An Accretion Disk Model for Periodic Variations of PSR B1828-11

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Abstract At the present time, the debate about the nature of Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) has aroused researchers' great interests in the pulsar (PSR) astronomy. There coexist two prevalent lines of thoughts, the magnetar models (neutron stars with super-strong magnetic fields) and the accretion models (neutron stars or strange stars with fossil disks and ordinary pulsar magnetic fields), which try to explain the SGRs/AXPs. In this paper, we present an accretion disk model for periodic variations of PSR B1828-11. Fitted with reasonable parameters, the observed phenomenon of PSR B1828-11 (Stairs et al. 2000) can be explained. This may link radio pulsars and AXPs and give a support for the fossil disk model of SGRs & AXPs.

1 Debate about SGRs/AXPs

SGRs/AXPs distinguish themselves from ordinary radio pulsars by many distinct observational properties, among which the fact, that their X-ray luminosities are about 1 - 4 magnitude greater than their rates of rotational energy loss while the reverse for radio pulsars, is the most prominent one. Hence, any model attempting to interpret SGRs/AXPs should have a "new" energy source other than rotational energy loss, which powers the radiation of radio pulsars. Among the debates about SGRs/AXPs, magnetism-powered or accretion-powered, has been the focus. In the magnetar models, SGRs/AXPs are thought to be neutron stars with super-strong magnetic fields ($10^{14} - 10^{15}$ G) and their luminosities are produced by the magnetic field decay. On the other hand, the accretion models suppose that SGRs/AXPs are neutron stars or strange stars with ordinary pulsar magnetic fields ($10^{11} - 10^{12}$ G) and their radiations are powered by the accretion from fossil disks. The direct criteria to test these two kinds of models lies in whether the super-strong magnetic field or the accretion disk exists or not. Our accretion disk model for periodic variations of PSR B1828-11 may cast some light on the debates.

2 Free or Disk-Induced Precession

Recently, Stairs, Lyne and Shemar (2000) discovered long-term, highly periodic and correlated variations in both the pulse shape and the rate of spin-down of the pulsar PSR B1828-11 (see Figure 1). They emphasized this is evidence for free precession which is caused by asymmetry in the shape of the pulsar. Some authors (Jones & Andersson 2001, Link & Epstein 2001, Rezania 2002) proposed different models to explain this phenomenon within the framework of free precession. Unfortunately, this scenario seriously challenges our understanding of the liquid interior of the neutron star. Torque-free precession of a solitary pulsar should be damped out due to the dissipation caused by the vortices pinning in its superfluid interior within the timescale of several hundred precession periods. Thus we present an accretion disk model instead. In our model, the total torque exerted on the pulsar by the fossil disk is nonzero due to the asymmetry in pulsar shape and nonalignment between the pulsar rotation axis and the axis of pulsar moment of inertia. The long time scale precession of the pulsar can be well elucidated with our model. Hence, we suggest a forced precession model, other than the free precession model, might be more reasonable.

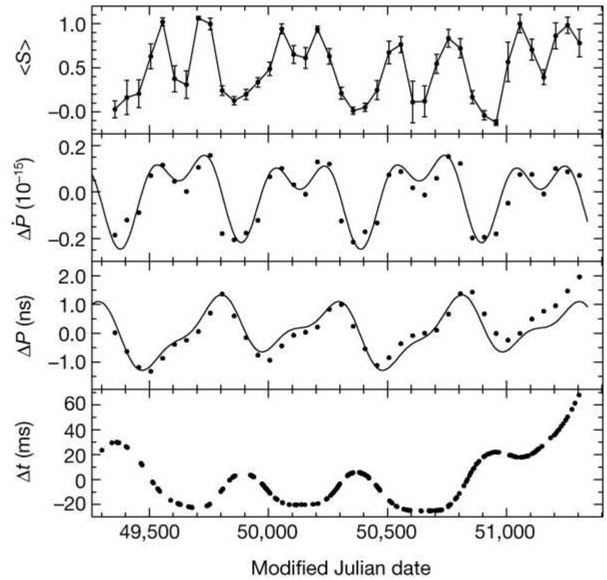

Fig. 1 Variations in rotation and pulse shape in PSR B1828-11. The displayed time series are the residuals in arrival time $\triangle t$, the period $\triangle P$, the period derivative $\triangle \dot{P}$, and the mean pulse shape parameter $< S >$ for the most recent 2000 days. These periodic patterns continue back through the entire 13-year data set. The solid curves indicate a fit of three harmonically-related sinusoids with the fundamental period 1009 $\pm$ 8 days (Stairs, Lyne & Shemar 2000).

