SGR 0418+5729—HOW DOES A YOUNG NEUTRON STAR SPIN DOWN TO A 9 s PERIOD WITH A DIPOLE FIELD LESS THAN 10^{13} G?

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ABSTRACT

The period derivative bound for the soft gamma-ray repeater SGR 0418+5729 establishes the magnetic dipole moment to be distinctly lower than the magnetar range, placing the source beyond the regime of isolated pulsar activity in the P–$\dot{P}$ diagram and giving a characteristic age $>2 \times 10^7$ yr, much older than the 10^5 yr age range of SGRs and anomalous X-ray pulsars. So the spin-down must be produced by a mechanism other than dipole radiation in vacuum. A fallback disk will spin down a neutron star with surface dipole magnetic field in the 10^{12} G range and initial rotation period $P_0 \sim 100$ ms to the 9.1 s period of SGR 0418+5729 in a few 10^4 to $\sim 10^5$ yr. The current upper limit to the period derivative gives a lower limit of $\sim 10^5$ yr to the age that is not sensitive to the neutron star's initial conditions. The total magnetic field on the surface of SGR 0418+5729 could be significantly larger than its 10^{12} G dipole component.

Key words: accretion, accretion disks – pulsars: individual (AXPs) – stars: neutron – X-rays: bursts

1. INTRODUCTION

The recently discovered SGR 0418+5729 (van der Horst et al. 2010) has a period $P = 9.1$ s (Göğüş et al. 2009) in the narrow range of anomalous X-ray pulsar (AXP) and soft gamma-ray repeater (SGR) periods (Mereghetti 2008). The spin-down rate has not been measured yet (Kuiper & Hermsen 2009; Woods et al. 2009; Esposito et al. 2010; Rea et al. 2010). The best period derivative upper limit, $\dot{P} < 6 \times 10^{-15}$ s s^{-1} (Rea et al. 2010), evaluated as dipole spin-down of an isolated star, gives a surface dipole magnetic field $B_0 < 1.5 \times 10^{13}$ G at the poles, much lower than fields previously deduced from spin-down rates of magnetars. The characteristic age $P/(2\dot{P}) > 2.5 \times 10^7$ yr, while AXPs and SGRs, some of which are associated with a supernova remnant (Esposito et al. 2009; Mereghetti 2008, and references therein), are believed to be young neutron stars with ages $\sim 10^5$ yr. SGR 0418+5729 is similar to other AXPs and SGRs in all observed properties except for $\dot{P}$. The energy in its soft gamma-ray bursts requires a total magnetic field $\sim 10^{12}$ G on the neutron star surface, but if all SGRs have super-outbursts occasionally, as has been observed so far from SGR 1806-20, SGR 0526-66, and SGR 1900+14, the total surface magnetic field $B_{\rm total} \sim 10^{14}$–$10^{15}$ G according to the magnetar model (Duncan & Thompson 1992; Thompson & Duncan 1995). If SGR 0418+5729 is a standard magnetar, it provides a clear counterexample to the proposition that for magnetars the dipole component of the magnetic field is of the same order as the total field.

If the spin-down to the present period was achieved by magnetic dipole radiation, SGR 0418+5729 would be an exceptional object, mimicking all SGR and AXP properties while not belonging to the class. Its position in the P–$\dot{P}$ diagram, beyond the so-called death valley, makes it exceptional also among the rotation-powered isolated pulsars: the only other source located similarly in P–$\dot{P}$ is the radio pulsar PSR J2144-3933. Furthermore, if SGR 0418+5729 is older than 2.5×10^7 yr as its characteristic age $P/(2\dot{P})$ suggests, its quiescent X-ray luminosity cannot be explained by cooling, reheating, or magnetic field decay, let alone explaining soft gamma-ray outbursts occurring at such old age. If SGR 0418+5729 is much younger than its characteristic age with dipole spin-down, its initial rotation period would have to be close to the present 9.1 s period, again making this source unique, standing far out from the initial period distribution inferred from population synthesis (Faucher-Giguére & Kaspi 2006).

The dipole component of the field B_0 determines torques due to electromagnetic radiation and interactions with the environment. Estimates of B_0 from spin-down rates depend on the torque mechanism. The total surface magnetic field is derived from measurements of cyclotron lines (Ibrahim et al. 2002) and the spectral continuum (Güver et al. 2007, 2008). Historically, the dipole field measurements came first (Kouveliotou et al. 1998). The field inferred with the dipole spin-down torque was in the magnetar range, supporting the magnetar model which had been proposed to explain the SGR bursts and other SGR and AXP properties including spin down to long periods at a young age (Duncan & Thompson 1992; Thompson & Duncan 1995). The identification of the dipole component with the total field has been taken for granted.

