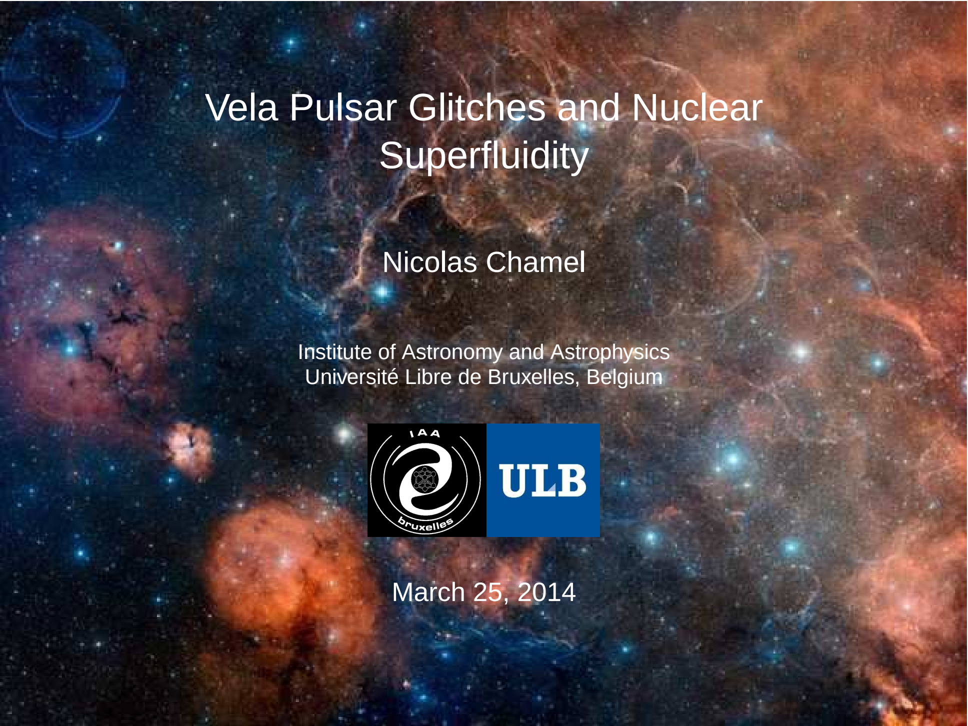

Vela Pulsar Glitches and Nuclear Superfluidity

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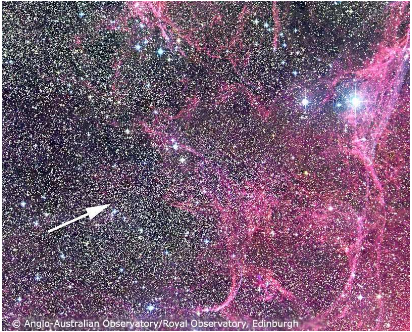
Vela pulsar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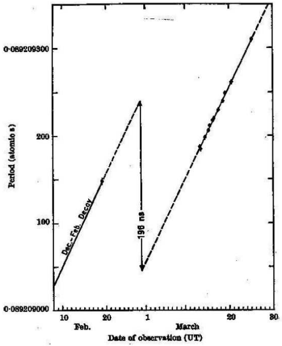
In October 1968, astronomers from the Sydney University discovered a pulsar with a period of 89 ms in the Vela constellation.

The Crab pulsar was found the next month by astronomers from the Green Bank observatory.

The discovery of these pulsars confirmed the predictions of Baade and Zwicky 35 years earlier that neutron stars are the compact remnants of supernova explosions.

Observations of the first glitch

Between February 24 and March 3 1969, Vela was found to pulse more rapidly than before!



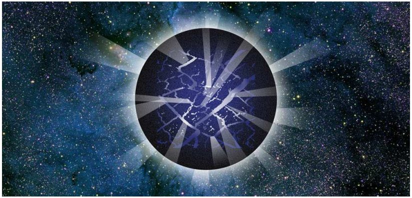
The rotational frequency had increased by $\Delta\Omega/\Omega \simeq 2 \times 10^{-6}$.

