matter

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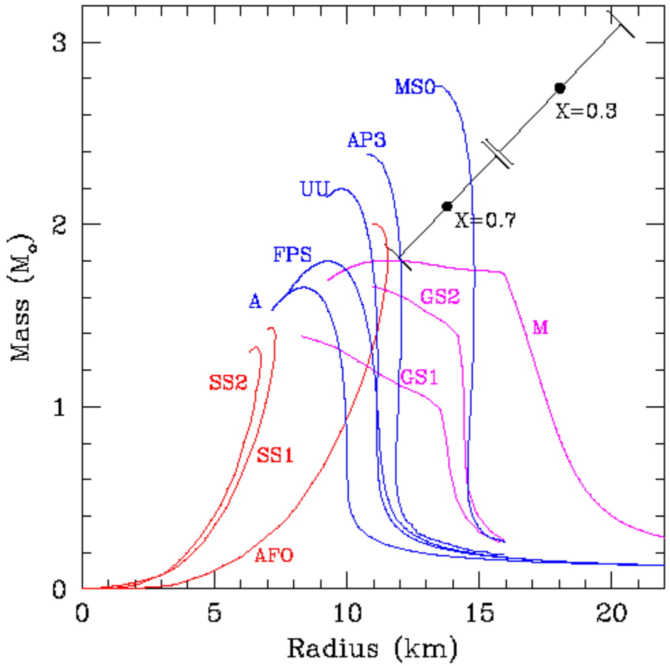
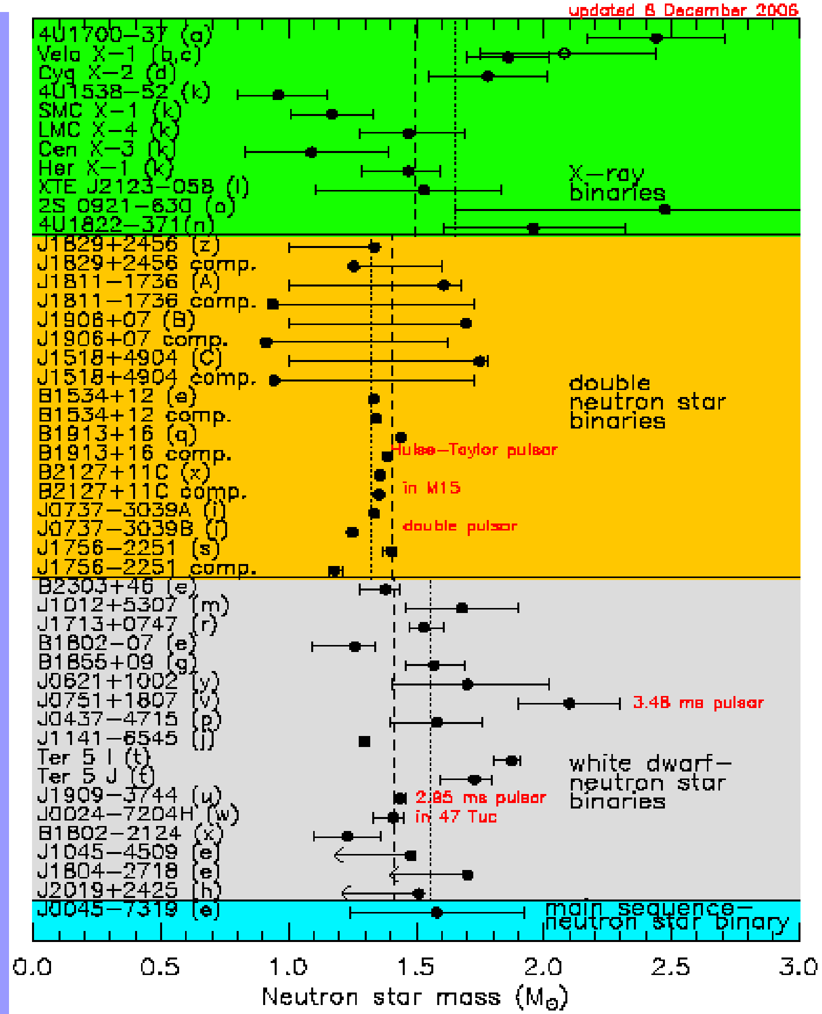


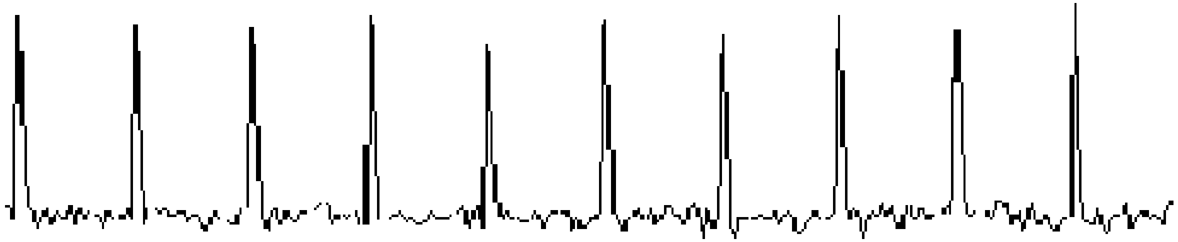
Figure 2. The constraints on the neutron star equations of state imposed by observations of EXO 0748−676. The predicted mass-radius relations for a number of representative equations of state of neutron stars without condensates (blue), with condensates (magenta), and for strange stars (red).[17,18] The curve labels and the corresponding references can be found in



Neutron Star Observations: Prognosis for Equation of State Constraints

James M. Lattimer[1] and Madappa Prakash[2]

The Vela pulsar (PSR B0833-45) has been monitored daily at HartRAO since the 1980's. Real-time glitch detection software has enabled us to capture the behaviour of the pulsar from almost immediately after several of its glitches.



This is what we observe from the Vela pulsar with the radio telescope at Hartebeesthoek. These pulses occur roughly every tenth of a second.

The "sound" – pulses - of the Vela pulsar

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

The first glitches from the Vela and Crab pulsars came in 1969:

Vela Pulsar $\Delta\Omega/\Omega \sim 10^{-6}$

Crab Pulsar : $\Delta\Omega/\Omega \sim 10^{-8}$-$10^{-9}$

Detection of a Change of State in the Pulsar *PSR* 0833-45

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The pulsation period of *PSR* 0833–45 is known to be gradually increasing, but between February 24 and March 3 the periodicity abruptly decreased by two parts per million.

Nature **222**, 229 - 230 (19 April 1969); doi:10.1038/222229a0

Observed Decrease in the Periods of Pulsar *PSR* 0833–45

P. E. REICHLEY & G. S. DOWNS

Jet Propulsion Laboratory, California Institute of Technology

The abrupt decrease in the period of *PSR* 0833–45 has also been detected at the Goldstone Tracking Station.

THE ASTROPHYSICAL JOURNAL, **175**:217–241, 1972 July 1

OPTICAL TIMING OF THE CRAB PULSAR, NP 0532*

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Received 1971 September 30; revised 1972 February 7

ABSTRACT

Absolute times of arrival of NP 0532 pulses have been measured over a 2-year period. The data are shown to be consistent with a cubic polynomial which describes the secular slowdown, a sudden increase and subsequent exponential decay of the frequency (the glitch of 1969 September 29), and an intrinsic $1/f$ noise component in the frequency.