We proceed, by Occam's razor, to posit that SGR 0418+5729 is a member of the same class of young neutron stars as the other SGRs and AXPs, but its spin-down is not due to magnetic dipole radiation. So there must be matter around the star, in a bound state, therefore carrying angular momentum. For *isolated* neutron stars, a fallback disk, which can be formed in some supernovae (Michel 1988; Chevalier 1989; Lin et al. 1991), will provide this. The fallback disk model was proposed by Chatterjee et al. (2000) for AXPs, and independently by Alpar (2001) as a possible way of explaining the different classes of young neutron stars, including the X-ray dim isolated neutron stars (XDINs) and compact central objects (CCOs) as well as AXPs and SGRs. The prime motivation was to address the period clustering which strongly suggests a regulating store of angular momentum. For a given value of $\dot{P}$, the dipole moment inferred with the fallback disk model is generally less than that derived assuming isolated dipole spin-down. The differences in $\dot{P}$ between sources of similar periods are not primarily due to differences in magnetic dipole moment, with the fallback disk also playing a critical role in evolution. The model indicates surface dipole fields $\sim 10^{12}$–10^{13} G. The bursts may be powered by strong total magnetic fields $B_{\rm total} \sim 10^{14}$–$10^{15}$ G as in the magnetar model, implying that the dipole field is smaller than the total field. The discovery of a disk around AXP 0142+61 (Wang et al. 2006) gave strong support to the fallback disk model. Ertan et al. (2007) showed that the entire non-pulsed optical to mid-IR spectrum can be understood as emission from a gaseous disk, while the pulsed optical signal is produced in the magnetosphere (Ertan & Cheng 2004; Cheng & Ruderman 1991).

This Letter investigates evolutionary scenarios for SGR 0418+5729 employing a fallback disk. We show that the period derivative as well as the period and X-ray luminosity in quiescence are explained quite naturally, and a fallback disk can spin down the neutron star to a period of 9.1 s in a few 10^4 to $\sim 10^5$ yr.

2. EVOLUTION WITH A FALLBACK DISK

The mass and mass inflow rate of the fallback disk decay through viscous dynamics, modified by irradiation from the neutron star. The fallback disk, though truncated at the inner radius, follows the self-similar solutions with power-law decay in time (Pringle 1974) quite closely as long as the entire disk is viscous (Ertan et al. 2009). Viscous activity stops when the local temperature falls below a critical temperature $T_p \sim 100$ K, becoming too cold for sufficient ionization for the magneto-rotational instability to generate viscosity and sustain mass inflow (Inutsuka & Sano 2005). Such passive regions grow starting from the outer disk. Irradiation by the star can keep the outer disk at temperatures higher than T_p for a while, delaying the passive phase, keeping a larger part of the disk active. This interaction between the gradual transition to a final passive phase, and the effect of irradiation to prolong the active phase determines the evolution in a complicated way. To calculate the irradiation flux impinging on the disk, we employ the same irradiation efficiency as in our best fits for the disk observed around AXP 0142+61 (Ertan et al. 2007; see Ertan & Çalışkan 2006 for the other AXPs).

At each step in the evolution, a solution for the entire disk is constructed taking all these effects into account. The mass inflow rate $\dot{M}_{\rm in}$ arriving at the inner disk is obtained and the inner disk radius $r_{\rm in}$ is determined as the Alfvén radius,

$$r_{\rm A} = 10^9 \,\mathrm{cm}\, \mu_{30}^{4/7} (\dot{M}_{\rm in15})^{-2/7} (M/M_\odot)^{-1/7}. \qquad (1)$$

Here, $M_\odot$ is the solar mass, $\dot{M}_{\rm in15}$ is the mass inflow rate in 10^{15} gm s^{-1}, and μ_{30} is the dipole magnetic moment in 10^{30} G cm^3. The important distance scales are the light cylinder radius $r_{\rm LC} = c/\Omega$, the corotation radius $r_{\rm co} = (GM)^{1/3}/\Omega^{2/3}$, and $r_{\rm A}$. The fallback disk will effect the evolution when the disk's inner radius is within the neutron star's light cylinder. The effect of the disk will decrease drastically when the disk moves outside the light cylinder.