The increase in the spin-down rate was even larger $\Delta\dot{\Omega}/\dot{\Omega} \simeq 7 \times 10^{-3}$.

Radhakrishnan& Manchester, Nature 222, 228 (April 1969)

Reichley& Downs, ibid. 229

Speculations about the origin of the Vela glitch



Ruderman proposed that the glitch is the manifestation of **crustquakes** (spin-down induced crustal stress).

Ruderman, Nature 223, 597 (August 1969).

According to his theory, glitches should be rare, as would be later confirmed

Smoluchowski, PRL 24, 923 (1970); Baym&Pines, Ann. Phys. 66, 816 (1971)

But Ruderman realized that the observation of the first glitch would thus have been an unlikely coincidence!

Dyson speculated that glitches could be more frequent if the crustal stress is induced by the accumulation of materials from volcanoes.

Dyson, Nature 223, 486 (August 1969).

Further observations and speculations

A smaller glitch was observed in the Crab pulsar in September 1969.

In the fall of 1971, a **second glitch occurred in Vela** thus ruling out Ruderman's crustquake theory.

Other theories were proposed:

- accretion
- volcanic activity
- corequakes
- planetary perturbations
- magnetospheric instabilities.

But none of them was really convincing.

see, e.g., Pines, Shaham & Ruderman, IAU proceedings 53, 189 (1974).

Since no such phenomena had ever been observed in other celestial bodies, glitches had to do with specific properties of neutron stars.

First hints about nuclear superfluidity

Cameron and Greenstein proposed that the Vela glitch was due to the onset of **fluid instabilities** induced by differential rotation between the core and the outer layers (*“we shall assume viscous effects to be unimportant”*). *Nature 222, 862 (May 1969)*

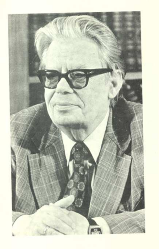
After about one year, the spin-down rate of Vela relaxed to the value it had before the glitch. This **long relaxation time** provided strong evidence for **superfluidity**.
Baym, Pethick, Pines, Nature 224, 673 (November 1969)

In 1972, Packard suggested that glitches could be related to the **metastability** of the superfluid flow (*PRL 28, 1080*).

In 1975, Anderson & Itoh advanced the seminal idea that glitches are triggered by the sudden **unpinning of superfluid vortices** in neutron-star crust (*Nature 256, 25*).

Superfluidity and superconductivity in neutron stars

At the beginning of the 1970’s, several superconductors were known but only helium was found to be superfluid (in 1937 for ^{4}He, in 1972 for ^{3}He).



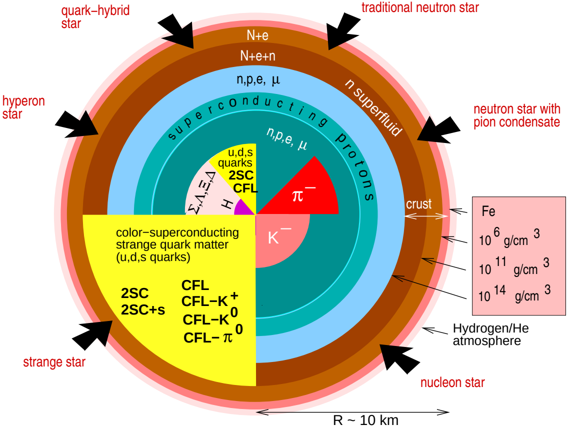
N.N. Bogoliubov, who developed a microscopic theory of superfluidity and superconductivity, was the first to explore its application to nuclear matter.

Dokl. Ak. nauk SSSR 119, 52 (1958).

In 1959, Migdal predicted neutron-star superfluidity (*Nucl. Phys. 13, 655*), which was first studied by Ginzburg & Kirzhnits in 1964 (*Zh. Eksp. Teor. Fiz. 47, 2006*) *before* the pulsars discovery.

Today’s picture of neutron star interiors

Neutron-stars could contain various kinds of superfluids and superconductors.



