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Ejector and propeller spin-down: How might a superluminous supernova millisecond magnetar become the 6.67 hr pulsar in RCW 103

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ABSTRACT
The X-ray source 1E 161348−5055 in the supernova remnant RCW 103 recently exhibited X-ray activity typical of magnetars, i.e. neutron stars with magnetic fields $\gtrsim 10^{14} - 10^{15}$ G. However, 1E 161348−5055 has an observed period of 6.67 hr, in contrast to magnetars which have a spin period of seconds. Here we describe a simple model which can explain the spin evolution of 1E 161348−5055, as well as other magnetars, from an initial period of milliseconds that would be required for dynamo generation of magnetar-strength magnetic fields. We propose that the key difference between 1E 161348−5055 and other magnetars is the persistence of a remnant disk of small total mass. This disk caused 1E 161348−5055 to undergo ejector and propeller phases in its life, during which strong torques caused a rapid increase of its spin period. By matching its observed spin period and $\approx 1-3$ kyr age, we find that 1E 161348−5055 has the (slightly) highest magnetic field of all known magnetars, with $B \sim 5\times10^{15}$ G, and that its disk had a mass of $\sim 10^{24}$ g, comparable to that of the asteroid Ceres.

Key words: accretion, accretion discs – stars: magnetars – stars: magnetic field – stars: neutron – stars: individual (1E 161348−5055; RCW 103) – supernovae: general.

1 INTRODUCTION

The recent detection by D'Aì et al. (2016); Rea et al. (2016) of high energy activity from the neutron star (NS) 1E 161348−5055 in supernova remnant RCW 103 (also known as SNR G332.4−0.4) finally provides insights into its perplexing nature. Tuohy & Garmire (1980) discovered the X-ray point source 1E 161348−5055 using *Einstein*, but no corresponding optical/IR or radio counterpart has been found to date (Tuohy et al. 1983; De Luca et al. 2008), which argues in part against the source being in a binary system. The age of RCW 103 is ~ 3.3 kyr (Clark & Caswell 1976) or within the range 1.2 − 3.2 kyr (Nugent et al. 1984; Carter et al. 1997). Garmire et al. (2000) find that 1E 161348−5055 pulsates with a period of $\sim$ 6 hr, with a more definitive and refined detection of 6.67 hr determined by De Luca et al. (2006). Continued monitoring of 1E 161348−5055 yields a constraint on the time derivative of this period of $\dot{P} \leqslant 1.6\times10^{-9}$ s s^{-1} (Esposito et al. 2011), which is higher than the $\dot{P}$ of all known isolated pulsars. The 6.67 hr period makes 1E 161348−5055 a particularly interesting object.

Some characteristics of 1E 161348−5055 match those of the central compact object (CCO) class of NSs, which are found near the center of SNR and are only seen in X-rays, and thus 1E 161348−5055 had been associated with this class (see De Luca 2008; Halpern & Gotthelf 2010; Gotthelf et al. 2013, for review; see also Ho 2013). CCOs have an inferred magnetic field $B \sim 10^{10} - 10^{11}$ G, and three CCOs have a measured spin period P: two have $P = 0.1$ s and one has $P = 0.4$ s. If the 6.67 hr period of 1E 161348−5055 is ascribed to its spin, then this value is in sharp contrast to the spin period of CCOs.

However the recent high energy activity is very similar to activity seen in another class of NSs, that of the magnetars. Magnetars traditionally include two types of NSs observed at high energies, anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs), almost all of which have an inferred magnetic field $B \sim 10^{14} - 10^{15}$ G (see Mereghetti et al. 2015; Turolla et al. 2015, for review). Thus it is likely that 1E 161348−5055 also possesses a magnetic field in this range, and hereafter we will assume this is the case. While B may be similar to other magnetars, the 6.67 hr period of 1E 161348−5055 (which we will assume is its spin period; see D'Aì et al. 2016; Rea et al. 2016) is drastically longer than the spin period of other magnetars, which are all in the range 2 − 12 s. Furthermore, this long period of 1E 161348−5055 could be used to argue against the generation of magnetar-strength magnetic fields via a dynamo mechanism, since this mechanism requires an ini-

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tial rapid (possibly millisecond) spin period (Thompson & Duncan 1993; Bonanno et al. 2005; Spruit 2009; Ferrario et al. 2015).

