Vela pulsar glitches and nuclear superfluidity

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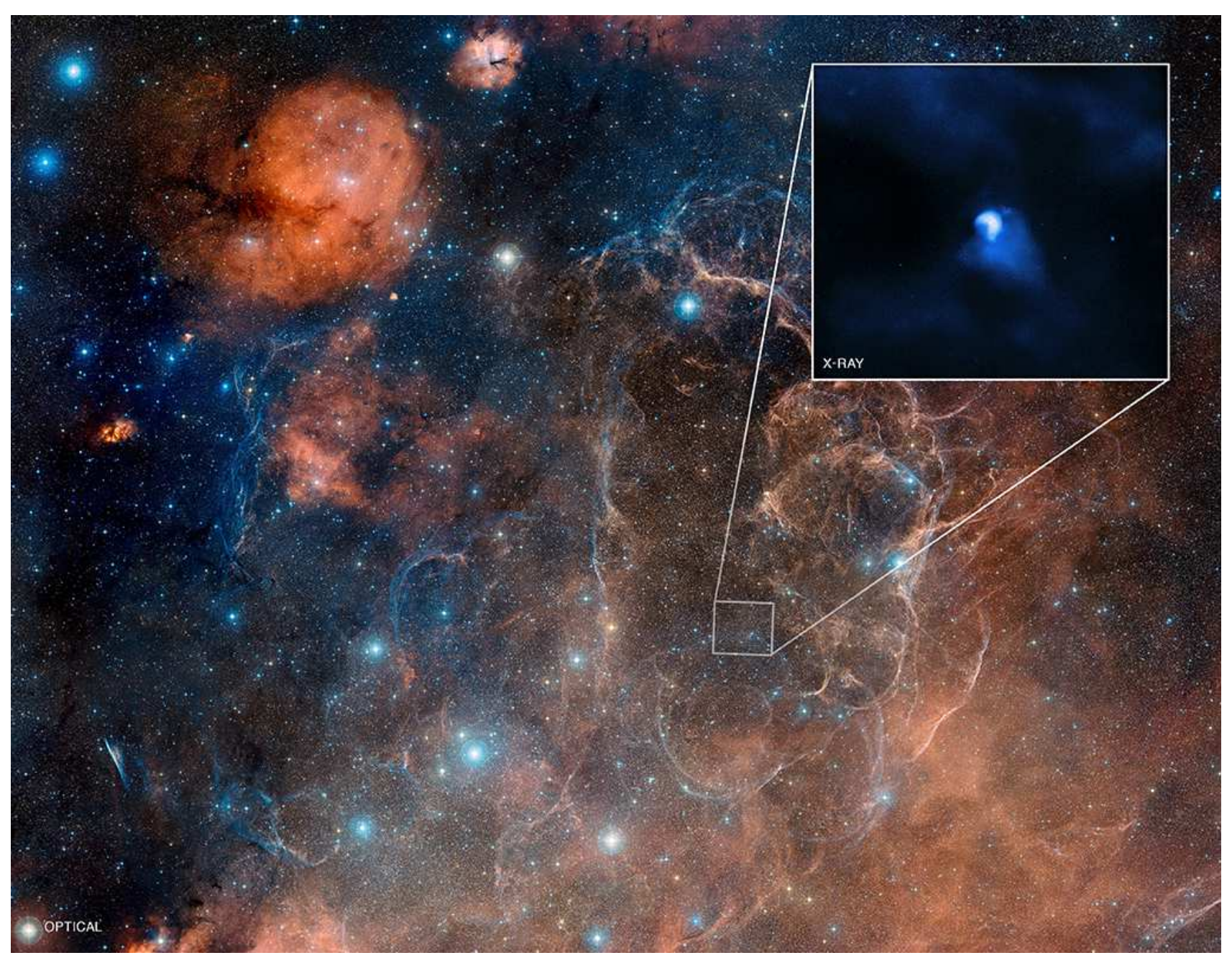
Abstract

At the endpoint of stellar evolution, pulsars are spinning extremely rapidly with periods ranging from milliseconds to seconds and delays of a few milliseconds per year at most, thus providing the most accurate clocks in the Universe. Nevertheless, some pulsars exhibit sudden decreases of their spin period. Because it was the first observed pulsar to exhibit such "glitches", Vela has become the testing ground for glitch theories. Sudden pulsar spin-ups have long been thought to be the manifestation of a neutron superfluid permeating the crustal layers of these dead stars. However, recent calculations indicate that this scenario is unrealistic because neutrons are very strongly coupled to the crust due to non-dissipative entrainment effects. These effects, which were previously ignored, not only challenge the interpretation of Vela pulsar glitches but also suggest that a revision of the interpretation of other observed neutron-star phenomena might be necessary.