3 Possible Evolutions in the Accretion Model

Although the exact evolutionary tracks of neutron stars in the accretion scenario are unclear, there exist some hypotheses trying to elucidate them. Here a possible series of evolutionary tracks for neutron stars are presented (cf. Chatterjee et al. 2000).

After the supernova explosion, there are 3 possible outcomes of the newly born neutron star: (a) The neutron star may be born without any accretion disk and present itself as a radio pulsar. (b) An accretion disk may be formed by the matter falling back onto the neutron star. The accretion disk will exist for radii only beyond the magnetospheric radius $R_m \cong 0.5(B^4R_*^{12}/8GM\dot{M}^2)^{1/7}$ (Frank et al. 1992), where M, R_* and B are the mass, radius and magnetic field of the neutron star, respectively, $\dot{M}$ is the rate of accretion, G is the gravitational constant. Once $R_m > R_{LC}$ ($R_{LC} = c/\Omega$, the light cylinder radius, where c is the speed of light and Ω is the angular velocity of the neutron star), the coupling between the disk and the neutron star is unlikely to happen. Thus most of the neutron stars may live as ordinary radio pulsars even if they acquire debris disks through fallback. (c) In other cases, accretion will be permitted and the neutron star will behave as an accreting X-ray source. If $R_{LC} > R_m \gg R_{co}$ ($R_{co} = (GM/\omega^2)^{1/3}$, the corotation radius defined by

$\Omega = \Omega_K(R_{co})$, where $\Omega_K(R)$ is the Keplerian rotation rate at radius R), which corresponds to $\Omega \gg \Omega_K(R_m)$, the neutron star may be in the phase, in which accretion onto the neutron star is inefficient due to centrifugal forces acting on the matter. The neutron star will spin down and be X-ray faint (e.g. Compact Central Objects (CCOs) may be the kind of X-ray faint sources which have just begun to spin down). As Ω approaches $\Omega_K(R_m)$, the system enters a quasi-equilibrium phase (happening at the time of t_{trans}), in which the spin of the star roughly matches the rotation of the disk at R_m. In this phase, the neutron star will be X-ray bright due to accretion. It is possible that the advection-dominated accretion flow (ADAF) will occur at the time of t_{ADAF}, when much of the mass will be ejected prior to reaching the neutron star surface. The X-ray luminosity of the neutron star will decline rapidly with time due to $\dot{M}_X$ (the rate of accretion onto the star surface) diminishing. Therefore, the bright AXPs may exist only between t_{trans} and $2t_{ADAF}$ (about 5000 - 40000 years). Finally, the weak X-ray luminosity will be powered by rotational energy loss since accretion ceases (the matter of the disk is exhausted). Consequently, the neutron star will be observed as a dim isolated neutron star near our galaxy (e.g. Dim Thermal Neutron Stars (DTNs) may be the kind of dim X-ray isolated neutron stars with the distances $\leq$ 0.4 kpc).

According to the rough evolutionary scenario above, PSR B1828-11 may be presently in the phase of just beginning to spin down rapidly and being X-ray faint. Its X-ray radiation (if have) may be too faint to be observed, thus it is regarded as a radio pulsar. If our interpretation for the precession phenomenon is right, it may show some hints for the future studies on the acc