In Section 2, we present calculations of a simple scenario that can describe the spin evolution of the magnetar 1E 161348−5055, starting from its birth with a spin period of a millisecond to its current 6.67 hr, and how 1E 161348−5055 is different from other known magnetars. The scenario is as follows: A supernova gives birth to a rapidly rotating NS. The rapid spin rate allows us to retain the dynamo mechanism as a viable means to explain the magnetic fields of 1E 161348−5055 and other magnetars (Thompson & Duncan 1993; Bonanno et al. 2005; Spruit 2009). We also note that our theoretically conceived millisecond magnetar connects observed magnetars (that are $\gtrsim 10^3$ yr old) to those thought to power superluminous supernovae (see, e.g. Chatzopoulos et al. 2013; Inserra et al. 2013; Nicholl et al. 2014). Next, after an initial epoch during which the immediate environs surrounding the newborn NS settles into a relatively homogeneous low density plasma and the magnetic field organizes itself into an ordered dipole field, we begin at time t_0 with a millisecond magnetar (with $P_0 \sim 1$ ms and $B \sim 10^{14} - 10^{15}$ G). This millisecond magnetar evolves as a standard pulsar, i.e. it loses rotational energy and slows down as a result of the NS emitting electromagnetic dipole radiation. For most known magnetars, this spin-down continues for thousands of years until their present age and produces NSs that have a spin period of a few seconds (see after equation 3), just as observed. In contrast, we propose that for 1E 161348−5055, there remained some material that was not ejected by the supernova (we estimate a total mass of about that of the asteroid Ceres; see Sect. 3), and it forms a remnant disk around the NS (see, e.g. Michel 1988; Lin et al. 1991; Perna et al. 2014). The rapid rotation of the NS causes it to be in an ejector state/phase and prevents the remnant disk from interacting with the NS (Illarionov & Sunyaev 1975). The duration of the ejector phase $t_{\rm ej}$ can be hundreds to thousands of years (see equation 7), and all the while the NS emits dipole radiation and its spin period increases. Eventually its rotation becomes slow enough for disk material to couple to the NS magnetosphere, and the NS transitions to a propeller state/phase. In this state, matter is expelled by the (still) rapidly rotating NS, and the resulting spin-down torque on the NS is much stronger than that due to dipole radiation. The NS spin period increases at an exponential rate (see equation 12) for a short time $t_{\rm prop}$ (see equation 11), before reaching spin equilibrium, when torques on the NS balance. The result is a slowly spinning, strongly magnetized NS, like 1E 161348−5055.

Here we briefly mention previous works which sought to explain the 6.67 hr period of 1E 161348−5055 as its spin period. De Luca et al. (2006) (see also Esposito et al. 2011) ignore the ejector phase and begin their calculation of propeller phase spin-down at $P_0 = 300$ ms, finding that 1E 161348−5055 has $B = 5\times10^{15}$ G and a remnant disk mass of $3\times10^{-5}M_\odot$. Li (2007) describe an ejector and propeller evolution scenario and perform Monte Carlo simulations to obtain the magnetar spin period distribution. Pizzolato et al. (2008) consider the torque exerted by a binary companion star and find that 1E 161348−5055 has $B\sim10^{15}$ G and is in spin equilibrium. Ikhsanov et al. (2013) consider 1E 161348−5055 to have $B\sim10^{12}$ G and is accreting from a magnetized remnant disk. We also note the earlier studies of AXPs and SGRs as normal magnetic field ($\sim10^{12}$ G) NSs that are accreting in the propeller phase, but near spin equilibrium, from a fossil disk (with constant mass; Alpar 2001; or with decreasing mass; Chatterjee et al. 2000; Ertan et al. 2009). While in the final stages of preparing our work, we became aware of the work of Tong et al. (2016), who consider a similar scenario as described here but obtain a much larger disk mass of $\sim10^{-5}M_\odot$ (see Sec. 3).