OPTICAL TIMING OBSERVATIONS OF THE CRAB PULSAR 1969-1979

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Received November 19, accepted July 22, 1980

Summary.-Our own observations of the Crab pulsar are compared with those made at Princeton (Groth 1975) and Arecibo (Gullahorn et al. 1977). They show the following features :
a) a jump in frequency derivative of $\Delta\dot{\nu} = -6\text{x}10^{-4}\ d^{-2}$ together with the large glitch on 1975 Feb 04 ($\Delta\nu = 0.10\ d^{-1}$, $\tau = 11$ d, and $Q = 0.7$) ;
b) several smaller glitches of typically $\Delta\nu = 6\text{x}10^{-3}d^{-1}$ and marginal jumps in $\dot{\nu}$ of $6\text{x}10^{-5}d^{-2}$;
c) a frequency noise which may consist of events as large as $\Delta\nu = 5\text{x}10^{-4}d^{-1}$ occurring at a rate as low as 0.2 per day ;
d) identical braking indices $n = 2.516$ before and after the large glitch.

Key words : pulsars - neutron stars - glitches

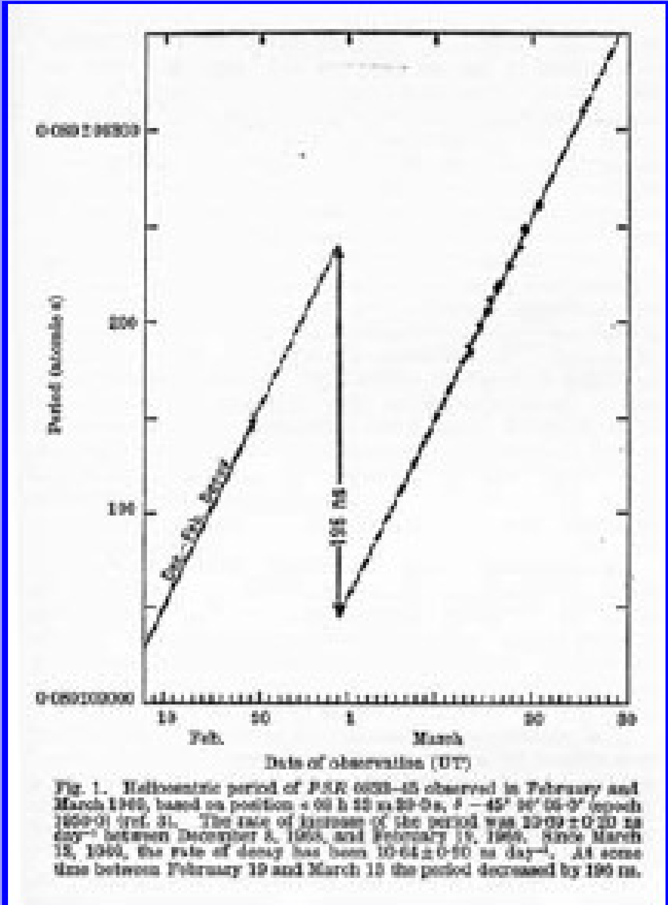
Glitch monitoring: neutron stars not only contain the most amount of superfluid at the highest observable densities and lowest temperatures. They are also the most observed superfluid systems:

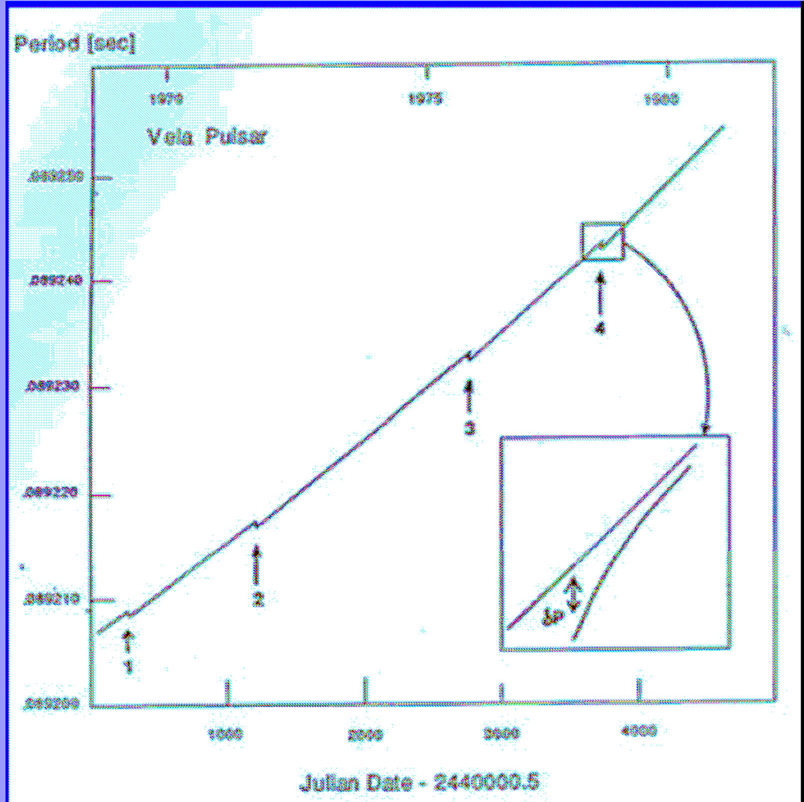
Out of mere curiosity in a new kind of object and enthusiasm about a new data acquisition system designed by E. Høg, I began to observe the Crab pulsar at the 60 cm refractor of Hamburg Observatory in September 1969. The high timing precision which could be achieved with this system and the relation of sudden jumps in pulse frequency ("glitches") to neutron star structure induced me to continue these observations for almost ten years now.

Because of the low speed of the punching device, an ASR 33 Teletype, the light curve is punched in binary format at only one character per phase bin, requiring about 20 seconds for each run. In order to match the 12 bit memory contents to the 8 bit paper tape format, they are devided by a suitable power of two after subtraction of the minimum count. This

Vela Pulsar glitches: $\Delta\Omega/\Omega \sim 10^{-6}$ repeat about every two years.
(There are also occasional Crab-sized $\Delta\Omega/\Omega \sim 10^{-9}$ glitches from Vela.)

Part of the glitch spin-up $\Delta\Omega$ NEVER relaxes back!





