

The birthplace and age of the isolated neutron star RX J1856.5-3754

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Accepted 2012 December 12. Received 2012 December 12; in original form 2012 August 30

ABSTRACT

X-ray observations unveiled various types of radio-silent isolated neutron stars (INSs), phenomenologically very diverse, e.g. the \sim Myr old X-ray-dim INSs (XDINSs) and the \sim kyr old magnetars. Although their phenomenology is much diverse, the similar periods ($P = 2\text{--}10$ s) and magnetic fields ($\approx 10^{14}$ G) suggest that XDINSs are evolved magnetars, possibly born from similar populations of supermassive stars. One way to test this hypothesis is to identify their parental star clusters by extrapolating backwards the NS velocity vector in the Galactic potential. By using the information on the age and space velocity of the XDINS RX J1856.5–3754, we computed backwards its orbit in the Galactic potential and searched for its parental stellar cluster by means of a closest approach criterion. We found a very likely association with the Upper Scorpius OB association, for a NS age of 0.42 ± 0.08 Myr, a radial velocity $V_r^{\text{NS}} = 67 \pm 13$ km s^{−1}, and a present-time parallactic distance $d_\pi^{\text{NS}} = 123_{-15}^{+11}$ pc. Our result confirms that the ‘true’ NS age is much lower than the spin-down age ($\tau_{\text{sd}} = 3.8$ Myr), and is in good agreement with the cooling age, as computed within standard cooling scenarios. The mismatch between the spin-down and the dynamical/cooling age would require either an anomalously large braking index ($n \sim 20$) or a decaying magnetic field with initial value $B_0 \approx 10^{14}$ G. Unfortunately, owing to the uncertainty on the age of the Upper Scorpius OB association and the masses of its members, we cannot yet draw firm conclusions on the estimated mass of the RX J1856.5–3754 progenitor.

Key words: stars: neutron.

1 INTRODUCTION

X-ray observations performed in the last two decades unveiled the existence of isolated neutron stars (INSs) which are mostly radio silent and not powered by the star rotation, such as the Myr-old X-ray-dim INSs (XDINSs; Turolla 2009) and the kyr-old magnetar candidates (Mereghetti 2008). Despite their different phenomenology, with XDINSs featuring stable and thermal soft X-ray emission ($kT \sim 50\text{--}100$ eV) and magnetars featuring transient and bursting high-energy activity and non-thermal spectral tails, both INS classes are thought to be linked by evolution. This is implied by their close location in the period–period derivative ($P\text{--}\dot{P}$) diagram and their similar values of the surface magnetic fields B_{surf} , inferred either from the NS spin-down or by the observation of absorption features

in the X-ray spectra, that can be both in the $\approx 10^{13}\text{--}10^{14}$ G range. While finding more similarities in their multiwavelength emission would strengthen such a link, confirming it is more challenging.

If linked by evolution, both magnetars and XDINSs should follow a common evolutionary path. Interestingly, some magnetars seem to be associated with supermassive star clusters (Muno et al. 2006), thus with putative progenitors of $\gtrsim 40 M_\odot$, more massive than those of ‘normal’ NSs ($8\text{--}25 M_\odot$; Heger et al. 2003). However, identifying the parental clusters of the XDINSs is more complicated because of their larger ages with respect to the magnetars. Indeed, the results are affected by the uncertainty on the orbit extrapolation in the Galactic potential for time-scales of a few Myr. This depends on unknowns like the NS distance and proper motion (hence its tangential velocity), measured from optical astrometry once the counterpart is known, and the NS age, inferred either from the spin-down (τ_{sd}), once the period derivative is measured, or from the NS cooling (τ_{cool}), once both a model and a reference value of the

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surface temperature are assumed. A further unknown is the NS radial velocity, whose uncertainty dramatically increases the chances of spurious matches with clusters or stellar associations and hampers all identification attempts (e.g. Mignani, Pavlov & Kargaltsev 2010). However, in some cases, the radial velocity can be inferred from the modelling of the bow-shock profile formed as the INS moves supersonically through the interstellar medium and its fitted inclination angle with respect to the line of sight (LOS), like it had been done for Geminga (Pellizza et al. 2005). The association with the parental cluster also gives an estimate of the NS dynamical age (τ_{dyn}).