Throughout the evolution $r_{\rm A} > r_{\rm co}$, so the neutron star is a fast rotator, and the torque applied by the disk is always a spin-down torque. The neutron star is in the propeller regime (Illarionov & Sunyaev 1975). In contrast to the original propeller picture, the fallback disk model takes some portion $\dot{M}_{\rm acc}$ of the mass inflow $\dot{M}_{\rm in}$ to be accreting onto the neutron star during spin-down (Chatterjee et al. 2000; Alpar 2001). Rappaport et al. (2004) have shown from general considerations of accreting neutron stars that partial accretion must be taking place. This provides the X-ray luminosity in the fallback disk model throughout most of the evolution, when $r_{\rm co} < r_{\rm A} < r_{\rm LC}$. The luminosity evolution is determined by the unknown fraction $\dot{M}_{\rm acc}/\dot{M}_{\rm in}$ and the initial fallback disk mass M_d, which effects the evolution of $\dot{M}_{\rm in}$.

The spin-down rate of a neutron star under disk torques is given by

$$I\dot{\Omega} = \dot{M}_{\rm in} (GMr_{\rm A})^{1/2} F(\omega), \qquad (2)$$

where I is the moment of inertia, $\dot{\Omega}$ is the spin-down rate, Ω is the rotation rate, $\dot{M}_{\rm in}$ is the mass inflow rate arriving from the disk at its inner boundary, and M is the star's mass. $F(\omega)$ is the dimensionless torque which depends on the fastness parameter $\omega \equiv \Omega/\Omega_{\rm K}(r_{\rm A})$, $\Omega_{\rm K}(r_{\rm A})$ being the Keplerian rotation rate at $r_{\rm A}$. A dimensionless disk torque

$$F(\omega) = (1 - \omega^2) \cong -\omega^2 \qquad (3)$$

is indicated by our earlier results (Ertan et al. 2009; Ertan & Erkut 2008). This torque is due to the azimuthal bending of magnetic field lines from the co-rotating magnetosphere at $r_{\rm co}$ to the slower rotating inner disk at $r_{\rm A} > r_{\rm co}$. Equations (1)–(3) show that the torque is independent of $\dot{M}_{\rm in}$ ($F(\omega) \cong -\omega^{2+\delta}$ gives a weak dependence $\propto \dot{M}_{\rm in}^{-3\delta/7}$). We integrate $\dot{\Omega}$ to get Ω, reconstruct the disk with current $r_{\rm A}$ and $r_{\rm LC}$, irradiated by the current luminosity, and proceed by iteration.

As $\dot{M}_{\rm in}$ decreases and the star spins down, $r_{\rm A}$ increases with time faster than $r_{\rm LC}$ does. Near and beyond the light cylinder $r_{\rm LC}$, the electromagnetic field gradually changes from the dipole magnetic field to wave fields. The inner disk radius is somewhat larger than $r_{\rm A}$ in this region. Ekşi & Alpar (2005) have studied the transition toward the wave zone. They show that the disk is stable beyond the light cylinder as long as the inner disk radius $r_{\rm in}$ remains within a critical distance which depends on the angle between the rotation and magnetic axes of the star, ranging from 2.5 $r_{\rm LC}$ for a perpendicular rotator to many $r_{\rm LC}$ for an almost aligned rotator. The torque and luminosity should drop within a narrow range of $r_{\rm in} \cong r_{\rm LC}$—the disk can be stable far beyond $r_{\rm LC}$, but is causally disconnected from the star and magnetosphere. Cooling or energy dissipation in the neutron star accounts for a much reduced X-ray luminosity. For the torque we consider two distinct models: (1) We assume that the disk remains undetached from the light cylinder and set $r_{\rm in} = r_{\rm LC}$. This can be qualitatively justified as mass lost by the disk cannot penetrate into the magnetosphere, but will tend to pile up around the light cylinder. As the disk inner radius reaches $r_{\rm LC}$ from inside, the mass pile-up is likely to keep $r_{\rm in}$ from detaching from $r_{\rm LC}$. (2) The minimal torque is the dipole radiation torque taking over immediately when $r_{\rm in} \geqslant r_{\rm LC}$. The actual torque should show a transition from disk torque to dipole radiation torque.