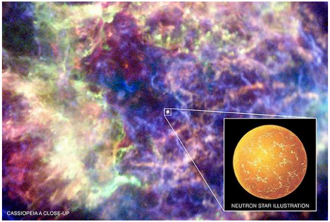
picture from F. Weber

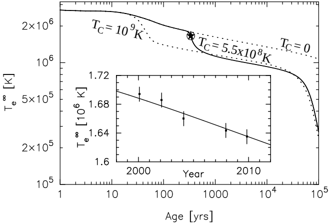
Observational evidence for neutron-star superfluidity

Apart from glitches, other observations suggest the existence of neutron-star superfluidity.

- Observations of Cassiopeia A provide strong evidence for neutron-star core superfluidity.

  Page et al., PRL 106, 081101; Shternin et al.,MNRAS 412, L108.





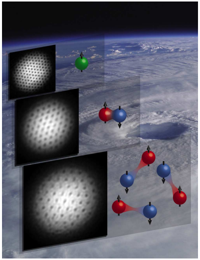
- Observations of quasi-persistent soft X-ray transients provide evidence for neutron-star crust superfluidity.

  Shternin et al., Mon. Not. R. Astron. Soc.382(2007), L43.

  Brown and Cumming, ApJ698 (2009), 1020.

Vortex-mediated glitch theory

A rotating superfluid is threaded by a regular array of **quantized vortex lines**. Each line carries an angular momentum $\hbar$. The surface density of vortices is proportional to the angular velocity.



Vortices in cold gases (MIT)

Vortex-mediated glitch theory in a nut shell

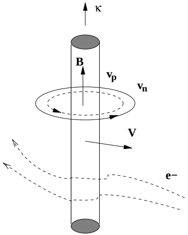
Vortices move outwards as the superfluid spins down with the rest of the star due to mutual friction forces.

Vortex pinning by nuclei gives rise to crustal stress until:

- vortices are suddenly unpinned (Anderson&Itoh)
- the crust cracks (Ruderman).

Entrainment and dissipation in neutron-star cores

Historically the **long post-glitch relaxation** was the first evidence of neutron-star superfluidity. But...



picture from K. Glampedakis

Due to (non-dissipative) mutual entrainment effects, neutron vortices carry a **fractional magnetic quantum flux**

Sedrakyan and Shakhabasyan, Astrofizika 8 (1972), 557; Astrofizika 16 (1980), 727.

The core superfluid is strongly coupled to the crust due to electrons scattering off the magnetic field of the vortex lines.

Alpar, Langer, Sauls, ApJ282 (1984) 533

Glitches are therefore expected to originate from the crust.

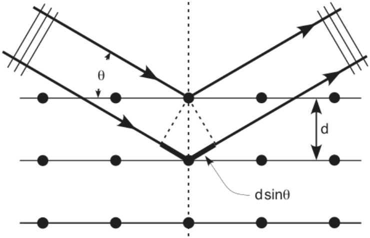
Entrainment in neutron-star crusts

Despite the absence of viscous drag, the crust can still resist the flow of the superfluid due to non-local and non-dissipative entrainment effects.

Carter, Chamel & Haensel, Nucl.Phys.A748,675(2005).

A neutron with wavevector ***k*** can be **coherently scattered** by the lattice if $d \sin\theta = N\pi/k$, where $N = 0, 1, 2, ...$ (Bragg's law).

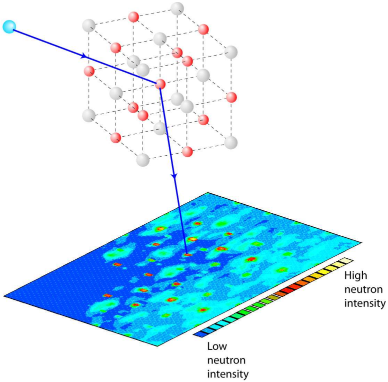
In this case, it does not propagate in the crystal: it is therefore entrained!



Neutron diffraction

For decades, neutron diffraction experiments have been routinely performed to explore the structure of materials.