The XDINS RXJ1856.4–3754 (Walter, Wolk & Neuhäuser 1996) is the best target for this goal. It has the brightest optical counterpart amongst XDINSs ($V \sim 25.7$; Walter & Matthews 1997) and its proper motion and parallax distance have been measured with high accuracy with the *Hubble Space Telescope* (*HST*), e.g. Walter et al. (2010), while the radial velocity has been inferred by modelling the bow-shock (van Kerkwijk & Kulkarni 2001) detected in H α by the Very Large Telescope (VLT). Moreover, the period derivative of RXJ1856.5–3754 has been measured (van Kerkwijk & Kaplan 2008) yielding the value of $\tau_{\text{sd}} = 3.8$ Myr. In this paper, we report on the search for the parental stellar association of RXJ1856.5–3754, based on the backward extrapolation of its orbit in the Galactic potential. This paper is organized as follows. The description of the orbit simulation code and its application to the NS and to candidate parental clusters/OB associations is given in Section 2, and the results are presented in Section 3 and discussed in Section 4.

2 ORBIT SIMULATION

For the Galactic orbit simulation, we used the code of Vande Putte & Cropper (2009), already successfully applied in Rauch et al. (2007), Vande Putte, Cropper & Ferreras (2009) and Vande Putte et al. (2010) and we refer to these publications for further details. As discussed in Section 1, in order to extrapolate the orbit of RXJ1856.5–3754 in the Galactic potential and localize its putative birth place, accurate measurements of its proper motion μ^{NS} , parallax distance d_{π}^{NS} and inclination angle i of the space velocity vector along the LOS are required. Both the proper motion and parallax distance of RXJ1856.5–3754 have been repeatedly measured through optical astrometry techniques with the *HST*. As seen from Table 1, all measurements of the RXJ1856.5–3754 proper motion agree within the quoted uncertainties. For the parallax distance, we assumed the most recent value of Walter et al. (2010), which confirms the earlier measurement of Walter & Lattimer (2002) and is consistent with that of Kaplan, van Kerkwijk & Anderson (2002),

Table 1. Compilation of the proper motion (μ^{NS}) and parallax distance (d_{π}^{NS}) measurements for RXJ1856.5–3754.

Parameter	Value	Reference
μ^{NS} (mas yr $^{-1}$)	332 ± 1	Walter (2001)
	333 ± 1	Kaplan et al. (2002)
	331.2 ± 2.0	Walter et al. (2010)
d_{π}^{NS} (pc)	140 ± 40	Kaplan et al. (2002)
	117 ± 12	Walter & Lattimer (2002)
	161^{+18}_{-14}	van Kerkwijk & Kaplan (2007) ^a
	167^{+18}_{-15}	Kaplan et al. (2007) ^a
	123^{+11}_{-15}	Walter et al. (2010)

^aThis value has not been used in the current analysis.

but it is more accurate.¹ The inclination angle i along the LOS has been measured by van Kerkwijk & Kulkarni (2001) by fitting the intensity profile of the bow-shock detected in H α by the VLT. This is $i = 60^\circ \pm 15^\circ$, which means that the NS would not move far from the plane of the sky. The alternative ionization nebula model considered by van Kerkwijk & Kulkarni (2001), which yielded inclination angles closer to the LOS, has been ruled out by Kaplan et al. (2002) because the nebula’s opening angle would be incompatible with any of the parallax distance measurements.