3. SPIN AND LUMINOSITY EVOLUTION OF SGR 0418+5729

We have carried out a detailed investigation of SGR 0418+5729 using the code developed earlier (Ertan & Erkut 2008; Ertan et al. 2009) which successfully generated AXP and SGR properties at their likely ages by luminosity and spin-down evolution driven by a fallback disk. Many combinations of initial conditions were tried in search for a scenario to produce the present day SGR 0418+5729. Each calculation starts with a choice of dipole moment and initial rotation period for the neutron star, and an initial disk mass.

The disk around SGR 0418+5729 cannot still be inside the light cylinder at present: if it were, $\dot{P}$ would be approximately (or exactly, in our torque model) independent of $\dot{M}_{\rm in}$ in this epoch, so that the age estimate would be given by $\sim P/\dot{P} = 5 \times 10^7$ yr, an untenably old age. We find that SGR 0418+5729 was spun

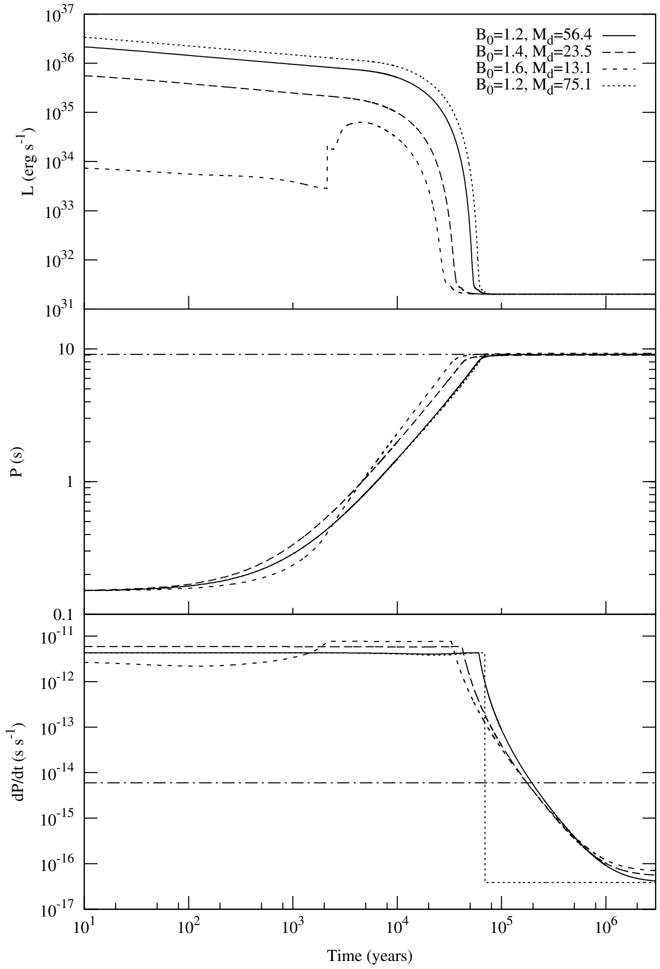

Figure 1. Luminosity, period, and period-derivative evolution of model sources for an initial period $P_0 = 150$ ms. Values of the initial disk mass (in units of $10^{-6} M_{\odot}$) and the magnetic field (in 10^{12} G) at the poles of the neutron star are given in the figure. The horizontal lines correspond to the period (9.1 s) and the present upper limit on the period-derivative of SGR 0418+5729 (6×10^{-15} s s^{-1}). We also present the minimal torque case (dotted curve) where the disk torque is assumed to vanish when $r_{\rm A} \geqslant r_{\rm LC}$.