I Introduction

Since their fortuitous discovery by Jocelyn Bell and Anthony Hewish in 1967, more than 2000 pulsars have been found. Their identification as neutron stars, the compact residues of type II supernova explosions, was definitively established the next year after the discoveries of pulsars in the Crab and Vela supernova remnants.



This optical image from the Anglo-Australian Observatory's UK Schmidt telescope shows the enormous apparent size of the Vela supernova remnant (about eight degrees across). The inset shows the Vela pulsar, as seen by the Chandra X-ray observatory (NASA). Scale: Wide field optical is 9.3 x 8.5 deg.

Credit: Optical DSS/Davide De Martin (Skyfactory).

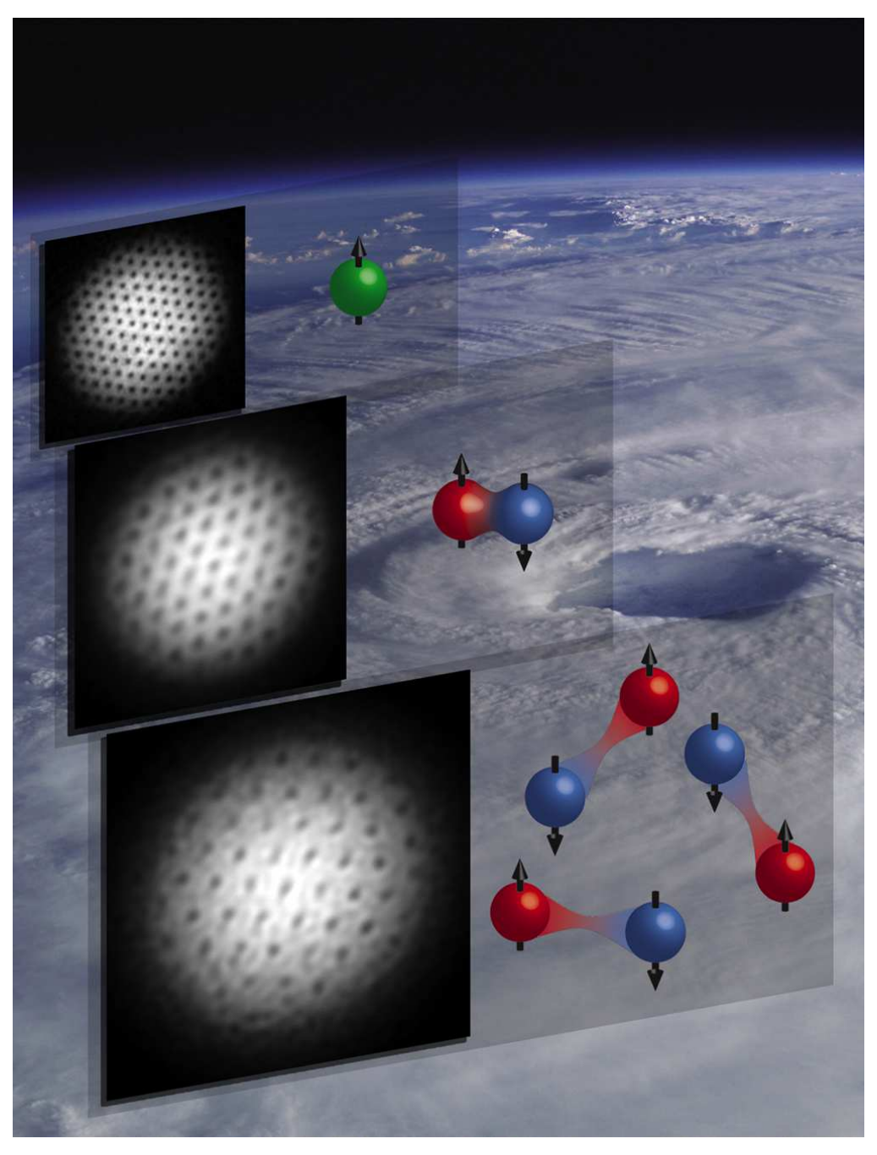
Pulsars are among the most accurate clocks in the Universe with periods ranging from about 1.4 ms up to several seconds (the delays associated with the spin-down are at most of a few of ms per year). Nevertheless, irregularities have been detected in long-term pulsar timing observations. In particular, some pulsars exhibit sudden increases in their rotational frequency Ω. These "glitches", whose amplitude varies from $\Delta\Omega/\Omega \sim 10^{-9}$ up to $\sim 10^{-5}$ are generally followed by a relaxation over days to years (see, e.g., Sec. 12.4 in Ref. [1]).