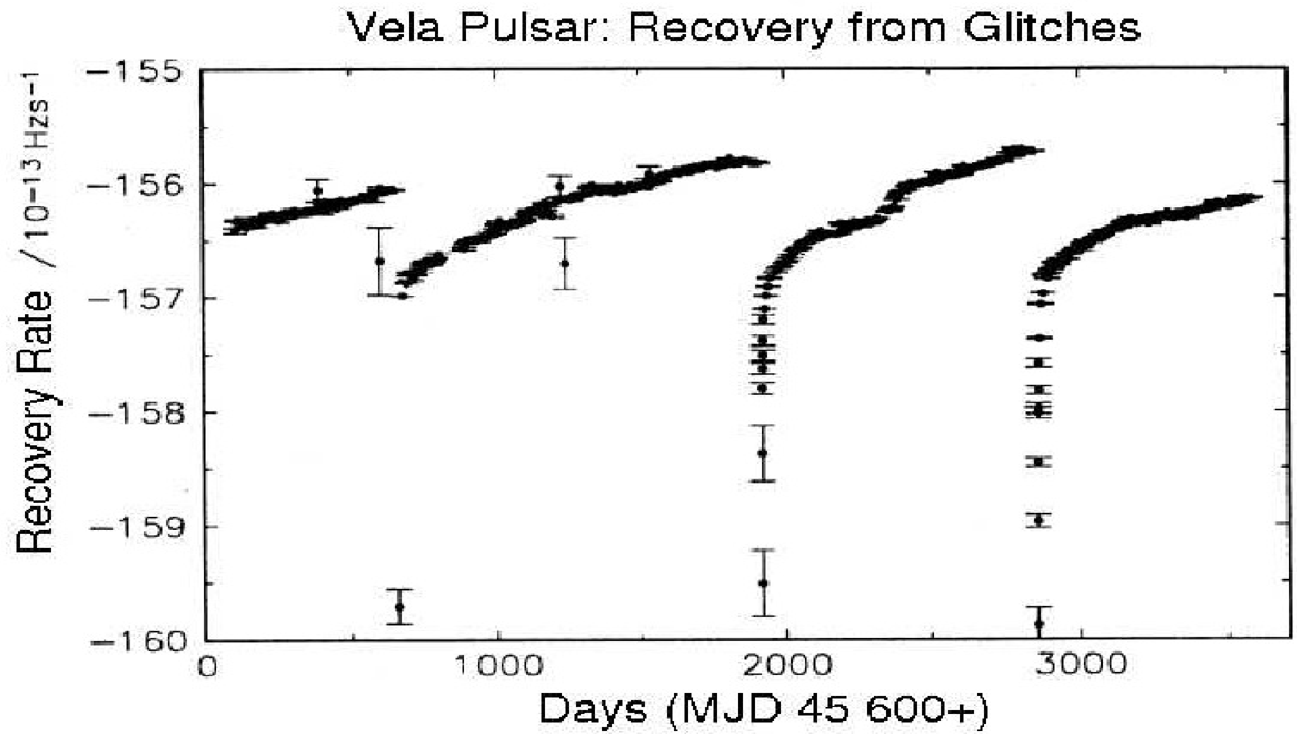


Image courtesy of Claire Flanagan

The changing rotation rate of the Vela pulsar over ten years is shown above. The glitches are the sudden decreases in the rotation rate. These occur every few years in this pulsar. These glitches are

THE JUMP in the SPINDOWN RATE

$| \Delta(d\Omega/dt) | / |d\Omega/dt|_i \sim$ a few 10^{-4} - $10^{-3} \sim I_i / I_{total}$ (also for Crab !)

$\Sigma_i I_i / I_{total} \sim 10^{-2} \rightarrow$ crust superfluid

GLITCH RISE TIME < 2 min

→The rest of the star is coupled very tightly to the observed crust.

POSTGLITCH RECOVERY

PROMPT RELAXATION with exponential relaxation times τ_i ~ hrs, few days, months.

LONG TERM BEHAVIOR I.
Persistent shifts: part of $\Delta(d\Omega/dt)$ not relaxing at all.
$|\Delta(d\Omega/dt)|_{persistent} / |d\Omega/dt| \sim$ a few 10^{-4} - 10^{-3},
associated with Crab glitches

LONG TERM BEHAVIOR II.
A part recovering slowly till the next glitch, with a constant $d^2\Omega/dt^2$. The next glitch arrives roughly after the interglitch time interval

$$t_g \sim |\Delta(d\Omega/dt)|_{long\ term} / d^2\Omega/dt^2$$

20% accuracy , improves if persistent shifts (I) are allowed for
(2007, 2006: Vela, PSR 1737-30, PSR J 0537-6910).

MODELS I : Starquakes

Solid component – crust/ core solid?- sudden quake, reduces moment of inertia- spinup. Associated diispation of elastic energy > observed X-ray luminosity for Vela glitches. Quakes are OK for Crab-size glitches.

For Vela glitches, to have such huge events every two years, a much stronger solid than the neutron crust lattice is required → a solid core for the neutron star? But then the amount of elastic energy to be dissipated in a Vela-sized glitch far exceeds the observed thermal X-ray luminosity of the Vela pulsar.

Starquake models do not explain the large Vela-sized glitches.

MODELS II: Vortex unpinning:

Transfer of angular momentum from pinned superfluid to crust:

Associated dissipation of rotational energy is consistent with observed limits on X-ray luminosity enhancement for Vela glitches.

letters to nature

Nature **256**, 25 - 27 (03 July 1975); doi:10.1038/256025a0

Pulsar glitches and restlessness as a hard superfluidity phenomenon

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SEVERAL pulsars[1] have "restless" behaviour of the period similar to that of the Crab and Vela pulsars[2] which has been explained[3] as due to "microquakes" in the crust. A glitch has also been observed[1] with, possibly, a new type of signature, in PSR1508+55. We suggest that these phenomena can be explained at least equally well by noisiness in the rate of creep of vorticity through the neutron superfluid in the crust, in almost precise analogy to the well known noisy behaviour of flux creep in hard superconducting magnets[4]. In addition, even the macroglitches, especially those in the Vela pulsar, may be caused by the catastrophic release of pinned vorticity.

VOLUME 28, NUMBER 16 PHYSICAL REVIEW LETTERS 17 APRIL 1972

Pulsar Speedups Related to Metastability of the Superfluid Neutron-Star Core

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(Received 13 March 1972)

The sudden speed changes observed in the Vela and Crab pulsars may be caused by transitions between metastable flow states in the superfluid interior of the star.

Migdal (1959) :"It should be noted that superfluidity of nuclear matter may lead to some interesting cosmic phenomena if stars exist which have neutron cores. A star of this type would be in a superfluid state with a transition temperature corresponding to 1 MeV."
Ginzburg & Kirzhnits (1965) Gap estimate ~ exp (-1/N(0)V) ~1 MeV.

Type II superconductivity of the protons in the neutron star core is expected:
Baym, Pethick and Pines 1969: normal crust matter conductivity high enough that the initial flux through the neutron star core is frozen.Estimates of the proton $^1S_0$ gap imply the protons form a Type II superconductor carrying an Abrikosov lattice of flux lines.

VOLUME 24, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1970

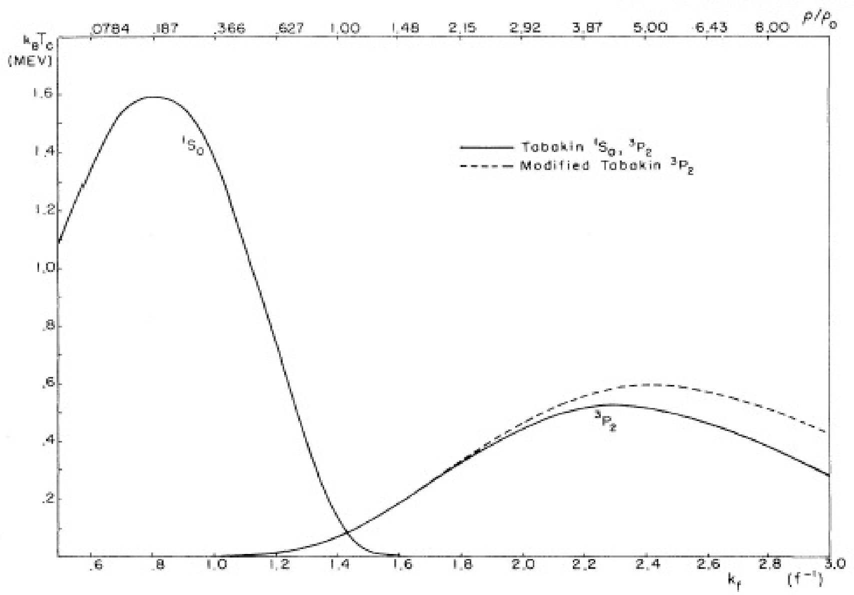

FIG. 1. Computed superfluid transition temperature for neutron matter as a function of Fermi wave number k_F (bottom scale) and of neutron density ρ (top scale) with $\delta^* = \delta$ and $m^* = m$. The neutron density ρ_0 in normal nuclei is 1.5×10^{14} g cm^{-3} and the density at the core-crust interface of a neutron star is about 5×10^{13} g cm^{-3}. The solid curves were obtained with Tabakin's potentials (see Ref. 6), and the dashed curve with a one-term modification of the Tabakin potential.

