HOT SPOT EMISSION FROM A FREELY PRECESSING NEUTRON STAR

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ABSTRACT

Recent observations of 1E 161348 — 5055, the neutron star candidate at the center of the supernova remnant RCW 103, show that a component of its emission varies sinusoidally with a period of approximately 6 hours. We argue that this period is what one would expect for a freely precessing neutron star with a spin period of about 1 s. We produce light curves for a freely precessing neutron star with a hot spot. By a suitable choice of parameters, we obtain light curves which are constant with rotational phase when the flux from the star reaches a maximum. At other phases of the precession, the flux varies as the star rotates, but the total flux decreases by a factor of several. These models can explain the behavior observed from 1E 161348 — 5055 and predict that the spin period should be detectable at minimum flux from sufficiently sensitive measurements.

Subject headings: stars: neutron — stars: oscillations — X-rays: stars

1. INTRODUCTION

Garmire et al. (2000) have noted that the X-ray source 1E 161348 — 5055, located near the center of the supernova remnant RCW 103, has a sinusoidal light curve with a period of approximately 6 hours. The authors suggest that this period implies that the X-ray source has a low-mass, underluminous companion with a 6 hour orbital period. Furthermore, it would have the longest period for a binary underluminous companion with a 6 hour orbital period. This period implies that the X-ray source has a low-mass, underluminous companion with a 6 hour orbital period. The authors suggest that this period is what one would expect for a freely precessing neutron star with a precession period of about 6 hours. We produce light curves for a freely precessing neutron star with a hot spot. By a suitable choice of parameters, we obtain light curves which are constant with rotational phase when the flux from the star reaches a maximum. At other phases of the precession, the flux varies as the star rotates, but the total flux decreases by a factor of several. These models can explain the behavior observed from 1E 161348 — 5055 and predict that the spin period should be detectable at minimum flux from sufficiently sensitive measurements.

2. FREE PRECESSION

A body will precess freely if its rotation axis does not coincide with one of its principal axes. More specifically, if the body is only slightly prolate or oblate, the angular velocity vector (ω) of the star will make a constant angle (κ) with one of the principal axes (the 3-axis) forming the body cone, and will trace a cone in space (the space cone) with half-opening angle κ as well. The rate of the precession is given by Goldstein (1980)

\[ \Omega = \frac{I_3 - I_1}{I_1} \omega_3 = \epsilon \omega_3. \]

Values of \( \epsilon = 10^{-3} - 10^{-4} \) agree with the glitching behavior of neutron stars and the inferred gravitational-radiation spin-down from the Crab pulsar (Shapiro & Teukolsky 1983). Forced precession by an orbiting companion typically has a frequency lower by a factor of 2/(3Ω*ω3), where Ω* is the angular frequency of the orbit.

Internal magnetic fields may distort a neutron star significantly. Ostriker & Gunn (1969) estimate the distortion of a neutron star due to internal fields,

\[ \epsilon \approx \frac{4}{3} \times 10^{-6} \frac{3(B_{p,15})^2}{(B_{p,15})^2} \],

where \( B_{15} \) is the value of the magnetic field in units of 10^{15} G and angle brackets denote a volume-weighted average over the star. Here, \( B_p \) and \( B_\phi \) refer to the poloidal and azimuthal components of the magnetic field, respectively. One expects the internal fields of the neutron star to be significantly larger than the field inferred by magnetic dipole radiation due to the contribution of higher multipoles and the concentration of magnetic flux in flux tubes (e.g., Pines & Alpar 1985).