Soon after the first glitch observations in the Vela and Crab pulsars, several scenarios were advanced [2]. In particular, glitches were thought to be the manifestations of starquakes, but this could not explain the frequent occurrence of Vela pulsar glitches [3]. **On the other hand, the long relaxation times following glitches provided strong evidence for the presence of superfluids in neutron star interiors and hinted at its possible role in the glitch mechanism itself [4, 5]**. Anderson and Itoh developed the fruitful idea that Vela like glitches are related to the dynamics of the neutron superfluid permeating the inner crust of neutron stars [6].

II Vortex-mediated glitches

Nuclear superfluidity in neutron stars was predicted and studied even before the discovery of pulsars [7, 8]. **At temperatures $T < T_c$, nucleons may form pairs like electrons in superconductors.** These pairs are bosons that can behave coherently on a very large scale: **the nucleon condensate can thus flow without any viscosity**, analogous to superfluid helium-3. **In particular, the neutron liquid that permeates the inner crust of a neutron star is expected to be superfluid** (see, e.g., Sec. 8 in Ref. [1]).

A rotating superfluid is threaded by an array of vortex lines, each carrying a quantum $\hbar$ of angular momentum. Such vortices have been observed in various superfluid systems in laboratory. Similarly, a pulsar is expected to contain quantized neutron vortex lines. The number of vortices is proportional to the angular velocity: about 10^{18} for the Vela pulsar!