First neutron superfluid gap calculations:
Hoffberg, Glassgold, Richardson, Ruderman (1969):

Neutron star dynamics is governed by the motion of quantized vortex lines in the neutron superfluid.

What determines the motion of vortex lines:

(i) Continuous interaction of vortex lines with ambient normal matter.

(ii) Pinning at sites attractive for the vortex line. Vortex motion as statistical average of pinning and unpinning : vortex creep, and sporadic vortex discharges → glitches.

Pinning to nuclei in the neutron star crust, $I_i / I \sim 10^{-3}$, and to flux lines in the neutron star core.

Neutron star matter at sub-nuclear densities

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Received 19 January 1973. Available online 18 October 2002.

Abstract

An extremely simple form for the energy density of a nuclear many-body system derived from the two-body nucleon-nucleon interaction is used to determine the ground state configuration of matter at sub-nuclear density. As the baryon density is increased, nuclei become progressively more neutron rich until neutrons eventually escape, yielding a Coulomb lattice of bound neutron and proton clusters surrounded by a dilute neutron gas. The clusters enlarge and the lattice constant decreases with increasing density, approaching a completely uniform state near nuclear density.

IV. RESULTS

The magnitude of the pinning force on a nuclear cluster is estimated as

$$F_p = \rho_G \left[\frac{\Delta^2(\rho_G)}{E_F(\rho_G)} - \rho_0 \frac{\Delta^2(\rho_0)}{E_F(\rho_0)} \right] \frac{V}{x} , \qquad (2)$$

where V is the volume of a nuclear cluster and x the relevant length scale for vortex core–nuclear cluster interaction, taken to be the larger of ξ and R_N, where ξ

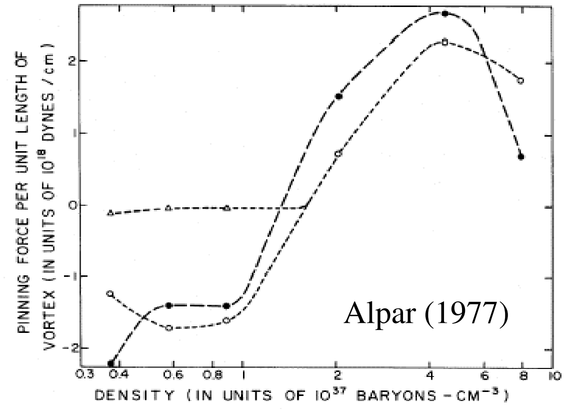


FIG. 2.—Pinning/threading forces per unit length of vortex line, as a function of macroscopic density in the neutron star crust. Computations were made for the six lattice configurations given by Negele and Vautherin (1973) in the crust superfluid region. *Open circles*, results using Takatsuka's (1972) values for the gap; *filled circles*, those from Hoffberg *et al.* (1970). The correction factor, $\sim 10^{-2}$–10^{-1} using Takatsuka's gap values, gives the threading force values indicated by triangles. The corresponding factor using the gap given by Hoffberg *et al.* is $\sim 10^{-3}$.

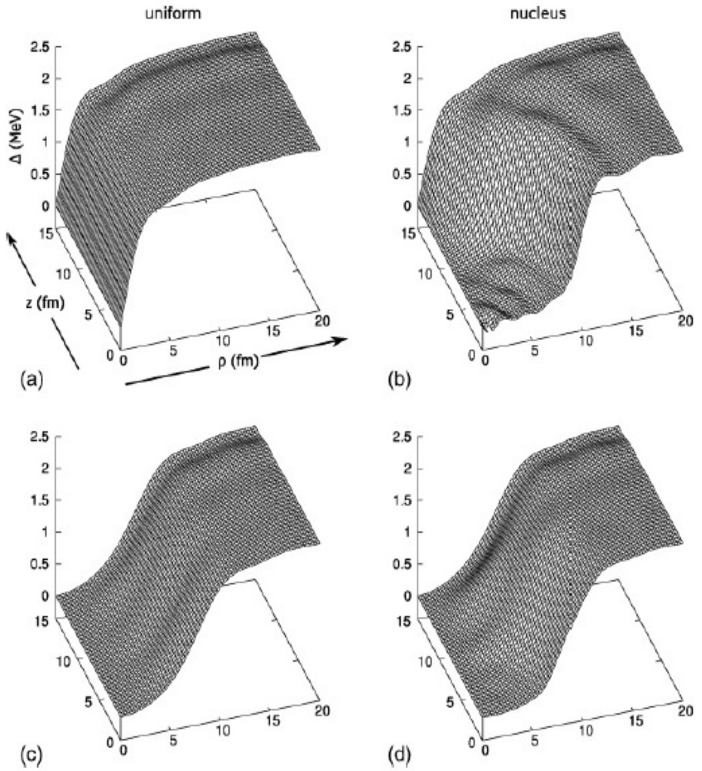
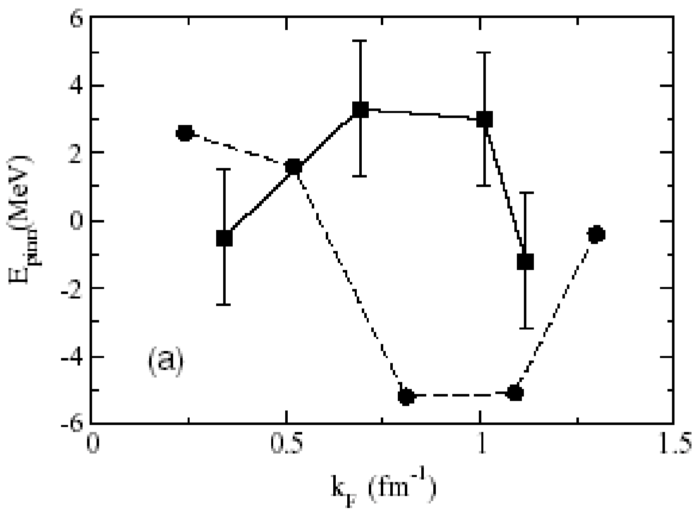


FIG. 1. Pairing gap associated with a $\nu = 1$ and a $\nu = 2$ vortex, calculated in the cylindrical box described in the text for $k_F = 0.69\ \mathrm{fm}^{-1}$. Only the region $0 < z < 15$ fm, $0 < \rho < 15$ fm is shown. (a) Gap associated with a $\nu = 1$ vortex in the cell without the nucleus. (b) Gap associated with a $\nu = 1$ vortex in the presence of the nucleus. (c) Gap associated with a $\nu = 2$ vortex in the cell without the nucleus. (d) Gap associated with a $\nu = 2$ vortex in the presence of the nucleus.