We would like to calculate the light curve from a hot spot on the surface of the freely precessing neutron star. Let us take the center of the cone that the angular velocity moves along to be the z-axis. Our line of sight (O) makes an angle ξ with this axis and forms a plane with z-axis. We measure the phase of the precession (φ) relative to intersection of the space cone with this plane.
The plane containing $z$ and $O$ also intersects the body cone. The angular momentum of the star points along the $z$-axis. In the body frame, the angular velocity of the star traces a cone centered on a principal axis of the star. We call this principal axis $3$. The hot spot is located at $\mu$, which makes an angle $\beta$ with $3$. Let us freeze the precession and the rotation of the star when $3$ points along $z$ (see Fig. 1). At this orientation, the angle between the $3-O$ plane and the $3-\mu$ plane is $\gamma$.

The use of spherical trigonometry (see Fig. 1) yields the angle between the line of sight and the rotation axis, $\zeta(\phi)$, and the angle between the hot spot and the rotation axis, $\alpha(\phi)$:

$$
\cos \zeta(\phi) = \cos \kappa \cos \xi + \sin \kappa \sin \xi \cos \phi, \quad (3)
$$
$$
\cos \alpha(\phi) = \cos \kappa \cos \beta + \sin \kappa \sin \beta \cos (\phi - \gamma). \quad (4)
$$

The star rotates as well as precesses. The phase of the rotation is given by $\eta$. When $\eta = 0$, the hot spot lies in the $\omega-O$ plane. The angle between the line of sight and the hot spot is $\theta$ and is given by

$$
\cos \theta = \cos \alpha(\phi) \cos \zeta(\phi) + \sin \alpha(\phi) \sin \zeta(\phi) \cos \eta. \quad (5)
$$

If the hot spot emits isotropically and we neglect gravitational lensing, the observed flux from the hot spot is simply proportional to $\cos \theta$ for $|\theta| < \pi/2$ and zero otherwise.

3. Gravitational Lensing

Page (1995) presents a detailed treatment of the gravitational lensing of the surface of a neutron star. Since the light trajectory is bent, the zenith angle of our detector ($\delta$) as seen from the hot spot is no longer equal to the angle between our line of sight and the hot spot ($\theta_{\text{hs}}$). They are related by

$$
\theta(\chi) = \int_0^\chi \frac{x du}{\sqrt{(1 - 2y)y - (1 - 2a)u^2x^2}}, \quad (6)
$$

where $y = GM/Rc^2$ and $x = \sin \delta$. For $y < 1/3$, the image of the hot spot will be visible if $\theta_{\text{hs}} + 2\pi j < \theta(1)$. If we assume for simplicity that the emission from the hot spot is isotropic, the observed flux from the hot spot is proportional to

$$
\sum_j \frac{x(\theta_{\text{hs}} + 2\pi j)}{\sin (\theta_{\text{hs}} + 2\pi j)} \left| \frac{dx}{d\theta} \right|_{\theta = \theta_{\text{hs}} + 2\pi j}, \quad (7)
$$

where $j$ counts over the number of images of the hot spot and $|\theta_{\text{hs}} + 2\pi j| \leq \theta(1)$.

4. Light Curves

To construct a light curve, we must specify several angles ($\xi, \kappa, \beta$, and $\gamma$). During some portion of the precessional period, the observed flux will be constant with orbital phase, if either $\beta = \kappa$ or $\xi = \kappa$. In the first case, the angular velocity vector will coincide with the location of the hot spot on the star. In the second case, the angular velocity vector will point along the line of sight once during each precession.

4.1. $\beta = \kappa = 90^\circ$

To maximize the flux during the portion of the precessional period where the flux does not vary with rotational phase, we take $\gamma = 0$ and $\beta = \kappa = 90^\circ$, and to minimize the flux during the rest of the precession, we take $\xi = \theta(1)$; consequently, during the portion of the precessional period when the observed emission from the star does vary, the total emission will be small, so that the variation will be difficult to detect.

If $\gamma \neq 0$, the maximum flux will not occur during that portion of precession when the flux does not vary with rotational phase. Taking $\beta = \kappa \neq 90^\circ$ will reduce the maximum flux, and $\xi \neq \theta(1)$ will change the portion of the time when the hot spot is not visible.