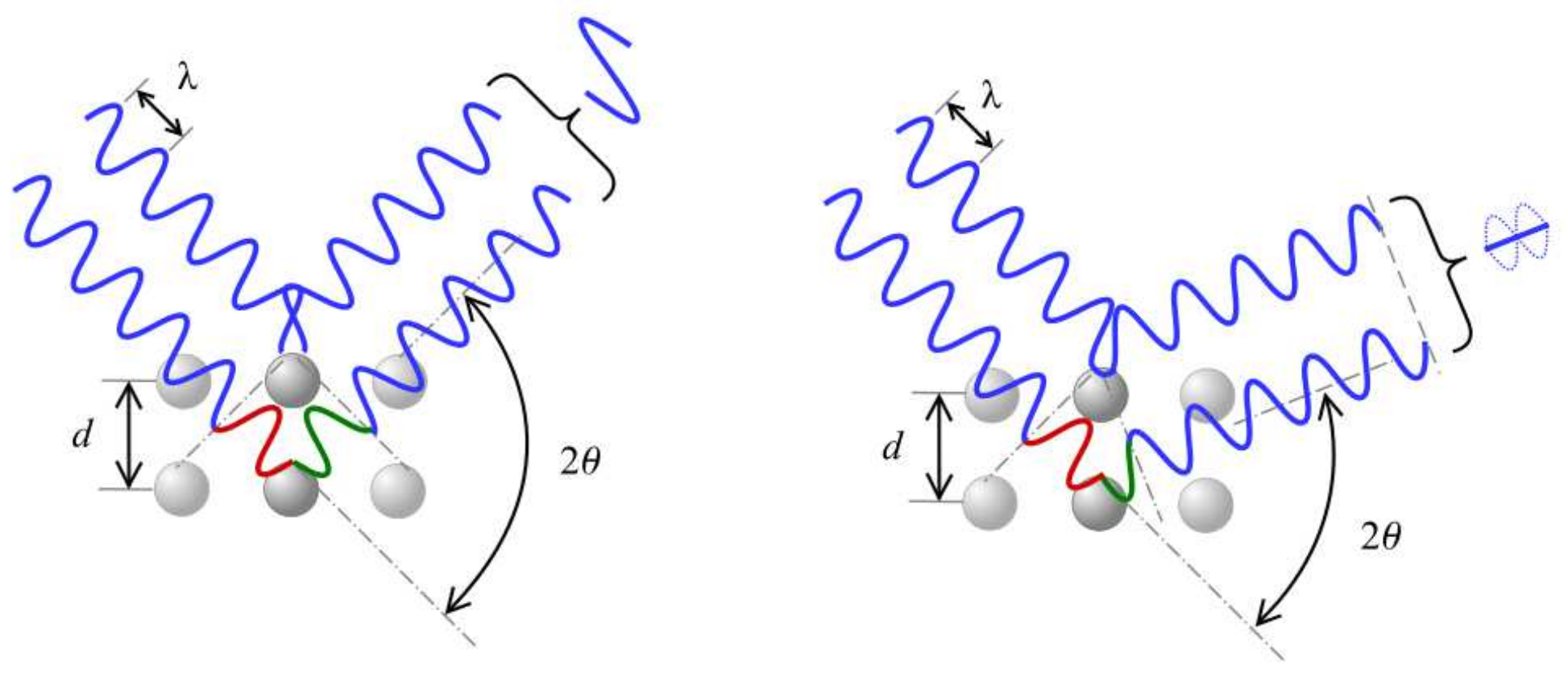
Shown is a vortex pattern in bosonic sodium atoms (green cartoon) in a magnetic trap, vortices in tightly bound lithium molecules (red-blue cartoon) and a vortex lattice in loosely bound fermion pairs presumably like the free neutrons in neutron-star crusts. The background shows a classical vortex (Hurricane Isabel in summer 2003, NASA image ISS007E14887).
Credit: Andre Schirotzek (MIT).

The neutron superfluid is weakly coupled to the crust by mutual friction forces and thus follows its spin-down via a radial motion of quantized vortices away from the rotation axis unless vortices are pinned to the crust. In this case, the superfluid can rotate more rapidly than the crust. **The lag between the superfluid and the crust induces a Magnus force acting on the vortices thereby producing a crustal stress. When the lag exceeds a critical threshold, the vortices are suddenly unpinned. As a result, the superfluid spins down and, by the conservation of the total angular momentum, the crust spins up leading to a glitch.** This scenario found some support from laboratory experiments in superfluid helium [9, 10]. In the meantime, it was argued that the core (supposed to contain superfluid neutrons and type I superconducting protons) is unlikely to play any role in glitch events [11].

The confidence in the vortex-mediated glitch interpretation comes from i) the regularity observed in many glitching pulsars and ii) the fact that the estimated ratio of the moment of inertia I_s of the superfluid component driving glitches to the total stellar moment of inertia I is about $I_s/I \sim 1-2\%$ at most, as expected if only the crustal superfluid is involved [12]. **However, many fundamental aspects of these models remain poorly understood.** For instance, the strength of vortex pinning, which is one of the crucial microscopic inputs, has been a controversial issue over the past years (see, e.g., Sec. 8.3.5 of Ref. [1]). The mechanism that triggers the unpinning of vortices like superfluid instabilities is also a matter of debate. **More importantly, these models ignore the nondissipative entrainment effects arising from the Bragg scattering of free neutrons by the crustal lattice, first discussed in Ref. [13].**

III Crustal entrainment and pulsar glitches

Neutron diffraction experiments are routinely performed to study crystal structures. Similarly, unbound neutrons in neutron-star crusts can be reflected by the crustal lattice, in which case they cannot propagate and are therefore entrained by the crust. Unlike viscous drag, entrainment is non-dissipative.