2 SPIN PERIOD EVOLUTION IN EJECTOR AND PROPELLER PHASES

The scenario for the evolution of the 1E 161348−5055 spin period described in Section 1 requires a model for ejector and propeller phases (defined below). At early times in the ejector phase, a NS spins down in a similar fashion to an isolated pulsar, i.e. the NS emits electromagnetic dipole radiation and loses rotational energy. This energy loss produces a torque on the NS

$$\begin{aligned} N_{\rm em} &= -\frac{2\mu^2\Omega^3\sin^2\theta}{3c^3} = -\frac{B^2R^6\Omega^3\sin^2\theta}{6c^3} = -\beta I\Omega^3 \\ &= -1.5\times10^{45}\ {\rm erg}\ B_{15}^2(P/1\ {\rm ms})^{-3}, \end{aligned} \quad (1)$$

where Ω ($=2\pi/P$) is spin frequency, θ is the angle between stellar rotation and magnetic axes, $\beta \equiv 2\mu^2/3c^3I = B^2R^6/6c^3I = 6.2\times10^{-12}$ s B_{15}^2, $B_{15} = B/10^{15}$ G, and we assume the magnetic dipole moment $\mu = BR^3/2$ and an orthogonal rotator, i.e. $\sin^2\theta = 1$. We take NS mass, radius, and moment of inertia to be $M = 1.4M_\odot$, $R = 10$ km, and $I = 10^{45}$ g cm^2, respectively. For simplicity we use the traditional vacuum dipole formula of Pacini (1968); Gunn & Ostriker (1969). Corrections due to a plasma-filled magnetosphere and in the θ-dependence only introduce changes of order unity (see, e.g. Spitkovsky 2006; Contopoulos et al. 2014). Torque on the star is defined by $N = I\dot{\Omega}$, and, without additional sources of torque on the pulsar, the resulting evolution equation for spin frequency is $d\Omega/dt = -\beta\Omega^3$, with solution

$$\Omega = \Omega_0(1+2\beta\Omega_0^2t)^{-1/2} = \Omega_0(1+t/t_{\rm em})^{-1/2} \quad \text{for } t_0 < t < t_{\rm ej}, \quad (2)$$

where Ω_0 ($=2\pi/P_0$) is initial spin frequency and spin-down occurs on the timescale

$$t_{\rm em} = 1/2\beta\Omega_0^2 = 2.0\times10^3\ {\rm s}\ B_{15}^{-2}(P_0/1\ {\rm ms})^2. \quad (3)$$

From eq. (2) we see that, in isolation, 1E 161348−5055 would spin down to $P \approx 2\pi(2\beta t)^{1/2} = 3.9$ s $B_{15}(t/1000\ {\rm yr})^{1/2}$, which coincides with the spin period range $P\approx 2-12$ s of other observed magnetars (Mereghetti et al. 2015; Turolla et al. 2015) but is much shorter than its current spin period of 2.4×10^4 s. This demonstrates that all magnetars except 1E 161348−5055 could simply have spun down to their current spin period via the torque due to electromagnetic dipole radiation (equation 1). For 1E 161348−5055, dipole radiation torque is too weak, and a stronger, additional or alternative torque, such as that due to mass accretion, is required to increase its spin period by its current age of a few thousand years.

Therefore let us suppose that when 1E 161348−5055 was first born, it was surrounded by a disk of material from, e.g. supernova ejecta that did not escape the system (Chevalier 1989). This material cannot interact with the pulsar as long as the pulsar light cylinder, defined by radius

$$r_{\rm lc} = c/\Omega = 47.7\ {\rm km}\ (P/1\ {\rm ms})\,, \quad (4)$$

is smaller than the magnetosphere, whose radial extent is approximately

$$r_{\rm m} = \xi r_{\rm A} = \xi\left(\frac{\mu^4}{8GM\dot{M}^2}\right)^{1/7} = 7.3\times10^5\ {\rm km}\ \xi B_{15}^{4/7}\dot{M}_{-12}^{-2/7}, \quad (5)$$

where $\xi\sim 0.5-1$ (see, e.g. Ghosh & Lamb 1979; Wang 1996), the Alfvén radius $r_{\rm A}$ is derived from balancing ram pressure of the accreting material with pressure of the pulsar magnetic field

(Lamb et al. 1973; Lipunov 1992), $\dot{M}$ is mass accretion rate, and $\dot{M}_{-12} = \dot{M}/10^{-12} M_\odot\ \mathrm{yr}^{-1}$. Thus this ejector phase takes place when $r_{\rm lc} < r_{\rm m}$. The transition between ejector and propeller phases occurs at spin period

$$P_{\rm ej} = \frac{2\pi}{\Omega_{\rm ej}} = \frac{2\pi r_{\rm m}}{c} = 15\ \mathrm{s}\ \xi B_{15}^{4/7} \dot{M}_{-12}^{-2/7}, \quad (6)$$

and the duration of the ejector phase $t_{\rm ej}$ can be estimated from eqs. (2) and (6) and is

$$t_{\rm ej} = t_{\rm em}\left[\left(\frac{\Omega_0 r_{\rm m}}{c}\right)^2 - 1\right] \approx \frac{r_{\rm m}^2}{2\beta c^2} = 1.5\times 10^4\ \mathrm{yr}\ \xi^2 B_{15}^{-6/7} \dot{M}_{-12}^{-4/7}. \quad (7)$$

