PULSAR GLITCHES: SUPERFLUID UNPINNING

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In the neutron star crust, the neutron superfluid coexists with a lattice of nuclei. There are two different local densities of superfluid neutrons, inside and outside the nuclei, with a corresponding difference in the values of the superfluid gap and condensation energy.

Rotation in a superfluid is carried by quantized vortex lines. The superfluid can follow the slowdown of the neutron star crust only if the vortex lines can move outward freely. In the neutron star crust, there are pinning centers, the nuclei, which inhibit free vortex motion. The vortex lines have normal matter cores, of about the same radius as the nuclei, which is a third to a fifth of the lattice spacing: a very inhomogeneous medium for the vortex lines. The energy cost of the normal matter in the vortex core is $3/8\ \Delta^2/E_F$ per particle. Thus vortex lines will get pinned to the nuclei when this condensation energy is lower in the nuclei than outside. The pinning force per nucleus is:

$$F_p = \frac{V}{x}\left[\frac{3}{8}\ \frac{\Delta^2(\rho_1)}{E_F(\rho_1)} \cdot \rho_1 - \frac{3}{8}\ \frac{\Delta^2(\rho_0)}{E_F(\rho_0)} \cdot \rho_0\right]$$

where V is the volume of the nucleus, x its radius, ρ_1 and ρ_0 are superfluid densities outside and inside the nucleus, respectively.

As long as vortices are pinned, the superfluid velocity v_s, which is determined by the number of vortices, will remain constant, while the velocity v_n of the normal matter in the pulsar crust slows down under the pulsar torque. From the equation of motion for a vortex line, we can obtain the maximum velocity difference $v_s - v_n$ that the pinning

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forces can sustain:

$$(v_s - v_n) = f_p / \rho k$$

where f_p is the pinning force per unit length of vortex line, ρ the superfluid density, and k is the quantum of vorticity. This quantity is calculated on the basis of the crust calculations of Negele and Vautherin (1975), and the superfluid gap calculations (Hoffberg et al., 1970; Takatsuka, 1972).

We find that pinning is strong, in the sense that vortices can displace nuclei to achieve optimal pinning, in a certain layer of the crust. Further in, and further out, this is not the case. In these weak pinning layers, the vortices see a random pinning potential, and the effective pinning force is even weaker. We find $(v_s - v_n)_c \cong 10^4$ cm/s. With the $\dot{\Omega}$ of a given pulsar, this gives the time t_g between successive glitches which is about two years for the Vela pulsar. For older pulsars, t_g would be several hundred years. This is consistent with the fact that two large glitches have been observed in pulsars older than Vela so far (PSR 1641-45 and PSR 1325-43) in a total observation time of several hundred years.

When the inner weak pinning layer unpins, vortices move out into the strong pinning layers. An energy $\frac{1}{2} m (v_s - v_n)^2$ is dissipated per particle, where $v_s - v_n$ is now the velocity difference in strongly pinned layers. The resulting temperature rise will lower the gap and the pinning force, to give rise to further unpinning. This amplification yields Vela-type glitch magnitudes. We estimate $\Delta\Omega/\Omega \lesssim 10^{-5}$. Finally, the weak pinning layers will support vortex creep, and we expect non-exponential post-glitch behaviour, with timescales of the order of t_g.

REFERENCES

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