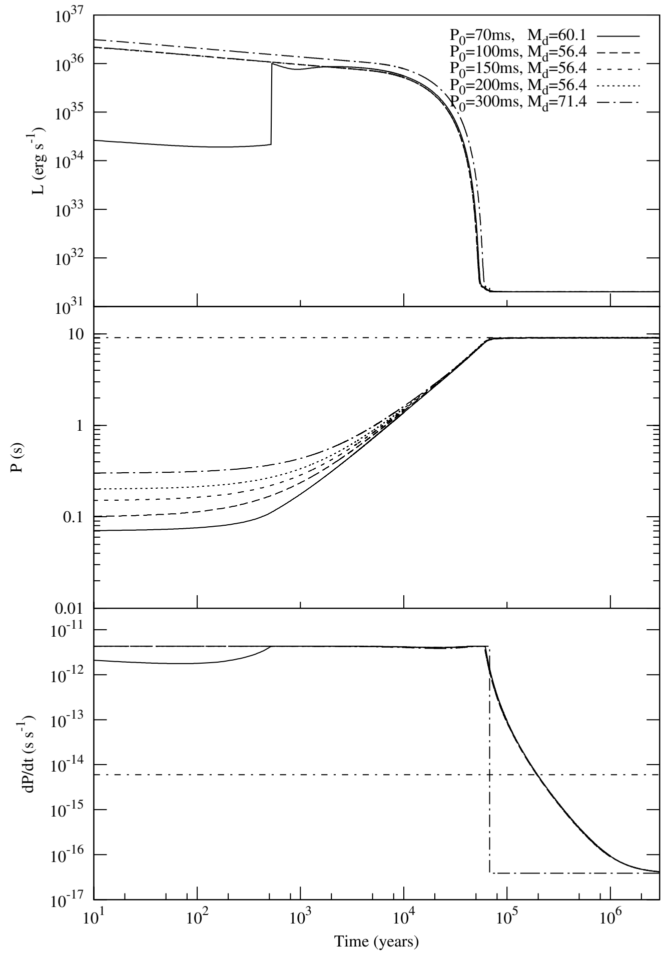

Figure 2. Luminosity, period, and period-derivative evolution of model sources for a polar magnetic field of $B_0 = 1.2 \times 10^{12}$ G on the surface of the neutron star. Values of the initial disk mass (in units of $10^{-6} M_{\odot}$) and initial period are given in the figure. The horizontal lines show the present period and upper limit on $\dot{P}$. The period derivative curves converge to a final value of $\sim 4 \times 10^{-17}$ s s^{-1}, a lower limit given by the dipole spin-down torque when the disk becomes inactive. The dipole spin-down case is given by the dot-dashed curve.

down to its period with efficient disk torques in a past epoch when the inner disk was within the light cylinder, $\dot{P}$ having subsequently decreased to its present value in the present epoch when the disk is at or beyond $r_{\rm LC}$.

Figures 1 and 2 show evolutionary tracks for luminosity, period, and period derivative, producing the present properties of SGR 0418+5729 for numerous combinations of the initial conditions. Figure 1 shows the evolutionary models with $P_0 = 150$ ms for $B_0 = 1.2, 1.4, 1.6 \times 10^{12}$ G, with initial disk masses $M_d = 5.6, 2.2, 1.3 \times 10^{-5} M_{\odot}$, respectively. In Figure 2, we show evolutionary tracks with $B_0 = 1.2 \times 10^{12}$ G and $P_0 = 70$–300 ms, with $M_d \simeq 6 \times 10^{-5} M_{\odot}$. A reference luminosity $L_x = GM\dot{M}_{\rm in}/R$ is plotted throughout the past epoch when the inner disk was inside the light cylinder. The true luminosity was less by the unknown fraction $\dot{M}_{\rm acc}/\dot{M}_{\rm in}$. This uncertainty does not influence the evolutionary models because its effect on the disk is folded into the irradiation efficiency. We took B_0 in the 10^{11}–10^{13} G range of dipole fields for most young pulsars, which worked in earlier applications (Ertan et al. 2009). All AXPs and SGRs have $L_x \lesssim 10^{36}\,{\rm erg\,s^{-1}}$, giving an upper limit for M_d in our searches. M_d is calculated for disk models extending to an outer radius $r_{\rm out} = 5 \times 10^{14}$ cm at the start. For given B_0, disks lighter than a certain M_d can never penetrate the light cylinder, and so cannot produce an AXP/SGR. For each B_0–M_d choice, there is a minimum P_0 for the inner disk to ever lie within $r_{\rm LC}$. The degeneracy of initial conditions producing SGR 0418+5729 shows that these correlations between workable initial conditions are not very strict constraints. For most B_0 and M_d, models start off with the inner disk within the light cylinder. (Models with stronger B_0 and lower M_d show different early evolution, with $r_{\rm A} > r_{\rm LC}$ initially. Starting off under the dipole spin-down torque, the low luminosity $\sim 10^{34}$–$10^{35}\,{\rm erg\,s^{-1}}$ in the initial phases is due to cooling (Page 2009) and dissipative dynamics inside the neutron star (Alpar 2007). These models show sudden luminosity and torque increase at $\sim 10^3$ yr when the inner disk enters the light cylinder.)