Once $r_{\rm lc} > r_{\rm m}$, the propeller phase begins, and the total torque on the star is approximately

$$N = N_{\rm acc} + N_{\rm prop} \equiv \dot{M} r_{\rm m}^2 \Omega_{\rm K}(r_{\rm m}) - \dot{M} r_{\rm m}^2 \Omega = N_{\rm acc}\left(1 - \hat{\omega}_{\rm s}\right), \quad (8)$$

where $N_{\rm acc}$ is accretion (spin-up) torque and $N_{\rm prop}$ is propeller (spin-down) torque (see Ho et al. 2014, for derivation; see also, e.g. Alpar 2001; Esposito et al. 2011; Piro & Ott 2011; alternative prescriptions for total torque can be found in, e.g. Menou et al. 1999; Ertan et al. 2009; Parfrey et al. 2016). The Kepler orbital frequency $\Omega_{\rm K}(r_{\rm m})$ at the magnetosphere radius has the corresponding period

$$P_{\rm K}(r_{\rm m}) = \frac{2\pi}{\Omega_{\rm K}(r_{\rm m})} = \left(\frac{4\pi^2 r_{\rm m}^3}{GM}\right)^{1/2} = 9.0\times 10^3\ \mathrm{s}\ \xi^{3/2} B_{15}^{6/7} \dot{M}_{-12}^{-3/7}. \quad (9)$$

The fastness parameter $\hat{\omega}_{\rm s}$ [$\equiv \Omega/\Omega_{\rm K}(r_{\rm m})$; Elsner & Lamb 1977] determines whether centrifugal force due to stellar rotation ejects matter and spins down the star (propeller phase with $\hat{\omega}_{\rm s} > 1$) or matter accretes and spins up the star (accretor phase with $\hat{\omega}_{\rm s} < 1$) (see, e.g. Wang 1995). The transition between these two phases ($\hat{\omega}_{\rm s} \approx 1$) is where the total torque is approximately zero and the NS is in spin equilibrium (Davidson & Ostriker 1973; Alpar et al. 1982) and occurs at spin period $P = P_{\rm K}$.

The evolution equation for spin frequency is obtained by equating eq. (8) to stellar torque $N = I\dot{\Omega}$, so that (see also Alpar 2001)

$$\frac{d\Omega}{dt} = -\frac{\dot{M} r_{\rm m}^2}{I}\left[\Omega - \Omega_{\rm K}(r_{\rm m})\right] = -\frac{\Omega}{t_{\rm prop}} + \frac{\Omega_{\rm K}(r_{\rm m})}{t_{\rm prop}}, \quad (10)$$

where

$$t_{\rm prop} \equiv \frac{I}{\dot{M} r_{\rm m}^2} = 96\ \mathrm{yr}\ \xi^{-2} B_{15}^{-8/7} \dot{M}_{-12}^{-3/7}. \quad (11)$$

We can obtain a simple solution of the evolution equation by assuming μ and $\dot{M}$ are constant (more sophisticated models with $\dot{M}(t)$ can be found in, e.g. Chatterjee et al. 2000; Ertan et al. 2009; Tong et al. 2016). Then the spin frequency as a function of time during the propeller phase, which starts from the end of the ejector phase at time $t_{\rm ej}$ with spin frequency $\Omega_{\rm ej}$, is

$$\Omega = \left[\Omega_{\rm ej} - \Omega_{\rm K}(r_{\rm m})\right] e^{-(t-t_{\rm ej})/t_{\rm prop}} + \Omega_{\rm K}(r_{\rm m}) \quad \text{for } t > t_{\rm ej}. \quad (12)$$