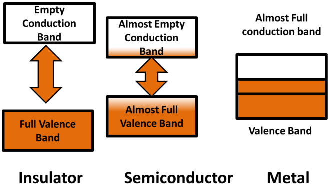
The main difference in neutron-star crusts is that neutrons are highly degenerate



A neutron can be coherently scattered if $k > \pi/d$. In neutron stars, neutrons have momenta up to k_{F}. Typically $k_{\mathrm{F}} > \pi/d$ in all regions of the inner crust but the shallowest. Therefore, Bragg scattering should be taken into account!

Nuclear band theory in a nut shell

Neutrons in neutron-star crusts are completely analogous to electrons in ordinary solids. Their properties can thus be determined by the band theory of solids.



Neutron conduction
Only neutrons in the conduction band can move throughout the crust.

The average density of “conduction” neutrons is proportional to the average group velocity over the Fermi surface

$$n_n^{\rm c} = \frac{m_n}{24\pi^3\hbar^2}\sum_\alpha \int_{\rm F} |\nabla_{\boldsymbol{k}}\varepsilon_{\alpha\boldsymbol{k}}| {\rm d}\mathcal{S}^{(\alpha)}$$

Neutron band structure calculations

The inner crust of a neutron star is supposed to be in full thermodynamic equilibrium at zero temperature.

1. The equilibrium structure of the inner crust is determined using the Extended Thomas-Fermi (4th order) + Strutinsky Integral method with Brussels-Montreal Skyrme functionals. This is a very fast approximation to the Hartree-Fock method.

   Onsi et al., Phys.Rev.C77,065805 (2008)

   Pearson et al,Phys.Rev.C85,065803(2012).

2. The neutron band structure is calculated using the ETFSI mean fields.

   Chamel,Phys.Rev.C85,035801(2012).

Brussels-Montreal Skyrme functionals (BSk)

These functionals were fitted to both experimental data (all atomic masses with $Z, N \geq 8$ from the Atomic Mass Evaluation) and N-body calculations using realistic forces.

Main features of the latest functionals:

- ▹ fit to realistic $^1S_0$ pairing gaps in symmetric and neutron matter (BSk16-17)
- ▹ removal of spurious ferromagnetic instabilities in infinite homogeneous matter (BSk18)
- ▹ fit to realistic neutron-matter eos with different degrees of stiffness (BSk19-21)
- ▹ fit of the 2012 AME with different symmetry energy coefficients (BSk22-26)
- ▹ optimal fit of the 2012 AME with a rms of 0.512 MeV (BSk27*)

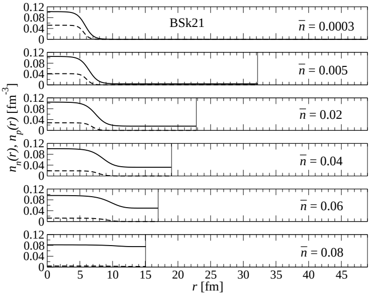
Goriely, Chamel, Pearson, Phys. Rev. C88,061302(R) (2013)

Structure of the inner crust of a neutron star (I) nucleon distributions

With increasing density, the clusters keep essentially the same size but become more and more dilute:

Crust-core transition properties

	$\bar{n}_{\rm cc}$ (fm^{-3})	$P_{\rm cc}$ (MeV fm^{-3})
BSk19	0.0885	0.428
BSk20	0.0854	0.365
BSk21	0.0809	0.268
SLy4	0.0798	0.361



The crust-core transition is very smooth: the crust dissolves almost continuously into a uniform mixture of nucleons and electrons.