Between 10^4 and 10^5 yr, there is a turnover to fast luminosity decay with rapid spin-down until the period settles to its present value of 9.1 s. The fallback disk is evolving toward its final passive phase. As $\dot{M}_{\rm in}$ drops, so does the rate of viscous heating. Effects of irradiation also start to drop as the accretion luminosity decreases with mass inflow rate. Starting from the outermost parts, more and more sections of the disk are cooling below the critical temperature T_p. As this continues, $\dot{M}_{\rm in}$ arriving at the inner disk to provide for accretion decreases even more rapidly. The positive feedback leads to a luminosity turnover and eventual cutoff. Throughout this phase, r_A is inside the light cylinder and the disk torque remains in effect. The light cylinder recedes as the star spins down, but the inner disk recedes more rapidly with the accelerated decay of $\dot{M}_{in}$, and finally reaches r_{LC}. The $\dot{P}$ now starts dropping very rapidly and the period remains almost constant from this point on. The luminosity is down to the cutoff luminosity, which we take to be 2×10^{31} erg s^{-1}, three times less than the slowly decaying present luminosity quoted by Rea et al. (2010) for a distance of 2 kpc, and consistent with the standard cooling luminosity range of neutron stars at ages of 10^5–10^6 yr. The choice of luminosity cutoff does not effect the evolution.

The optical and infrared emission of the disk around SGR 0418+5729 at present is much weaker than for other AXPs and SGRs. We expect luminosities in K_s and 4.5 μm bands about 10^3 and 10^5 times less than the corresponding luminosities of AXP 0142+61. The disk luminosity is even lower in the R band, since the magnetosphere truncates the inner disk of SGR 0418+5729.

4. DISCUSSION AND CONCLUSIONS

SGR 0418+5729 was spun down to its present period in an earlier epoch when the inner disk was within the light cylinder. The present state of exceedingly low spin-down rate was reached when the disk retreated to or beyond the light cylinder. Initial parameters $B_0 \simeq (1\text{–}2) \times 10^{12}$ G, $M_d \simeq 4 \times 10^{-6} M_\odot$ to $M_d \simeq 6 \times 10^{-5} M_\odot$, and $P_0 > 70$ ms work well, giving the period $P_0 = 9.1$ of SGR 0418+5729, consistently with the upper limit $\dot{P} < 6 \times 10^{-15}$ s s^{-1} at ages greater than about 2×10^5 yr. In the present epoch, the disk inner edge is at or beyond the light cylinder. We show tracks with a sustained disk torque, as well as tracks for evolution reduced to dipole spin-down. The luminosity is due to partial accretion until $t \sim (3\text{–}6) \times 10^4$ yr. For simplicity we show only a reference luminosity calculated for full accretion; the actual luminosity in this past epoch was smaller by an unknown fraction $\dot{M}_{acc}/\dot{M}_{in}$. The period $P = 9.1$ s is reached as an eventual constant period, already at $(3\text{–}6) \times 10^4$ yr, together with a drop in period derivative.

Figures 1 and 2 show that the present $\dot{P}$ upper limit gives a lower limit of $\sim 2 \times 10^5$ yr if the disk torque is still operating. If the disk is already out of contact with the star, the dipole spin-down track gives a lower limit of $\sim 10^5$ yr. A future measurement of $\dot{P}$ will give a rough estimate of the age, between this lower bound and the age at which the disk torque models give the observed $\dot{P}$. A measurement of $\dot{P} \sim 4 \times 10^{-17}$ s s^{-1} will establish dipole spin-down prevails at present. An even lower $\dot{P}$ measurement would signal dipole spin-down driven by $B_0 < 10^{12}$ G.

We conclude that the very low period derivative upper limit for SGR 0418+5729 can be naturally explained in terms of spin-down by a fallback disk. The neutron star has initial rotation period in the range expected for young neutron stars (Faucher-Giguére & Kaspi 2006). The dipole component of the surface field is in the 10^{12} G range. The higher multipoles and the total surface field could be much larger. Indeed, the X-ray spectrum of SGR 0418+5729 indicates a total surface field of 1.1×10^{14} G (Güver et al. 2011). Comparative investigation of total and surface dipole magnetic fields by different methods is likely to provide important clues to properties and evolution of magnetars, pulsars, and young neutron stars.

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