Equations (2) and (12) thus describe the complete evolution of NS spin frequency (or spin period) through the ejector and propeller phases, respectively. Figures 1 and 2 plot this evolution, assuming $\xi = 1$, an initial spin period $P_0 = 1$ ms, and different combinations of magnetic field B and average accretion rate $\dot{M}$. We note that, as long as $P_0 \ll P_{\rm ej}$, the evolution of spin period is unchanged for any P_0, except at very early times. During the early evolution (at $t < t_{\rm ej} \sim 10^2 - 10^3$ yr, depending on B and $\dot{M}$; see equation 7), the NS is in the ejector phase, and $P \propto t^{1/2}$ (see equation 2). At time $t_{\rm ej}$ when $r_{\rm m} = r_{\rm lc}$, the NS magnetosphere can interact with the remnant disk, and the NS enters the propeller phase. The spin

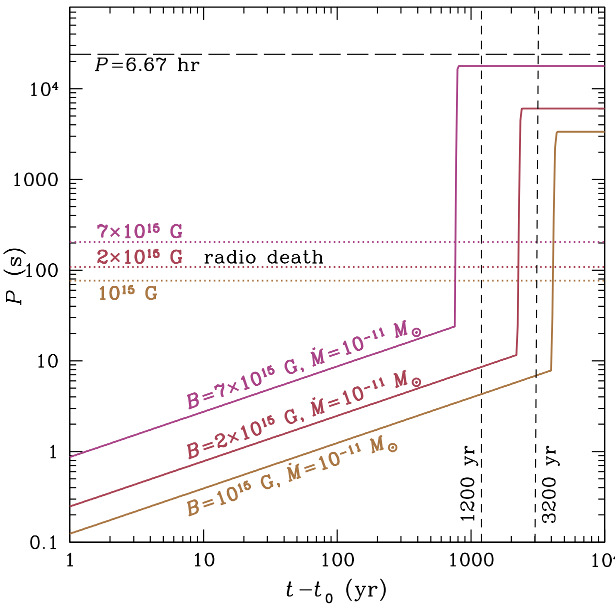

Figure 1. Spin period as a function of time, starting from ejector phase onset at t_0 with initial period $P_0 = 1$ ms, for magnetic field $B = 1$, 2, and 7×10^{15} G and average mass accretion rate $\dot{M} = 10^{-11} M_\odot\ \mathrm{yr}^{-1}$. Horizontal and vertical dashed lines denote the current spin period 6.67 hr and age range 1200–3200 yr, respectively, of 1E 161348−5055. Dotted lines indicate the (theoretically uncertain) death line for pulsar radio emission with the magnetic fields shown.

period increases rapidly in this phase ($P \propto e^t$; see equation 12) for a time $\sim t_{\rm prop}$ (see equation 11). Finally, when P approaches $P_{\rm K}(r_{\rm m})$ (see equation 9), propeller and accretion torques balance, so that the total torque on the star is zero and P is approximately constant, and the NS is in spin equilibrium. Figure 1 shows that, for a given accretion rate, more strongly magnetized NSs reach longer periods, while Fig. 2 shows that, for a given magnetic field, lower accretion rates produce longer spin period NSs (see also equation 9).

Since we know the spin period P and approximate age of 1E 161348−5055, only particular combinations of magnetic field and average mass accretion rate will satisfy eq. (12), i.e. for

$$\ln\frac{\Omega_{\rm ej}}{\Omega - \Omega_{\rm K}} = \frac{\left|\mathrm{age} - t_{\rm ej}\right|}{t_{\rm prop}}, \quad (13)$$

where we take $\Omega_{\rm ej} - \Omega_{\rm K} \approx \Omega_{\rm ej}$, the left-hand side must equal the right-hand side and spin frequency and age are set by $\Omega = 2\pi/(6.67\ \mathrm{hr})$ and age = 1200–3200 yr, respectively. The values of B and $\dot{M}$ which satisfy the above are indicated by the shaded region in Fig. 3, along with the magnetic field of several magnetars, inferred from their P and $\dot{P}$ (values taken from the ATNF Pulsar Catalogue[1]; Manchester et al. 2005; see also McGill Online Magnetar Catalog[2]; Olausen & Kaspi 2014), the highest of which is 4×10^{15} G for SGR 1806−20. If 1E 161348−5055 has a slightly higher field of $\approx 5\times 10^{15}$ G than SGR 1806−20 and is ≈ 2300 yr old, then it only requires an average accretion rate of $\approx 2.5\times 10^{-12} M_\odot\ \mathrm{yr}^{-1}$ to spin it down to a period of 6.67 hr (see also Fig. 2). If the accretion rate is much lower or higher (at this B), then 1E 161348−5055 would