Structure of the inner crust of a neutron star (II) composition

ETFSI calculations with different functionals:

with BSk14

$\bar{n}$ (fm^{-3})	Z	A
0.0003	50	200
0.001	50	460
0.005	50	1140
0.01	40	1215
0.02	40	1485
0.03	40	1590
0.04	40	1610
0.05	20	800
0.06	20	780

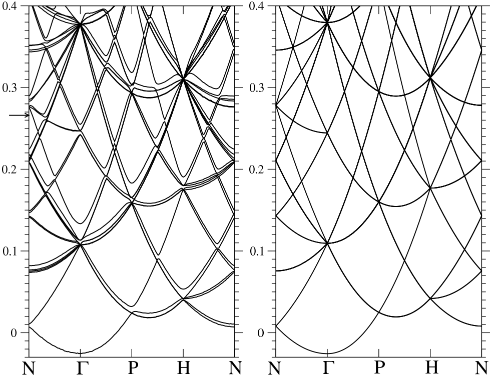
with BSk17

$\bar{n}$ (fm^{-3})	Z	A
0.0003	50	190
0.001	50	432
0.005	50	1022
0.01	50	1314
0.02	40	1258
0.03	40	1334
0.04	40	1354
0.05	40	1344
0.06	40	1308

with BSk19, BSk20 and BSk21, only $Z = 40$ is found.

Neutron band structure: shallow region

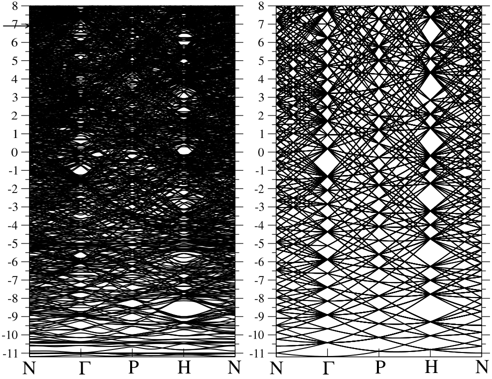
Neutron band structure with (left) and without (right) a bcc lattice of tin like clusters:



The band structure is similar to that of free neutrons: entrainment is therefore expected to be weak.

Neutron band structure: intermediate region

Neutron band structure with (left) and without (right) a bcc lattice of zirconium like clusters:



The band structure is very different from that of free neutrons: entrainment is therefore expected to be strong.

How “free” are neutrons in neutron-star crusts?

Results of systematic band structure calculations in all regions of the inner crust of a neutron star:

$\bar{n}$ (fm^{-3})	n_n^f/n_n (%)	n_n^c/n_n^f (%)
0.0003	20.0	82.6
0.001	68.6	27.3
0.005	86.4	17.5
0.01	88.9	15.5
0.02	90.3	7.37
0.03	91.4	7.33
0.04	88.8	10.6
0.05	91.4	30.0
0.06	91.5	45.9

$\bar{n}$ is the average baryon density
n_n is the total neutron density
n_n^f is the “free” neutron density
n_n^c is the “conduction” neutron density

In many layers, most neutrons are entrained by the crust!
Chamel,PRC85,035801(2012)

Entrainment impacts our understanding of Vela pulsar glitches.

Vela pulsar glitches and crustal entrainment

Vela pulsar glitches are usually interpreted as **sudden tranfers of angular momentum between the crustal superfluid and the rest of star**.

However this superfluid is also entrained ! Its angular momentum can thus be written as

$$J_s = I_{ss}\Omega_s + (I_s - I_{ss})\Omega_c$$

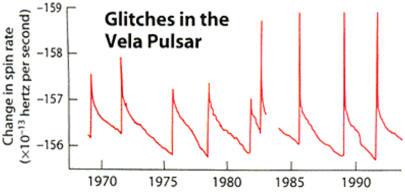
(Ω_s and Ω_c being the angular velocities of the superfluid and the “crust”), leading to the following constraint:

$$\frac{(I_s)^2}{I_{ss}I} \geq A_g \frac{\Omega}{|\dot{\Omega}|}, \qquad A_g = \frac{1}{t}\sum_i \frac{\Delta\Omega_i}{\Omega}$$

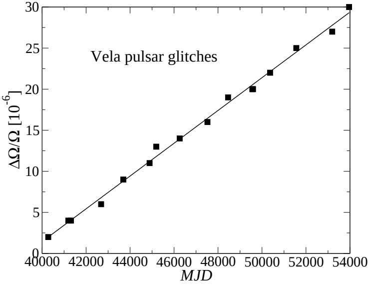
Chamel&Carter,MNRAS368,796(2006)

Pulsar glitch constraint

Since 1969, 17 glitches have been regularly detected. The latest one occurred in August 2010.