Bragg diffraction of an incident wave by a set of parallel crystal planes: the reflected waves may interfere constructively (left) or destructively (right). This is embedded in Bragg's law $2d\sin\theta = n\lambda$, in which n is any integer.

The specificity of neutron-star crusts is that neutrons form a highly degenerate quantum liquid. Due to Pauli's principle, neutrons have different wave vectors and are therefore diffracted differently. Entrainment can be characterized by the density $n_n^{\rm c}$ of conduction neutrons, i.e. neutrons that are effectively "free", or equivalently by an effective neutron mass $m_n^\star = m_n n_n^{\rm f}/n_n^{\rm c}$ where m_n is the bare neutron mass and $n_n^{\rm f}$ the density of unbound neutrons. **In most region of the inner crust, entrainment is very strong [14]**: $n_n^{\rm c} \ll n_n^{\rm f}$ or equivalently $m_n^\star \gg m_n$.

Due to entrainment, the angular momentum $J_{\rm s}$ of the superfluid depends not only on the angular velocity $\Omega_{\rm s}$ of the superfluid, but also on the observed angular velocity Ω of the pulsar and can be expressed as [15]

$$J_{\rm s} = I_{\rm ss}\Omega_{\rm s} + (I_{\rm s} - I_{\rm ss})\Omega\,, \tag{1}$$

with

$$I_{\rm s} = \int m_n n_n^{\rm f} \varrho^2 {\rm d}^3 r\,, \quad I_{\rm ss} = \int m_n^\star n_n^{\rm f} \varrho^2 {\rm d}^3 r\,, \tag{2}$$

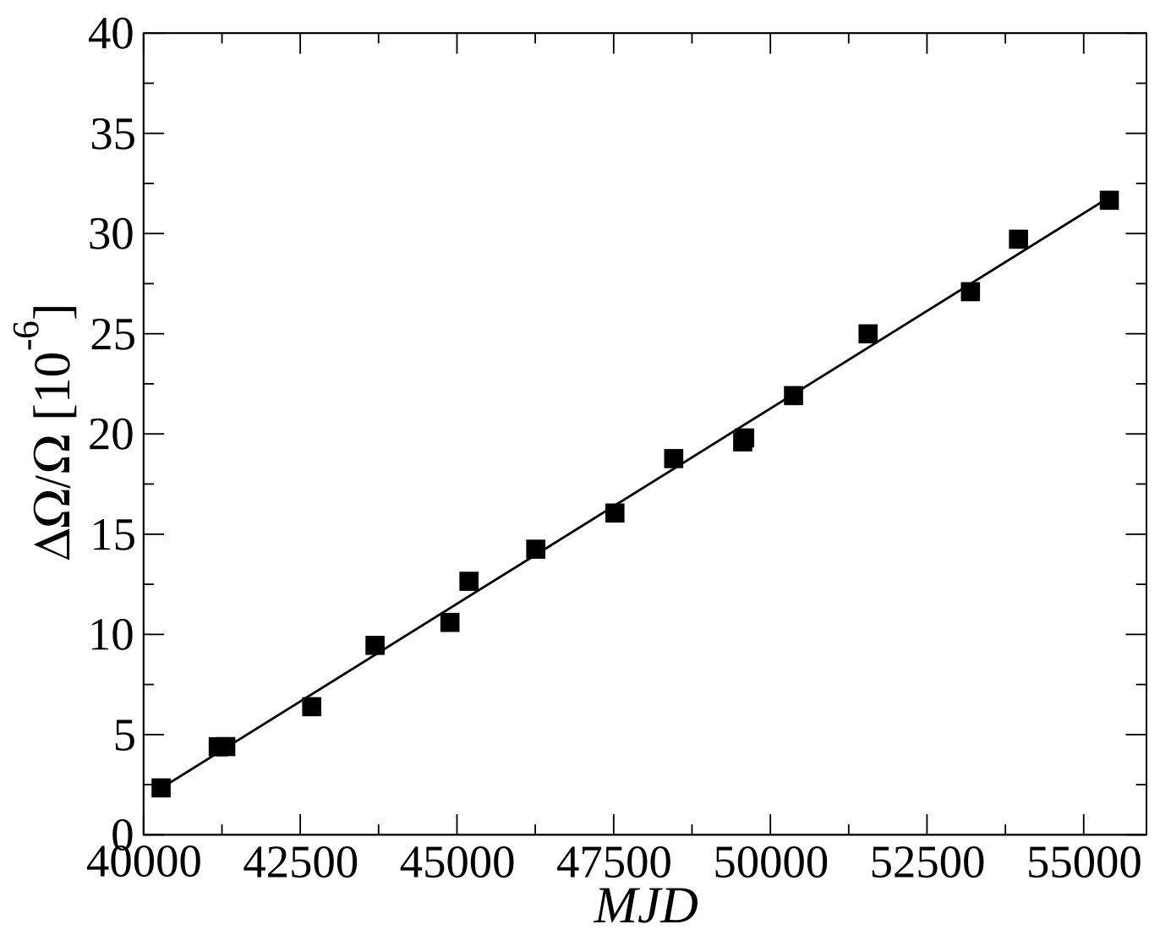
where ϱ is the cylindrical radius. **Pulsar glitches have been generally interpreted as sudden transfers of angular momentum between the superfluid and the rest of the star.** This model predicts that [15]