AVOGADRO, BARRANCO, BROGLIA, AND VIGEZZI



Our calculations were performed by solving the mean-field Hartree-Fock-Bogoliubov (HFB) equations (often called the De Gennes equations), within a cylindrical box of radius 30 fm and height 40 fm, imposing that the wave functions vanish at the border of the cell. We have solved the vortex-nucleus system in an axially symmetric basis, with the vortex directed along the z axis. The De Gennes equations have the form [5,8]

$$\begin{aligned} [K + V(\rho, z) - E_F]U_\alpha + \Delta V_\alpha &= E_\alpha U_\alpha, \\ -[K + V(\rho, z) - E_F]V_\alpha + \Delta^* U_\alpha &= E_\alpha V_\alpha \end{aligned} \qquad (1)$$

and have to be solved simultaneously with the number equation. The kinetic energy operator is denoted by K; V is the self-consistent Hartree-Fock mean field, which was determined using the SII force [9]. The $(S = 0)$ pairing field Δ and the quasiparticle amplitudes U_α and V_α depend on the coordinates z, ρ (the distance to the z axis in the x-y plane) and ϕ (the azimuthal angle). Equations (1) allow for different solutions, which can be labeled by the vortex number $\nu(= 0, 1, 2\ldots)$. For a given value of ν, the pairing gap depends on ϕ according to $\Delta(\rho, z, \phi) = \Delta(\rho, z)e^{i\nu\phi}$, and each Cooper pair carries ν units of angular momentum along the z axis. For $\nu = 0$ one recovers the usual equations for the superfluid ground state. The quasiparticle amplitudes are expanded on a basis of (free) single-particle wave functions:

$$\begin{aligned} U_\alpha(\rho, z, \phi) &= e^{il_\alpha\phi} \sum_{n,m} U_\alpha^{n,m} \psi_{n,l_\alpha}(\rho) \chi_m(z), \\ V_\alpha(\rho, z, \phi) &= e^{i[l_\alpha - \nu]\phi} \sum_{n,m} V_\alpha^{n,m} \psi_{n,l_\alpha-\nu}(\rho) \chi_m(z), \end{aligned} \qquad (2)$$

where the functions $\chi_m(z)$ are (longitudinal) plane waves and $\psi_{n,l_\alpha}(\rho)$ (radial) Bessel functions, with l_α being the single-particle angular momentum along the cylinder axis, chosen as quantization axis. The quantities $U_\alpha^{n,m}$ and $V_\alpha^{n,m}$ are determined by substituting Eqs. (2) into Eqs. (1). This

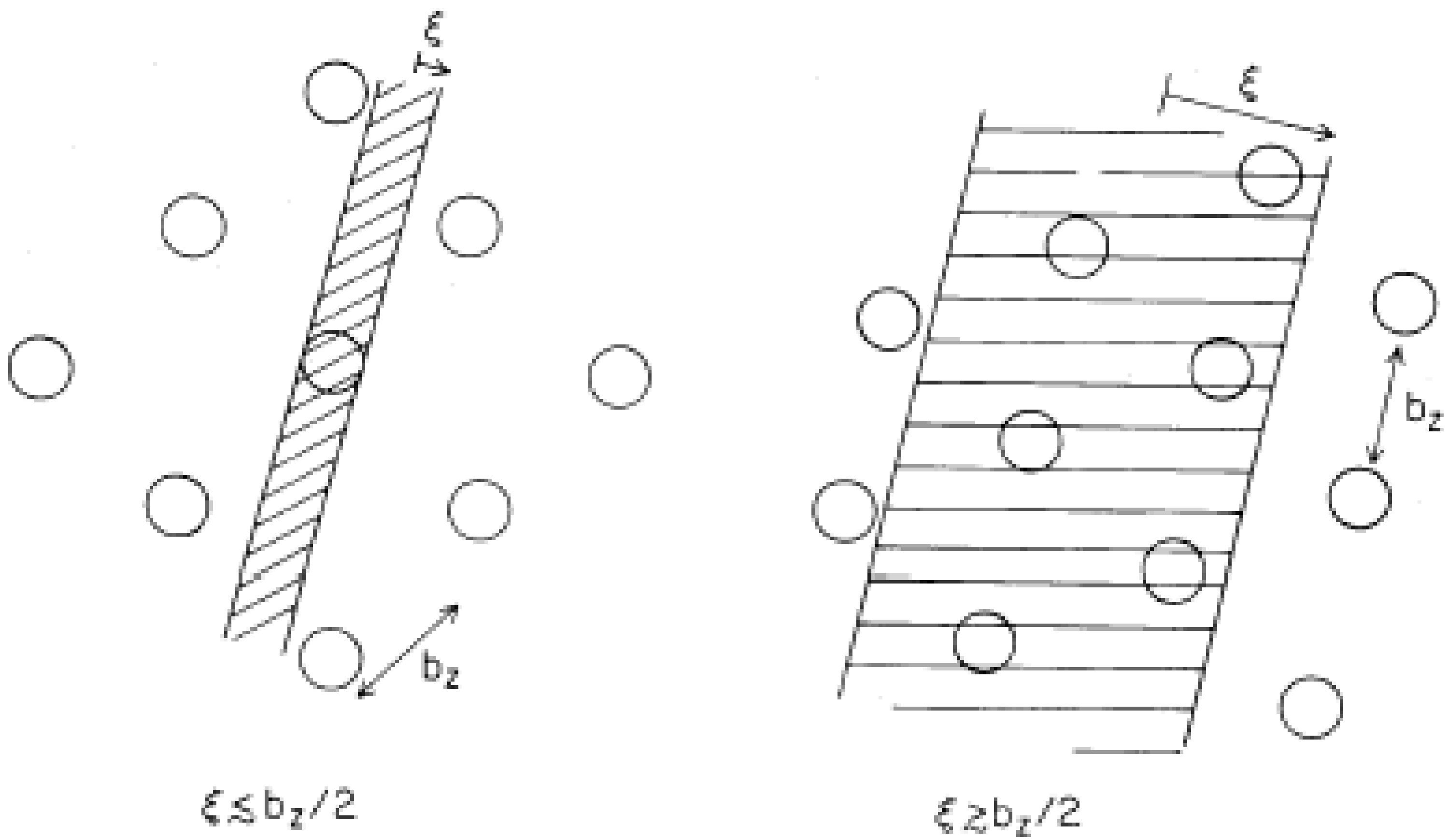


FIG. 2.—The pinning situation for $\xi \lesssim b_z/2$ and $\xi \gtrsim b_z/2$

VORTEX CREEP AND THE INTERNAL TEMPERATURE OF NEUTRON STARS. I. GENERAL THEORY[1]

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Received 1983 March 31; accepted 1983 June 2

The pinning energy is of the order of 1 MeV at each pinning to a nucleus.

There is a range of different effective pinning situations, characterized by ω_{cr}, the critical (maximal) lag in rotation rates between the superfluid and the crust lattice that can be sustained by the pinning. The Magnus equation of motion for vortices pinned to the lattice relates the pinning force per unit length of vortex line to the lag ω_{cr}:

$$E_p / (b\,\xi) = \rho\,\kappa\,R\,\omega_{cr}$$

b is the distance between pinnings along the vortex,
ξ is the vortex radius (coherence length),
ρ is the superfluid density,
κ is the vortex quantum
and R is the neutron star radius.