Cumulated glitch amplitude



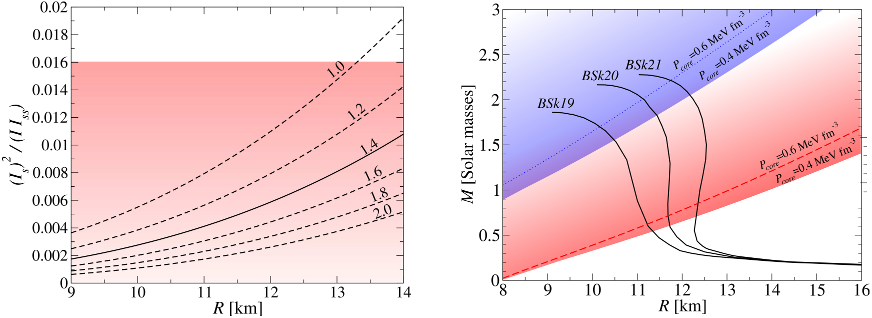
A linear fit of $\frac{\Delta\Omega}{\Omega}$ vs t yields

$$A_g \simeq 2.25 \times 10^{-14}\ \mathrm{s}^{-1}$$

$$\frac{(I_s)^2}{I_{ss} I} \geq 1.6\%$$

Pulsar glitch constraint

Shaded areas are excluded if Vela pulsar glitches originate in the crust.



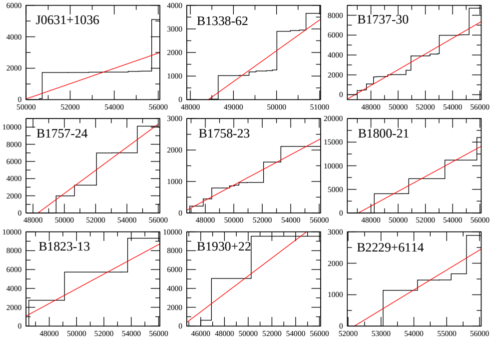
The inferred mass of Vela is unrealistically low $M < M_\odot$.

Due to entrainment, the superfluid in the crust does not carry enough angular momentum to explain large glitches.

Andersson et al.PRL 109, 241103; Chamel, PRL 110, 011101.

Vela like glitches

Vela is not the unique pulsar exhibiting large glitches.



Even though the statistics is low, $A_g \Omega / |\dot{\Omega}|$ is of the same order as for Vela.

Andersson et al.PRL 109, 241103.

Puzzling glitches

The vortex-mediated glitch theory has been challenged by other observations, even without including crustal entrainment:

- a huge glitch $\Delta\Omega/\Omega \simeq 2 \times 10^{-5}$ in PSR 2334+61 reported in 2010

  Alpar, AIP Conf.Proc.1379,166(2011)
- glitches with unusual post-glitch relaxation observed in PSR J1119$-$6127,

  Weltevrede et al., MNRAS 411,1917(2011)
- a huge glitch $\Delta\Omega/\Omega \simeq 3 \times 10^{-5}$ in PSR J1718$-$3718,

  Manchester & Hobbs, ApJ 736,L31(2011)
- an anti-glitch of magnitude comparable to that of Vela glitches observed in April 2012 in 1E 2259+586.

  Archibald et al.,Nature 497,591 (2013).

Summary

- Vela pulsar glitches have been generally thought to arise from the superfluid in neutron-star crust
- However, despite the absence of viscous drag the superfluid can still be entrained by the crust due to Bragg diffraction
- Entrainment effects turn out to be very strong thus challenging the interpretation of Vela pulsar glitches
- Entrainment may have implications for other astrophysical phenomena (e.g. neutron-star cooling, QPOs in SGRs)

Open issues: how does entrainment depend on pastas ? quantum and thermal fluctuations ? impurities and defects ?