$$\frac{(I_{\rm s})^2}{I I_{\rm ss}} \geq \mathcal{G} \equiv A_g \frac{\Omega}{|\dot\Omega|}\,, \tag{3}$$

where A_g is the glitch activity parameter defined by the sum over glitches occurring during a time t

$$A_g = \frac{1}{t}\sum_i \frac{\Delta\Omega_i}{\Omega} \tag{4}$$

while $\dot\Omega$ is the average spin-down rate and I is the moment of inertia of the star. Both A_g and $\dot\Omega$ can be measured from pulsar-timing observations.



Cumulated glitch amplitudes as a function of the modified Julian date for the Vela pulsar from Ref. [16] (square symbols) and linear fit (solid line).

IV Results and discussion

The ratio appearing in the left hand side of Eq. (3) can be decomposed as

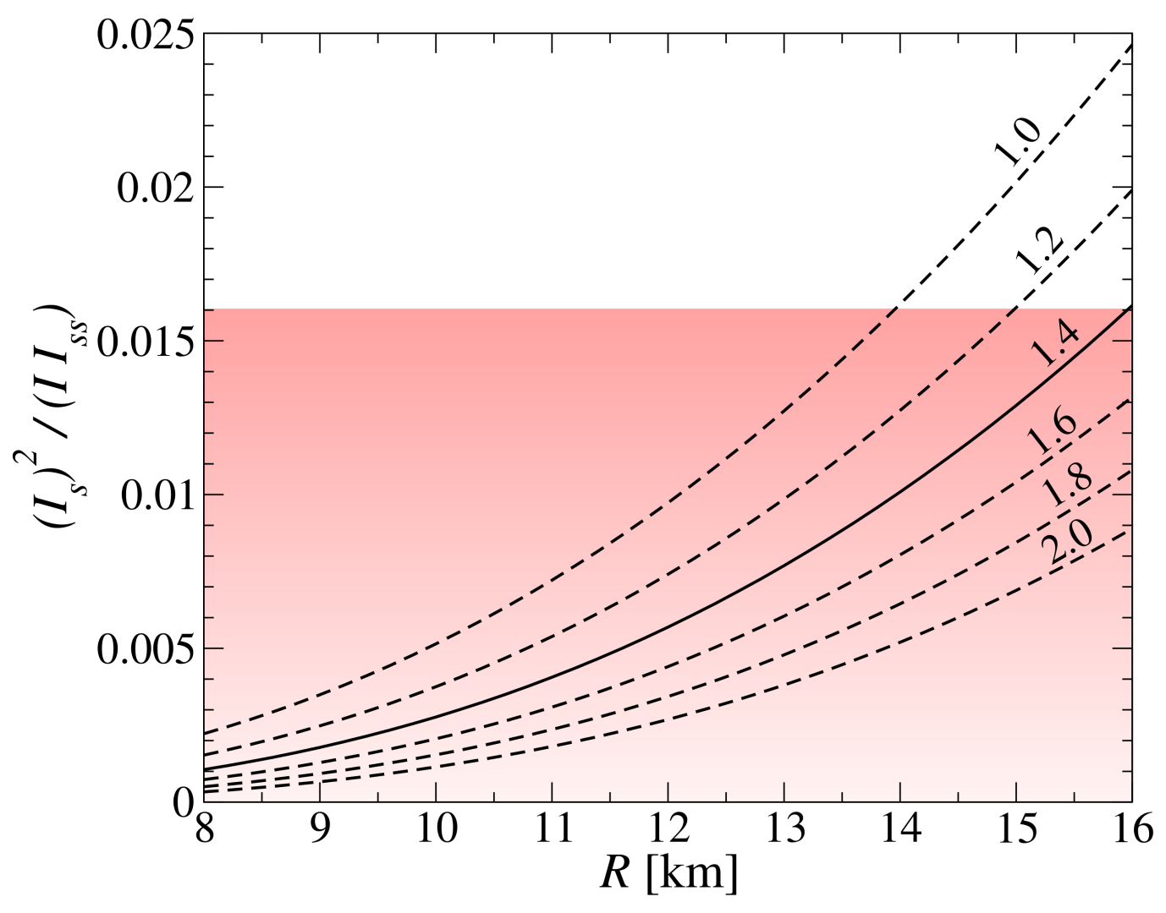
$$\frac{(I_{\rm s})^2}{I I_{\rm ss}} = \frac{I_{\rm crust}}{I_{\rm ss}}\left(\frac{I_{\rm s}}{I_{\rm crust}}\right)^2 \frac{I_{\rm crust}}{I}\,. \tag{5}$$