Figure 2 shows the observed flux from the hot spot as a function of the star’s precessional and rotational phase. Only half of a precessional period is depicted. The flux varies at twice the precession rate. As Figure 3 shows, the mean flux over the rotational period varies nearly sinusoidally. Twice during the precessional period, when the mean flux reaches its maximum, the flux does not vary with the rotational phase of the star. At other stages of the star’s precession, the hot spot spends much of the rotational period hidden behind the horizon on the neutron star surface. If $\beta = \kappa \neq 90^\circ$, one finds that the mean flux varies at the precessional frequency, resulting in a light curve similar to that presented in Figure 4.

4.2. $\xi = \kappa = \theta(1)$

In this case, we attempt to maximize the flux during the portion of the precession when the flux does not vary over the rotation. To do this, we take $\beta = \xi = \kappa = \theta(1)$ and $\gamma = 0$. If the bending of the photon trajectories is neglected (i.e., as $y$ approaches zero), $\theta(1)$ approaches $90^\circ$ and this case reduces to the previous one. However, for a realistic neutron star with $y \approx 0.2$, we have new light curve which varies at the precession rate (not twice that rate as the previous case). Taking $\beta \neq \kappa$ or $\gamma \neq 0$ also yields a portion of the light curve when the flux does not vary with rotational phase, but this does not coincide with the period when the mean flux reaches its maximum.

4.3. Random Geometry

The choices of $\xi, \gamma, \beta$, and $\kappa$ that we have made previously are not generic. One would expect the values of $\xi$ and $\gamma$ from a particular neutron star to be random. The values of $\beta$ and $\kappa$ are intrinsic to the star; therefore, one may find a physical motivation for a particular distribution of their values. Figure 5 presents two light curves for two randomly selected geometries.
We created a random sample of 10,000 geometries for $GM/Rc^2 = 0.0, 0.1, 0.2, 0.3$. Figure 6 shows that a significant fraction of the geometries yielded light curves qualitatively similar to those presented in Figure 2 and Figure 4. Although one would generally expect more complicated light curves, such as those depicted in Figure 5, a significant fraction of the geometries yield light curves in which the flux is constant with rotational phase when it reaches its maximum, and during the rest of the precessional period, the hot spot is hidden for a large portion of each rotation. For $GM/Rc^2 = 0.2$, about 3% of the geometries result in an observer pulsed fraction less than 10% during the brightest portion of the precession period.

5. DISCUSSION

We have explored several possible light curves of a freely precessing neutron star with a hot spot and focussed on those whose flux is constant with rotational phase when the flux reaches a maximum value. These possibilities indicate that 1E 161348 A 5055 may be a freely precessing neutron star. However, as the mean flux decreases from its maximum, it also begins to vary with the rotation of the star. Therefore, in the context of this model, we would expect that subsequent observations of 1E 161348 A 5055 may uncover its rotational period, which we would expect to be on the order of several seconds. The variation of the flux with the rotational phase of the star during some portion of the precession appears generic to freely precessing stars with a hot spot.

In general, the rotating neutron star may suffer more than one precessional mode. As discussed earlier, tidally induced precession tends to have a longer period, but the precession induced by radiative torques (Melatos 1999, 2000) may affect the expected light curve. To be precise, if
the field at the pole exceeds 10% of the typical internal field, the radiative and free precession will couple, complicating the dynamics. On the other hand, if the polar field is weaker, the two modes do not couple, but radiative torques will result in the alignment of the magnetic and body axis on a spin-down timescale, so the angle $\kappa$ may not be randomly distributed in the neutron star population. The treatment of the coupled radiative and free precession is beyond the scope of this paper.