[1] http://www.atnf.csiro.au/research/pulsar/psrcat/
[2] http://www.physics.mcgill.ca/ pulsar/magnetar/main.html

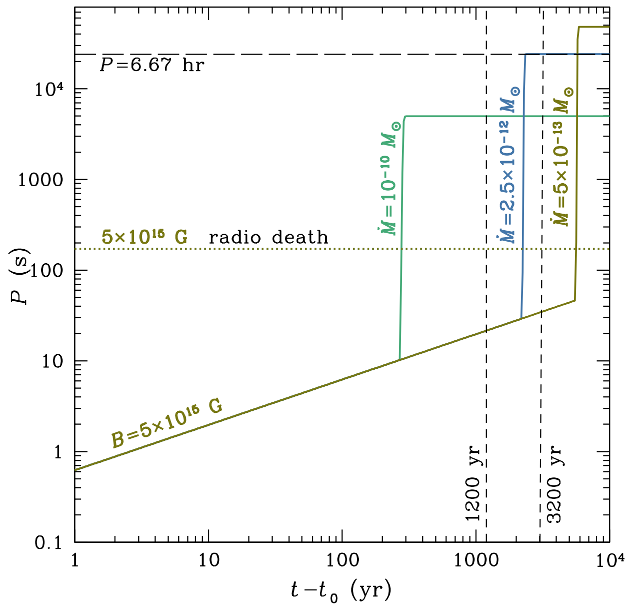

Figure 2. Spin period as a function of time, starting from ejector phase onset at t_0 with initial period $P_0 = 1$ ms, for magnetic field $B = 5\times10^{15}$ G and average mass accretion rate $\dot{M} = 10^{-10}$, 2.5×10^{-12}, and $5\times10^{-13}\,M_\odot$ yr^{-1}. Horizontal and vertical dashed lines denote the current spin period 6.67 hr and age range 1200–3200 yr, respectively, of 1E 161348−5055. Dotted line indicates the (theoretically uncertain) death line for pulsar radio emission with $B = 5\times10^{15}$ G.

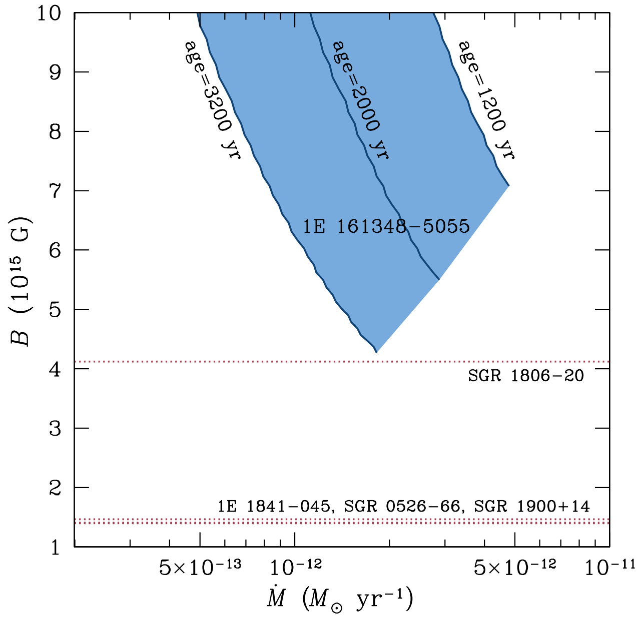

Figure 3. Constraints on magnetic field B and average mass accretion rate $\dot{M}$ of 1E 161348−5055. The shaded region denotes B and $\dot{M}$ values which produce a NS with a spin period of 6.67 hr after 1200–3200 yr from birth. Horizontal dotted lines indicate the magnetic field of particular magnetars inferred from their spin period P and spin period time derivative $\dot{P}$ (values taken from the ATNF Pulsar Catalogue; Manchester et al. 2005) and $B = 6.4\times10^{19}$ G $(P\dot{P})^{1/2}$.

be in the ejector phase or in spin equilibrium, respectively, with a spin period much shorter than 6.67 hr in both cases.

3 DISCUSSION

Recent observations by D'Aì et al. (2016); Rea et al. (2016) of the X-ray source 1E 161348−5055 in SNR RCW 103 strongly suggest it is a magnetar (NS with $B \gtrsim 10^{14}$ G) with an extremely long spin period $P = 6.67$ hr, in contrast to all other known magnetars which have 2–12 s spin periods. The long spin period of 1E 161348−5055 might argue against dynamo generation of magnetic fields because of a requirement for fast (millisecond) initial spin periods, and there is insufficient time for 1E 161348−5055 to lose enough rotational energy via conventional electromagnetic dipole radiation.