In the thin crust approximation,

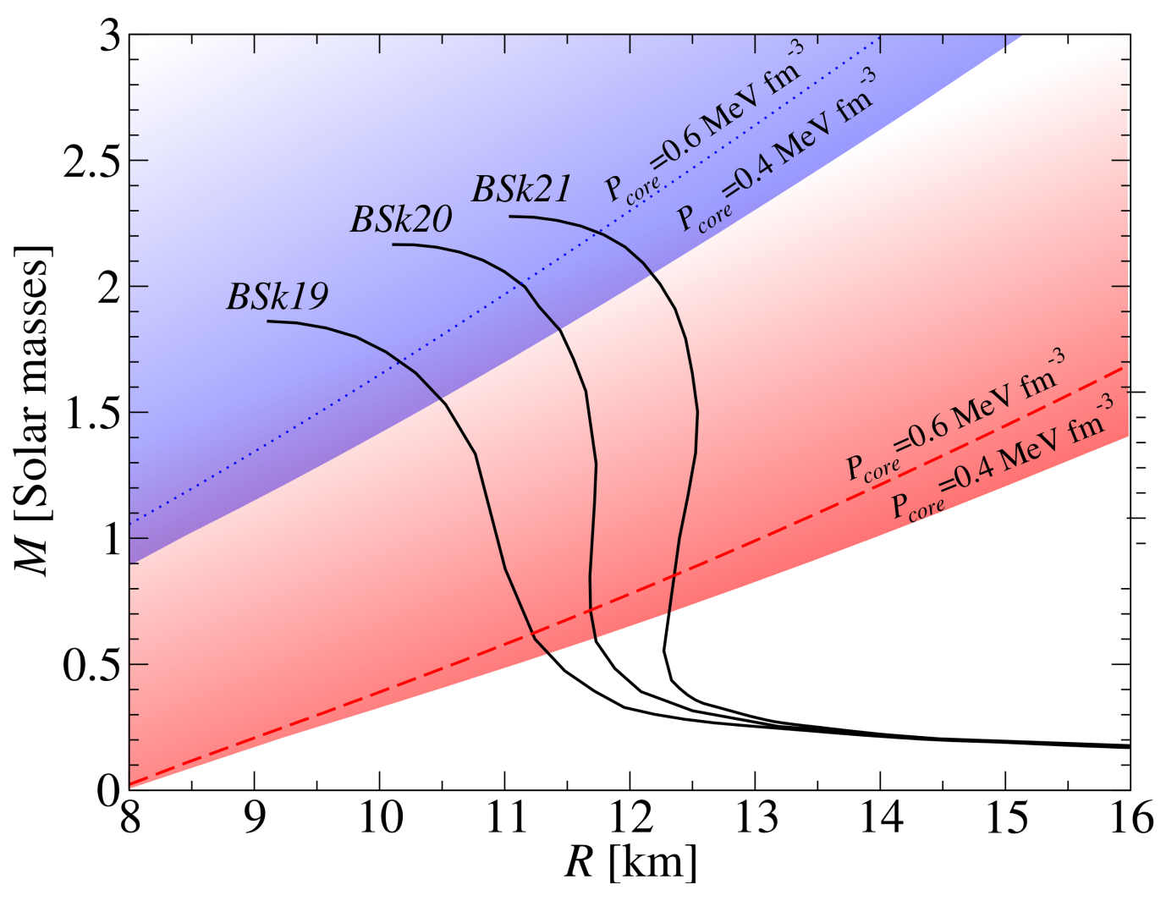
$$\frac{I_{\rm ss}}{I_{\rm crust}} \approx \frac{1}{P_{\rm core}}\int_{P_{\rm drip}}^{P_{\rm core}} \frac{n_n^{\rm f}(P)^2}{\bar n(P) n_n^{\rm c}(P)}{\rm d}P\,, \quad \frac{I_{\rm s}}{I_{\rm crust}} \approx \frac{1}{P_{\rm core}}\int_{P_{\rm drip}}^{P_{\rm core}} \frac{n_n^{\rm f}(P)}{\bar n(P)}{\rm d}P\,, \tag{6}$$