In neutron stars, precession has been proposed to explain long-term variations in their spin and pulse profiles (e.g., Davis & Goldstein 1970; Goldreich 1970; Ruderman 1970; Brecher 1972; Pines & Shaham 1972; Pines, Pethick, & Lamb 1973; Pines & Shaham 1974). If neutron stars rotate as rigid bodies, the precessional period would be $P/\epsilon$ (Pines & Shaham 1972, 1974), where $P$ is the rotational period. Ruderman & Sutherland (1974) proposed that neutron stars contain a superfluid component in their cores.

Shaham (1977) explored how the pinning of the superfluid vortices affects the free precession of a neutron star. He argued that the dissipation timescale for the precessional mode ($\tau_{d}$) is of the order of the postglitch relaxation time ($\tau$) times the ratio of the rotational to the precessional frequency. The value of $\tau$ ranges from a week for the Crab to nearly a century for 1641−45 (Shapiro & Teukolsky 1983); therefore, depending on the nature of the superfluid coupling, the precessional mode may last for millennia. Shaham (1977) also found that if the star is triaxial, the geometry of the precession is more complicated than for the purely free precession considered here. Additionally, the precessional
frequency in this case is given by angular velocity of the superfluid component of the star times the fractional contribution of the superfluid to the total moment of inertia of the star (about 1%).

Sedrakian, Wasserman, & Cordes (1999) have recently reexamined the precession of multicomponent neutron stars with imperfect vortex pinning and found several possibly long-lasting precessional modes with long periods, like the precession described here. The excitation and decay of precessional motions in neutron stars are still uncertain.

Evidence has been found for free precession in some radio pulsars (e.g., Cadez, Galicic, & Calvani 1997; Jones 1988), but it is not generic (e.g., Morgan et al. 1995); therefore, the question arises as to which properties of a neutron star would allow or prevent it from precessing and how those properties correlate with its radio emission. Melatos (1999, 2000) argues that precession is characteristic of strongly magnetized neutron stars (see eq. [2]). Usov & Melrose (1996) and Arons (1998) have proposed that strongly magnetized neutron stars are unlikely to produce radio emission collectively, due to the formation of bound electron-positron pairs. Alternatively, Baring & Harding (1997) suggest that in sufficiently strong fields \( B \gtrsim B_c \), the QED process of photon splitting (Adler 1971; Heyl & Hernquist 1997) can dominate one-photon pair production. This will effectively quench the pair cascade, making coherent pulsed radio emission impossible.

Since the timescales for both the excitation and decay of precessional motion in neutron stars are unknown, one can appeal to the relative youth of 1E 161348—5055 and the other members of the AXP class to explain why they may exhibit precession while radio pulsars generally do not. They are all several thousand years old, much younger than the vast majority of radio pulsars (Taylor, Manchester, & Lyne 1993). The appropriate timescales for precession may simply be shorter than the ages of most radio pulsars, while longer than those of AXPs. Furthermore, the hints of precession seen in the Crab pulsars (Cadez, Galicic, & Calvani 1997) may point toward this explanation.

We have examined the light curves of freely precessing neutron stars with a hot spot and focused on those geometries which exhibit an epoch during each precessional period where the flux does not vary as the star rotates. These geometries account for about 3% of a random sample and may provide an explanation for the emission from 1E 161348—5055. If this is the case, further observations of the light curve from 1E 161348—5055 should reveal a pulse period of the order of \( \epsilon \) times the precessional period of 6 hours. As \( \epsilon \) ranges from \( 10^{-7} \) to \( 10^{-4} \), the underlying period ranges from 10 ms to 10 s. Free precession may be a hallmark of young or highly magnetized neutron stars, and it is a direct probe of the structure of the crust and interior of the neutron star and the coupling between them.

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Fig. 6.—Cumulative distribution of mean pulsed fractions. For each geometry, the pulsed fraction is averaged over the brightest 20% of the precession period. From bottom to top, curves trace the results for \( GM/Re^2 = 0.0, 0.1, 0.2, 0.3 \). Pulsed fraction is defined in the standard manner to be the ratio of the difference in the maximum and minimum brightness over the rotation period of the star to its sum.