Here we demonstrate, using a simple model with simple assumptions, that the spin period of 1E 161348−5055 can increase from milliseconds to 6.67 hr over its 1.2–3.2 kyr lifetime by evolving through ejector and propeller phases while undergoing accretion from a disk. Our calculations show that a young NS, such as 1E 161348−5055, can spend quite a long time t_{ej} in the ejector phase, and thus this phase should not be neglected. The requisite disk might have remained bound to the NS during its formation in a (superluminous) supernova and may have significant impact even when it has very low total mass, which we estimate to be $\Delta M \sim 10^{-12} M_\odot\ \mathrm{yr}^{-1} \times 10^3\ \mathrm{yr} = 10^{-9} M_\odot$. This disk may still be present or has been completely accreted/dissipated. In the case of the former, since 1E 161348−5055 has evolved to be near spin equilibrium (when the total torque on the star is approximately zero), the long-term $\dot{P}$ is very low and could satisfy the observed constraint of $\dot{P} < 10^{-9}$ s s^{-1} obtained by Esposito et al. (2011). 1E 161348−5055 may on occasion accrete more or less material, which could explain the variability seen in X-rays (Gotthelf et al. 1999; De Luca et al. 2006). In fact, our derived $\dot{M} \sim 10^{-12} M_\odot$ yr^{-1} corresponds to a luminosity $L = GM\dot{M}/R \sim 10^{34}$ erg s^{-1}, which is on the order of that observed (De Luca et al. 2006).

If the disk is no longer present (with the observed X-ray variability due to typical magnetar variability), then the dipole radiation torque yields $\dot{P} \sim 10^{-13} - 10^{-12}$ s s^{-1}, well below the observed constraint. We also note that, while the exact nature of the mechanism that causes radio emission is uncertain, it is thought that there exists a "death line" which demarcates when observable radio emission ceases (Ruderman & Sutherland 1975; Bhattacharya et al. 1992). This death line is shown by dotted lines in Figs 1 and 2. It is clear that, while the NS is in the ejector phase, its spin period is below the death line, and as such, it could emit as a radio pulsar. However after transition to propeller phase, the spin period rapidly increases above the death line. Thus once the accretion disk material is exhausted and the propeller phase ceases, the NS will not emit as a radio pulsar.

Finally, our results suggest a possible unified formation scenario for various classes of observed NSs. This scenario is schematically described in Table 1 and depends on total accreted mass and time spent accreting following a chaotic and turbulent supernova (a scenario that includes more classes but is a function of accretion rate from a fallback disk is proposed in Alpar 2001). For short duration accretion (hours to possibly days) of a large amount of mass ($\gtrsim 10^{-4} M_\odot$), accreting matter can build up on the NS surface so fast that the magnetic field is buried temporarily. Once accretion slows or stops, the magnetic field re-emerges on a timescale of $\sim 10^2 - 10^4$ yr, depending on burial depth, and this increasing surface field could explain properties of CCOs (Ho 2011, 2013). For small to no accretion, we transition from CCO formation to pulsars

Table 1. Cases for formation of different neutron star populations

	time spent accreting	
	short	long
small ΔM	radio pulsar	1E 161348−5055
large ΔM	CCO	improbable formation

that have possible signatures of magnetic field growth, e.g. their braking index, to the majority of isolated radio pulsars (Pons et al. 2012; Ho 2015). In the case of accretion for long durations, the magnetic field will not be buried if the total mass is small. For large total mass (e.g. $10^{-5}M_{\odot}$, like that of the disk seen around magnetar 4U 0142+61; Wang et al. 2006), NSs with $B \sim 10^{13}$ G could end up with $P \sim 10$ s in $\lesssim 10^5$ yr. However, Perna et al. (2014) show that it is extremely difficult to retain such amounts for long durations during a supernova. For 1E 161348−5055, only a small amount of mass ($\Delta M \sim 10^{-9}M_{\odot}$) needs to be retained following its supernova. Thus 1E 161348−5055 is possibly a very special system, and the interaction of its magnetic field with this small mass over a thousand years is what leads to its long spin period of 6.67 hr.

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