Using our orbit simulation code, we then calculated several test sets of NS tracks by looping on various values of the NS distance, the inclination angle (hence of the tangential and radial velocity), and the NS age, computed around their reference values. In particular, we considered a grid of distance values which are $\pm 3\sigma$ around the best-fitting value of Walter et al. (2010), sampled with a spacing of 10 pc. From the corresponding sampled values of the transverse velocity, we then computed a grid of values for the radial velocity for different values of the inclination angle i (45° – 75°) sampled with a 5° step. For the backward extrapolation time, we considered a grid of values for the NS age sampled at intervals of 10 kyr. Since the uncertainty on the RXJ1856.5–3754 proper motion is $\lesssim 0.6$ per cent, we neglected its influence on the orbit extrapolation and the NS birth place localization. In the orbit computation, we did not account for possible changes in the NS spatial velocity caused by close encounters with other stars or known star clusters.

As a reference for the search of the parental stellar association, we first considered a sample of open clusters (OCs) selected from the latest version (3.1, released on 2010 November 24) of the data compilation of Dias et al. (2002), also referred to as the DAML catalogue. This contains entries for 2140 OCs, with sky coordinates, proper motions, radial velocities and associated errors, together with information on the cluster metallicity, size, colour excess, Trumpler type and age. Distances in the DAML catalogue are reported without associated errors, although a fiducial 10 per cent uncertainty is probably adequate for most cases (see e.g. Vande Putte et al. 2010). We also used as a reference the catalogues of nearby OB associations of de Zeeuw et al. (1999) and Melnik & Dambis (2009), based on *Hipparcos* data. Both catalogues contain sky positions and proper motions in Galactic coordinates, radial velocities and errors. In the de Zeeuw et al. (1999) catalogue, radial velocities are reported with no associated errors and we assumed a fiducial 20 per cent uncertainty. Distances are derived from the trigonometric parallaxes of association star members (if available) or from photometric parallaxes. For the OB associations in the Melnik & Dambis (2009) catalogue, we assumed their quoted 6 per cent uncertainty on the distance, while for both proper motion and radial velocity (for which no error is given) we assumed a conservative 50 per cent uncertainty. In all cases, we selected entries with non-null values of distance, proper motion and radial velocity (and associated errors). Although objects younger than ~ 100 Myr are obviously the most interesting candidates, initially we did not apply any selection based on the age of the OC or OB association, which can be uncertain by up to ~ 40 per cent, as well as on other parameters, like the metallicity or morphological type. Instead, we decided to use these parameters as validation elements once a potential association was

¹ The first measurement of the parallax distance, $d_{\pi}^{\text{NS}} = 61^{+9}_{-8}$ (Walter 2001), was not confirmed by Walter & Lattimer (2002) and Kaplan et al. (2002) and is not listed in Table 1, while those quoted in van Kerkwijk & Kaplan (2007) and Kaplan, van Kerkwijk & Anderson (2007) were presented without any supported evidence and are listed for completeness only.

found. Our list includes 439 OCs from the DAML catalogue and 77 OB associations from the de Zeeuw et al. (1999) and Mel'nik & Dambis (2009) catalogues.

We extrapolated back in time the orbits of the candidate parental OC and OB associations over the same age range as for RX J1856.5–3754, using as a reference their nominal values of distance, proper motion and radial velocity. Then, we looked for the combination of NS parameters (age, distance, radial velocity) which yielded the closest approach of the RX J1856.5–3754 orbit. We then regarded as likely associations those for which the approach was closer than a given threshold, defined as the overall uncertainty on the computed separation. The association threshold accounts for the uncertainty on the cluster/OB association orbit extrapolation due to the random errors associated with their distance, proper motion and radial velocity. As done in Vande Putte et al. (2010), we estimated this uncertainty through a Monte Carlo simulation. For each object, we simulated 1000 different values of the distance, proper motion and radial velocity, sampled within their formal errors, and computed the root mean square of the separation between their backward-extrapolated positions at the reference and the centre of the Galactocentric reference frame. In most cases, we found that the uncertainty on the orbit extrapolation was below 100 pc. The association threshold also accounts for the spatial extent of the OC or OB association computed from its angular size and distance and assuming, as a first approximation, a spherical symmetry. Since most OCs and OB associations tend to have irregular morphologies, this is the most conservative assumption we can make. For simplicity, we did not account for two opposite effects which could influence the actual OC or OB association angular size in the past: its expansion due to intrinsic member star proper motions and radial velocities, and its evaporation due to star escape from the local gravitational potential, which would yield angular sizes smaller and larger than those measured at the present epoch, respectively.