where M and R are the neutron-star mass and radius, $\bar n$ the average baryon density, $P_{\rm core}$ the crust-core transition pressure and $P_{\rm drip}$ the neutron-drip pressure. Using a realistic crust model, we find that $I_{\rm ss} \simeq 4.6 I_{\rm crust}$ and $I_{\rm s} \simeq 0.89 I_{\rm crust}$ leading to $(I_{\rm s})^2/I_{\rm ss} \simeq 0.17 I_{\rm crust}$ [17]. We have estimated the ratio $I_{\rm crust}/I$, which depends on the global structure of the star, using Eq. (47) of Ref. [18].

Because it was the first observed pulsar to exhibit glitches, Vela has become the testing ground for glitch theories. Using the latest glitch data [16], we find $\mathcal{G} \simeq 1.6\%$ [17]. This analysis implies that Vela should be less massive than our Sun. Such a low mass neutron star is not expected to be formed in a type II supernova explosion [19], contrary to observations.



$(I_{\rm s})^2/(I I_{\rm ss})$ for different neutron-star radii R and masses M from $1M_\odot$ (upper curve) to $2M_\odot$ (lower curve). The shaded area is excluded if Vela pulsar glitches originate from the neutron superfluid in the crust [17]. Note that any realistic equation of state of dense matter indicate that neutron stars with $M = M_\odot$ have a radius $R \lesssim 13$ km.



Neutron-star mass-radius diagram for three different unified equations of state [20]. The shaded area is excluded by Vela pulsar glitch data, assuming that only the neutron superfluid in the crust is involved. The lower (upper) shaded area is the constraint obtained with (without) taking into account crustal entrainment. The sensitivity of these constraints with respect to the crust-core transition pressure $P_{\rm core}$ is indicated by the dashed line and the dotted line. The pressure $P_{\rm core} = 0.4$ MeV fm^{-3} is the value found with the crustal model in Ref. [14].

Due to entrainment effects, the neutron superfluid in neutron-star crusts does not carry enough angular momentum to explain Vela pulsar glitches [17]. A similar conclusion has been reached in Ref. [21]. A closer examination of neutron superfluidity, crustal entrainment and crust-core coupling is required in order to elucidate the origin of Vela pulsar glitches. This work also shed light on the importance of crustal entrainment, which has been generally overlooked even though it may have implications for other astrophysical phenomena like the thermal emission from soft X-ray transients or quasiperiodic oscillations in soft gamma-ray repeaters.

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