PINNING REGIMES

i) Strong pinning, where the pinning energy per nucleus is enough to dislodge nuclei from lattice equilibrium sites so that the vortex line pins to nuclei at intervals of roughly the lattice spacing $b \sim b_z$ along the length of vortex line,
$b \sim b_z$, $\omega_{cr} \sim 1$ rad/s .

ii) Weak pinning. Nuclei not dislodged from equilibrium. Pinning at geometrically picked "random" sites, with
$b \sim b_z^{\,3} / (\pi \xi^2)$, $\omega_{cr} \sim 10^{-1}$ rad/s.

iii) Superweak pinning. $\xi >> b_z$, $\omega_{cr} < 10^{-2}$ rad/s.

AND OTHERS: Interstitial. Pasta. Vortex tension. 2 quantum vortices.. RANGE of PINNING SITUATIONS….

VORTEX CREEP

Equations of motion:

$$I_c \, d\Omega_c /dt + I_s \, d\Omega_s /dt = N_{ext}$$

$$d\Omega_s /dt = - n\kappa \langle v_r \rangle / r = - 2\Omega_s \langle v_r \rangle / r$$

steady state:

$$d\Omega_s /dt = d\Omega_c /dt = N_{ext}/(I_c + I_s) = (d\Omega /dt)_\infty$$

Vortex creep:

Pinning: superfluid is rotating faster.
If vortex lines move outward superfluid will spin down. It is energetically favourable to reduce differential rotation between normal matter and superfluid. So there is an energy bias favouring vortex motions that are radially outward.

Pinning energy at each pinning site = E_p

Energy bias: $\Delta E = E_p (\Omega_s - \Omega_c)/\omega_{cr} = E_p (\omega / \omega_{cr})$

$$\langle v_r \rangle = v_0 \{\exp - [(E_p - \Delta E)/kT] - \exp - [(E_p + \Delta E)/kT]\}$$
$$= 2 v_0 \exp(-E_p / kT) \sinh [E_p (\omega / \omega_{cr})/kT]$$

Depending on the $<v_r>$ value required in the steady state,

$$d\Omega_\infty /dt = -2\Omega_s < v_r > / r ,$$

vortex creep has linear and nonlinear regimes:

Linear: $\sinh [E_p (\omega / \omega_{cr}) /kT] \sim E_p (\omega / \omega_{cr}) /kT$

Nonlinear: $\sinh [E_p (\omega / \omega_{cr}) /kT] \sim \frac{1}{2} \exp [E_p (\omega / \omega_{cr}) /kT]$.

Pulsar spindown, glitches and postglitch response involves nonlinear as well as linear creep.

As a pulsar ages $T(t)$ and $| d\Omega/dt|$ both decrease, in such a way that more and more of the neutron star pinning spectrum Ep(r) falls in the nonlinear creep regime: pulsars go nonlinear as they mature.

Linear regime:

$d\Omega_s /dt = - 2\Omega_s <v_r> / r$
$= - (4\ \Omega_s\ v_0 / r\ ) \exp (- E_p / kT) .[E_p (\omega / \omega_{cr}) /kT]$

$= - \ \omega / \tau$
$= - \ (\Omega_s - \Omega_c\ ) / \tau,$

defining a linear creep relaxation time

$$\tau = (4\ \Omega_s\ v_0 / r\ )^{-1} [kT\ \omega_{cr}\ / E_p\ ]\ \exp (E_p / kT)\ .$$

In the linear regime the pinned superfluid behaves like a superfluid with continuous drag forces. Linear response to glitch induced perturbations→ exponential relaxation.

Nonlinear response is essential in understanding interglitch behaviour. Any perturbation $\delta\omega$ to the superfluid-normal matter lag ω can effectively stop creep, until the spindown of the normal component restores steady state creep conditions on a timescale $t_0 = \delta\omega / |d\Omega/dt|$.
Response time-width $\tau_{nonlinear} = (kT/E_p)\ (\omega_{cr} / |d\Omega/dt|\ )$

This is the signature observed in $d\Omega/dt$ if the glitch introduced a constant $\delta\omega$ throughout the pinned superfluid: Fermi function→

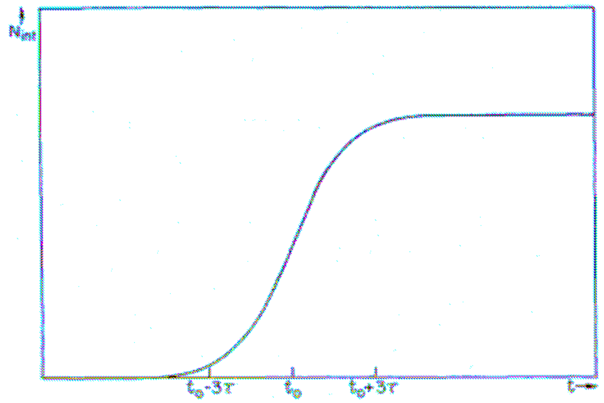


FIG. 4.—The internal torque for the case $t_0 \gg \tau$. Note the characteristic Fermi function behavior.

What happens if the glitch induced offset is not uniform throughout the pinned superfluid?

Nonlinear response to a 'mean field' uniform density of unpinned vortices: stacked Fermi functions →