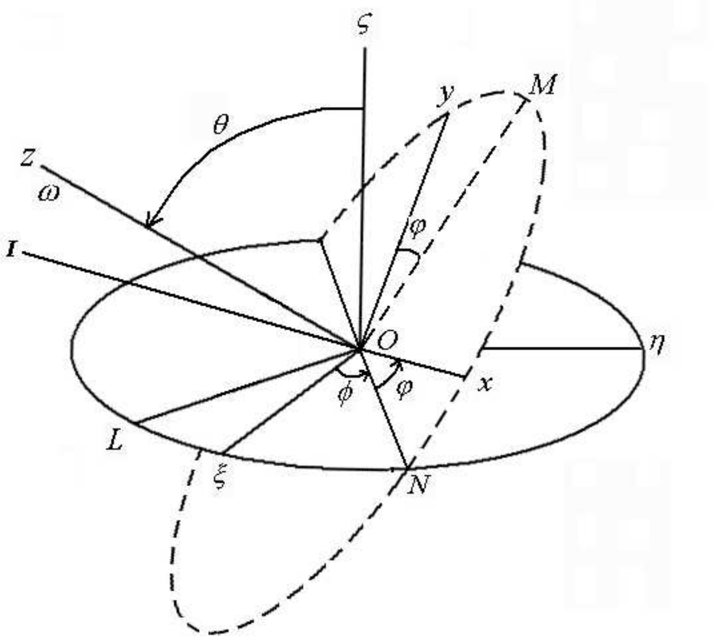

Fig. 2 The geometry and parameters for the calculations

4 Modelling the Precession

Consider the pulsar as a rotation ellipsoid with the principal moment of inertia I_1 =

$I_2 \neq I_3$ and the corresponding radii $a = a \neq b$. The geometry of the system is shown in Figure 2: the axis OI is the principal axis of moment of inertia of the neutron star, O-$\xi\eta\zeta$ is a coordinate system fixed in the space, O-xyz is the coordinate system fixed with the neutron star, θ, φ and ϕ are Euler angles, ω is the angular velocity of neutron star rotation. The parameters about PSR B1828-11 are as follows: the rotational period of this pulsar $P = 0.405$s ($\omega = 2\pi/P$), the period derivative $\dot{P} = 6.0 \times 10^{-14}$ ss^{-1}, the precession period $P_{pre} \approx 1000$ days, the magnetic field $B = 5.0 \times 10^{12}$G (Stairs et al. 2000). Thus we obtain the gravitational potential from the pulsar to the disk:

$$V = -\frac{2GMM_0}{c+d}[1 - \frac{b^2 + 2a^2}{10cd} + \frac{3b^2}{20cd} sin^2\theta + \frac{3a^2}{20cd}(1 + cos^2\theta)] \,. \tag{1}$$

where M, a and b are the mass, the equatorial and longitudinal radii of the pulsar, respectively, M_0 is the mass of the disk, c and d are the inner and outer radii of the disk, respectively. The precession angular velocity of the pulsar is derived according to the Lagrange's equation (Qiao et al. 1989):

$$\dot{\phi} = -\frac{3GM_0 cos\theta}{2cd(d+c)\omega}(1 - \frac{b^2}{a^2}) \,. \tag{2}$$

For simplification, $c \approx d \approx R$ is assumed, so that

$$\dot{\phi} = -\frac{3GM_0 cos\theta}{4R^3\omega}(1 - (1-\epsilon)^2) \,, \tag{3}$$

where $\epsilon = (a - b)/a$ is the oblateness of the pulsar. Through the numerical simulations, we gain the relations between M_0 and R derived from the 1000-day precession period for a group of θ. We find, in principle, M_0 can vary from less than $0.001 M_\odot$ to even $0.1 M_\odot$, and R from about $1R_{co}$ (or smaller) to $2 \sim 3R_{co}$ when θ varies within $0 \sim 90^o$.

5 Discussion and conclusion

Besides the accretion disk model, we think a pulsar with a small-mass companion star may also produce the precession phenomenon. In that case, two limits should be considered: the Roche Limit d_R (if the companion approached the neutron star closer than this limit, it would be torn asunder by tidal forces) and the Instability Limit d_I (if the company strayed farther than this limit, it would escape due to the differential perturbations from other celestial bodies). The details of that case will be discussed in another article.

Our accretion disk model for periodic variations of PSR B1828-11 can explain the observed $\sim$ 1000-day precession period avoiding the puzzle of the damping-out effect due to the vortices in the superfluid interior of neutron star. If our model is proved to be true, the link between radio pulsars and AXPs can be established and the fossil disk model for AXPs can be strengthened. It will also suggest the existence of the neutron star-fossil disk systems or neutron star-planet like systems.

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