RELAXATION OF THE ANGULAR VELOCITY OF PULSARS AFTER GLITCHES

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The rotational dynamics of superfluid neutron stars is examined in order to study the relaxation of the angular velocity of pulsars after glitches. The motion of the neutron-proton vortex system is investigated taking the sphericity of the superfluid core and vortex pinning and depinning into account. A relaxation solution is obtained for the angular rotation velocity of pulsars after glitches. In order to compare this solution with observational data for the Vela pulsar, the inverse problem of finding the initial distribution of vortices immediately after a glitch is solved.

Keywords: pulsars: angular velocity: relaxation

1. Introduction

Pulsars are a manifestation of neutron stars which is observed as electromagnetic emission from a source in periodic radio frequency pulses. The pulsed character of this emission has made it possible to determine the rotation periods of pulsars, since it is assumed that the emission source rotates in synchrony with the pulsar [1]. The rotation periods $P$ of pulsars range from a few milliseconds to on the order of 1 s [2,3]. Observations show that the rotation period of pulsars increase constantly because of rotational energy losses. The so-called secular variation in the period of pulsars is on the order of $\dot{P}/P \sim 10^{-18} - 10^{-12}$ s$^{-1}$.

Some pulsars have a unique activity in which the angular rotation velocity $\Omega$ and its derivative $|\dot{\Omega}|$ increase.
suddenly, after which they mostly relax to their value before this jump (glitch) [4,5]. Glitches in angular velocity have been observed in about 100 pulsars [3]. Based on an analysis of glitch activity and the relative magnitudes $\Delta \Omega/\Omega$ of the glitches, it is possible to distinguish two groups of pulsars. The first group includes the pulsars Vela PSR B0833-45 and Crab PSR J0531-21 and others like them for which the magnitude of the glitches is on the order of $\Delta \Omega/\Omega \sim 10^{-9} \text{ to } 10^{-6}$ and the time between glitches is on the order of 2-3 years, while there is no correlation between these quantities. The second group of pulsars includes the pulsars PSR J0537-6910 and PSR B1338-62 [3], which have periodic glitches, while the magnitude $\Delta \Omega/\Omega$ of the glitches correlates with the time $t_g$ between glitches; that is, for large $t_g$ the glitches are large.

The generally accepted model for pulsars is a magnetized neutron star with mass on the order of $M \sim M_\odot$ and radius on the order of $R \sim 10 \text{ km}$. As it rotates, the magnetized neutron star loses kinetic energy of rotation as a result of magnetic dipole radiation; the rather wide range of values of $\dot{P}/P$ can be explained in terms of magnetic fields on the order of $B \sim 10^9 \text{ to } 10^{13} \text{ G}$ on the stars’ surfaces. Studies of the properties of matter in the interiors of neutron stars at densities on the order of $\rho \sim 10^{14} \text{ g/cm}^3$ indicate the presence of superfluid neutrons and the existence of superconductivity of the protons in pulsars. The relaxation behavior of the angular velocity of the rotation following glitches also suggests the existence of a weakly coupled superfluid component. Observations of pulsars show that the time dependences of the angular rotation velocity $\Omega(t)$ and its derivative $\dot{\Omega}(t)$ have complicated structures and are described either by a sum of exponential functions [6] or by a polynomial dependence [7]. The characteristic relaxation times for the angular velocity after glitches range over a wide interval from on the order of one hour to several hundred days. The relaxation behavior of the angular velocity of pulsars after glitches can be explained in terms of a superfluid model for neutron stars. The slowing-down of the rotation of the normal component that takes place under the influence of an external torque is also accompanied by a continuous transfer of internal angular momentum from the superfluid component to the normal component. In this case the main theoretical question for explaining the relaxation of the angular velocity of pulsars is to clarify the mechanism by which the superfluid and normal components of the neutron star are coupled. It has been shown [8,9] that a system of neutron-proton vortex clusters parallel to the axis of rotation of a neutron star develops because of “entrainment” of superconducting protons by the superfluid neutrons in the core of the star. A magnetic field of order $10^{14} \text{ G}$ is generated in the clusters and the motion of the magnetized neutron vortices during the time the star is slowed down is accompanied by friction owing to scattering of electrons on the magnetic field of the cluster. This interaction between the two components of a neutron star makes it possible to introduce a dynamic relaxation time which indicates the characteristic time to approach steady-state rotation following a sudden change in the angular rotation velocity of one of the components. Features of the motion of the vortex system as the star is slowed down, such as the pinning and depinning of neutron vortices, have been discussed in Refs. 10 and 11. With these phenomena taken into account, relaxation solutions were obtained for the angular rotation velocity and its derivative in neutron stars following glitches. These solutions were compared with observational data on $\Omega(t)$ and $\dot{\Omega}(t)$, so it was possible to obtain information on the initial distribution of the vortices immediately after a glitch and to clarify the role of pinning and depinning in establishing this distribution. In these studies of the dynamics of the motion of the vortex system in the core of a neutron star, it has been assumed