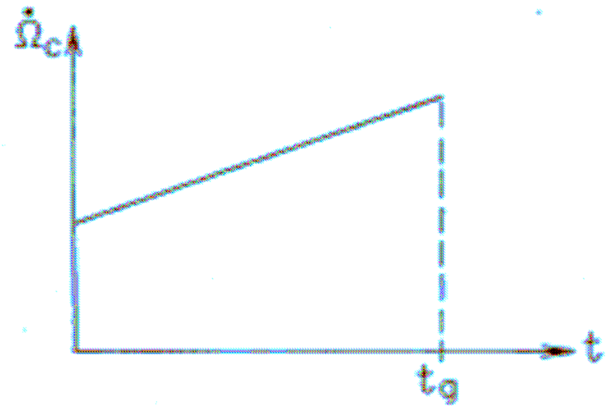
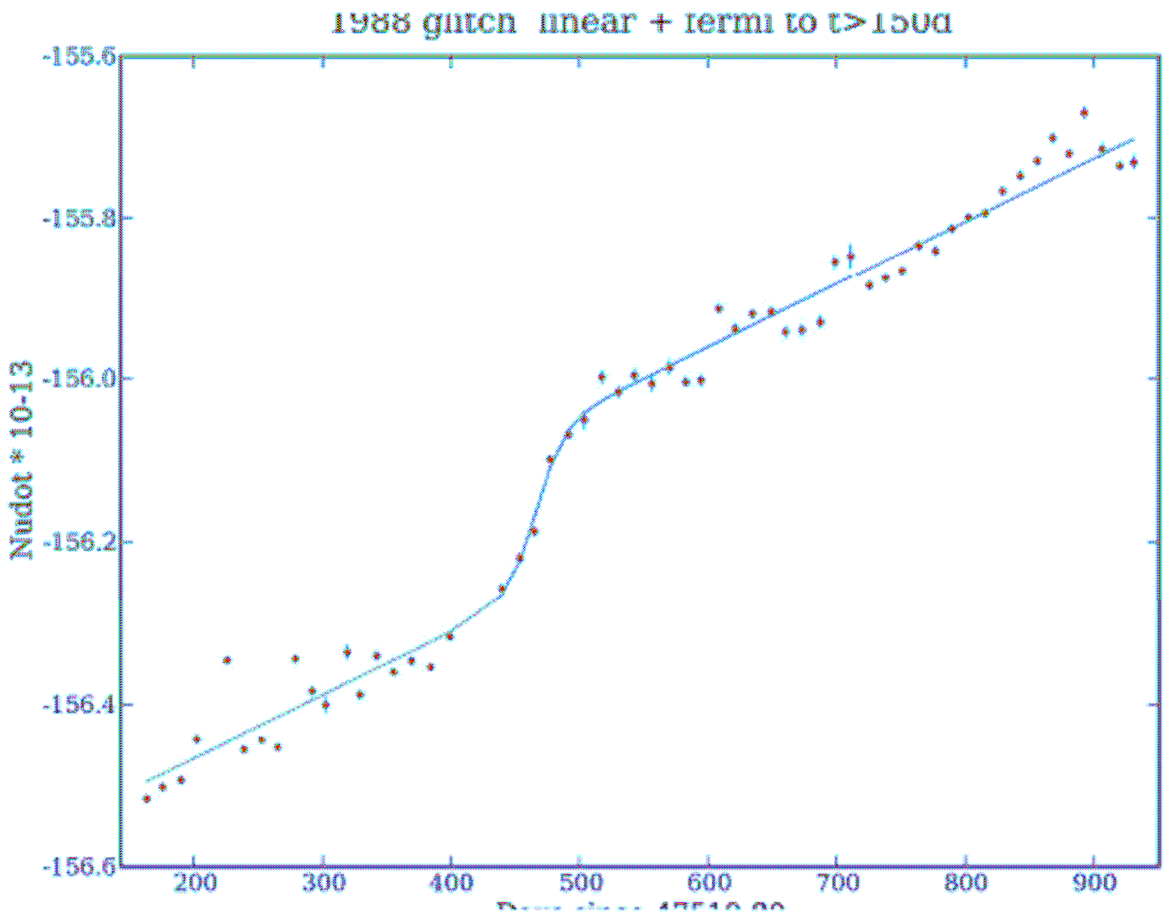
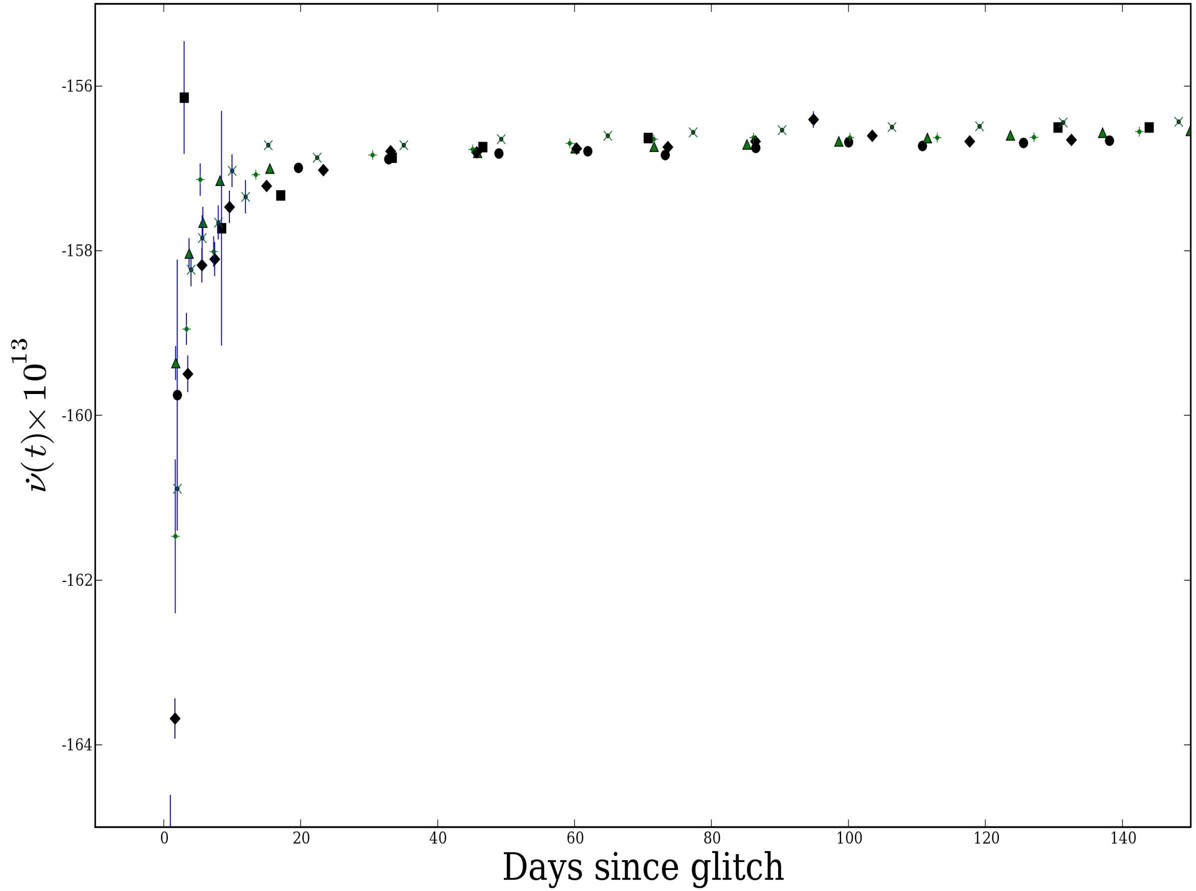


FIG. 4c


1988 glitch linear + fermi to t>150d
Nudot * 10-13
-155.6
-155.8
-156.0
-156.2
-156.4
-156.6
200
300
400
500
600
700
800
900



	Year	MJD
7	1985	46259
8	1988	47519.803
9	1991	48457.382
10	1994a	49559.057
11	1994b	49591.158
12	1996	50369.345
13	2000	51559.319
14	2004	53193.09
15	2006	53959.92

Postglitch relaxation of the spindown rate; 9 Vela pulsar glitches.

Data and fit: Sarah Buckner & Claire Flanagan, Hartebesthoek Radio Astronomy Observatory, South Africa

$\tau_1 =$ 0.49 d, $\tau_2 =$ 5.4 d, and $\tau_3 =$ 49 d

Vortex Creep can explain spindown behaviour, glitches and postglitch response. It seems there is a universal behaviour regarding glitches of pulsars of all ages.

The constant $d^2\,\Omega/dt^2$ interglitch
behavior sems universal among all older pulsars with glitch/interglitch data.
(Alpar and Baykal 2006)

ABSTRACT

Almost all pulsars with anomalous positive $\ddot{\Omega}$ measurements (corresponding to anomalous braking indices in the range $5 < |n| < 100$), including all the pulsars with observed large glitches ($\Delta\Omega/\Omega > 10^{-7}$) as well as post-glitch or interglitch $\ddot{\Omega}$ measurements, obey the scaling between $\ddot{\Omega}$ and glitch parameters originally noted in the Vela pulsar. Negative second derivative values can be understood in terms of glitches that were missed or remained unresolved. We discuss the glitch rates and a priori probabilities of positive and negative braking indices according to the model developed for the Vela pulsar. This behaviour supports the universal occurrence of a non-linear dynamical coupling between the neutron star crust and an interior superfluid component. The implied lower limit to dynamical energy dissipation in a neutron star with spindown rate $\dot{\Omega}$ is $\dot{E}_{\rm diss} > 1.7 \times 10^{-6} \dot{E}_{\rm rot}$. Thermal luminosities and surface temperatures due to dynamical energy dissipation are estimated for old neutron stars which are spinning down as rotating magnetic dipoles beyond the pulsar death line.

Key words: pulsars: general.

NEUTRON STAR CORE

Vortex lines are spontaneously magnetised by dragged proton supercurrent around neutron vortices.
Electron scattering off vortex lines couples the neutron superfluid to the normal matter – electrons – observed crust on timescales less than a minute,

$\tau \sim$ (400-10 000) P [proportional to $(m^*/\delta m)^2$!]

Faster than the coupling time of a normal matter neutron star core!

Two superfluids- He_3-He_4 Andreev & Bashkin 1975
Neutron Star application: Alpar, Langer & Sauls 1984

For slow spatial variations, $|f_g| \ll |f_u|$, the amplitudes are fixed by the condensation energy density f_u, so that $\psi_p = \psi_0 e^{i\chi_p}$, $\psi_n = \phi_0 e^{i\chi_n}$, and f_u = constant. The superfluid velocities are defined by the Galilean transformation properties of the order parameters, which imply that

$$v_p = \frac{\hbar}{2m_p} \nabla \chi_p , \tag{6}$$

$$v_n = \frac{\hbar}{2m_n} \nabla \chi_n . \tag{7}$$

The free energy density can then be written in terms of the superfluid velocities, the "bare" superfluid density (ρ_s^{pp} and ρ_s^{nn}), and the coupling density ρ_s^{pn} as

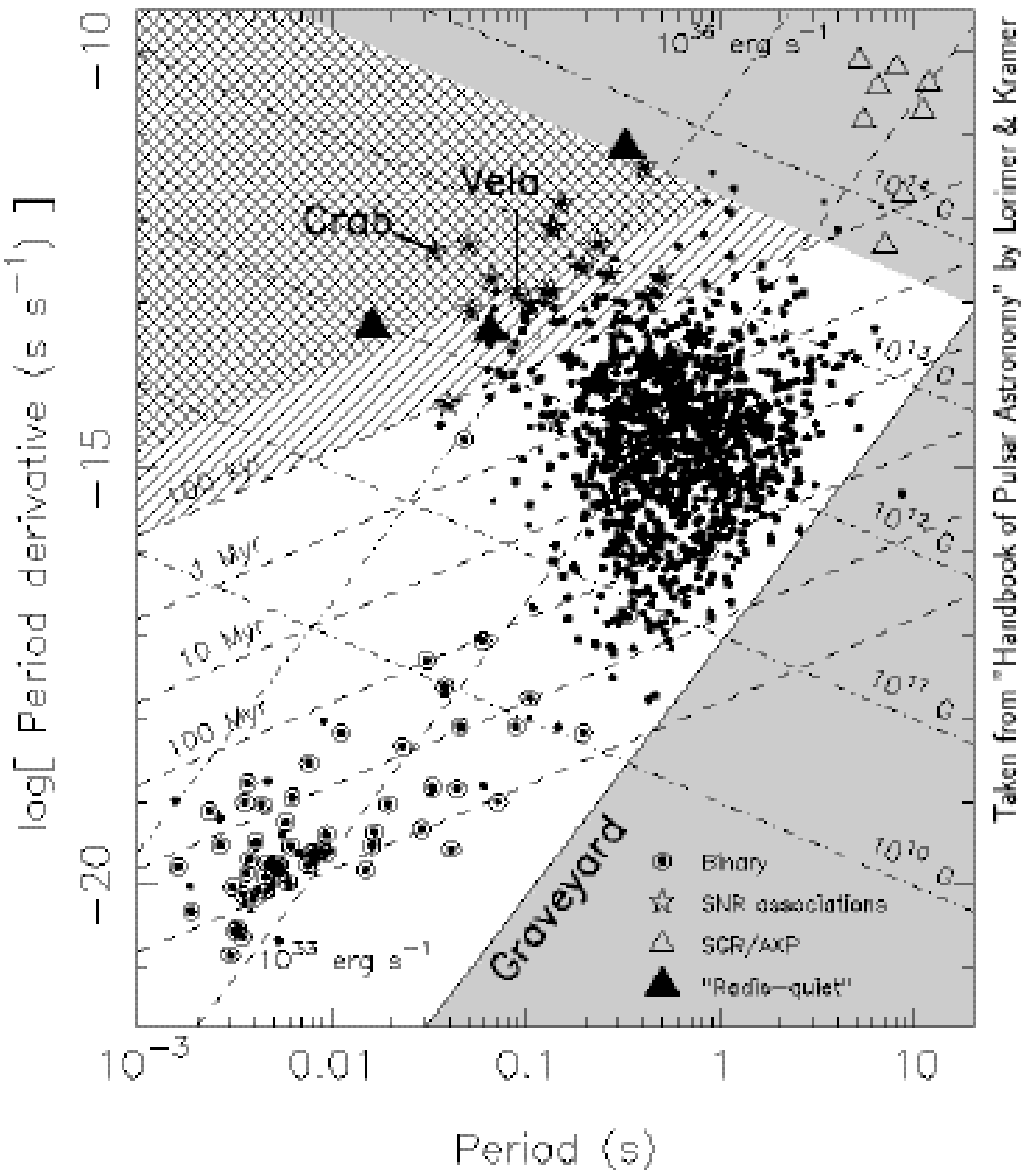
$$f_{GL} = f_u + \tfrac{1}{2}\rho_s^{pp} v_p^2 + \tfrac{1}{2}\rho_s^{nn} v_n^2 + \rho_s^{pn} v_p \cdot v_n , \tag{8}$$

[2] After completing this work we found that Vardanyan and Sedrakyan (1981) and Sedrakyan and Shakhbasyan (1980) have also considered the drag effect in charged-neutral mixtures; however, they do not discuss the implications of the drag effect for the rotational dynamics of pulsars.

Pinning can also take place in the core, between neutron vortex lines and proton flux lines (Sauls 1988).

Relevant to glitches and postglitch relaxation? Not likely: Does ~10^{-2} correspond to "easy" directions? Are there easy directions? Toroidal field ←→ flux rings? "Easy" depends on **B.Ω**, which cannot be universal for all pulsars.

Flux line vortex line pinning may be relevant to something else, the evolutionary history of many neutron stars through the age of the Galaxy/galaxies, 10^9-10^{10} years. Millisecond pulsars- weak B-field neutron stars spun up by accretion, in low mass X-ray binaries, to almost breakup rotation rates (Alpar, Cheng, Ruderman, Shaham 1982; also Radhakrishnan & Srinivasan).



Crab
Vela
Graveyard
Binary
SNR associations
SGR/AXP
"Radio-quiet"
100 kyr
1 Myr
10 Myr
100 Myr
10^{36} erg s^{-1}
10^{33} erg s^{-1}
10^{14} G
10^{13} G
10^{12} G
10^{11} G
10^{10} G
Period (s)
log[Period derivative (s s^{-1})]
Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

PERHAPS The field got reduced from 10^{12} G to 10^{9} G as vortex lines pushed out the flux lines over a 10^{8} year binary phase of neutron star spindown
(Srinivasan, Bhattacharya, Muslimov & Tsygan 1990).

PERHAPS it is the interaction of the vortices in the two BCS superfluids coexisting in neutron stars that brings about the fastest cosmic rotation and produces the sounds of the spheres:

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html