3 RESULTS

For completeness, we initially explored an age range of 2.8–3.8 Myr around the RX J1856.5–3754 spin-down age, with the caveat that this is an intrinsically uncertain age indicator since it depends on both the initial spin period of the NS and the value of the braking index n , which has not been measured yet for RX J1856.5–3754. For the assumed range of parameters, we could not find a likely cluster association for RX J1856.5–3754. Although it is possible that its parental OC/OB association is not a known one, owing to the relatively small distance (≈ 1.5 – 2.5 kpc) travelled in 2.8–4.8 Myr, it is unlikely that it has not been discovered yet. While it is also possible that it has been filtered out in the sample selection (see Section 2), the most likely conclusion is that the explored age range is not representative of the RX J1856.5–3754 age.

This conclusion is confirmed by our measurement of its cooling age τ_{cool} , computed using as a reference the most recent measurements of its surface temperature obtained from X-ray and optical-ultraviolet observations. It has been previously suggested that the surface temperature of RX J1856.5–3754 is non-uniform (Braje & Romani 2002; Pons et al. 2002; Trümper et al. 2004), as in other cooling INSS. The discovery of X-ray pulsations at a period of ~ 7 s (Tiengo & Mereghetti 2007) supports this picture. Indeed, in a recent analysis of archival *XMM-Newton* observations of RX J1856.5–3754, covering a time-span of almost 10 yr, Sartore

et al. (2012) found that a two-blackbody (BB) model is statistically preferred to a single-BB model in order to describe the 0.15–1.2 keV spectrum. The resulting BB temperatures are $T_{\text{h}} = 62.4$ eV and $T_{\text{c}} = 38.9$ eV for the hot and cold components, while the corresponding BB radii are $R_{\text{h}} = 4.7(d/120 \text{ pc}) \text{ km}$ and $R_{\text{c}} = 11.8(d/120 \text{ pc}) \text{ km}$, respectively. When extrapolated to optical-ultraviolet (optical-UV) wavelengths, the combined emission of the two BBs is consistent with the optical-UV fluxes obtained from *HST* photometry (Kaplan, Kamble van Kerkwijk & Ho 2011), and further supports the two-BB picture. This gives a luminosity (at infinity) of $31.4 \leq \log L (\text{erg s}^{-1}) \leq 32.5$, where the uncertainty is computed accounting both for the unknown viewing geometry and the uncertainty on the distance (Walter et al. 2010). This range of luminosity values is fully consistent with that of the single BB, $31.2 \leq \log L (\text{erg s}^{-1}) \leq 31.9$, and with those reported in the literature (see e.g. Burwitz et al. 2003; van Kerkwijk & Kaplan 2007; Walter et al. 2010), and lead to the same conclusions on the source age. Assuming a minimal cooling scenario (Page, Geppert & Weber 2006; Page et al. 2009), such luminosities imply cooling ages of ≈ 0.1 –1 Myr, depending on the star mass and chemical composition. This is incompatible with the estimated spin-down age (~ 4 Myr) of RX J1856.5–3754, unless the NS is closer than 90 pc, which is only marginally consistent with the 3σ uncertainty on the parallactic distance (Walter et al. 2010). To summarize, the estimates of the cooling age τ_{cool} suggest NS ages as low as ~ 0.1 Myr. Thus, we reran our orbit simulations exploring the dynamical age range 0.1–2.8 Myr.

We found that the closest OC associations are with NGC 6475 and ASCC 99 (see Table 2). For the former, the closest separation $\Delta r = 160$ – 170 pc for a NS age $\tau_{\text{dyn}} = 0.1$ – 0.3 Myr, a present-time distance $d^{\text{NS}} = 140$ – 150 pc and a radial velocity $V_r^{\text{NS}} = 60$ – 180 km s^{-1} , while for the latter the closest separation $\Delta r = 150$ – 160 pc for $\tau_{\text{dyn}} = 0.1$ – 0.2 Myr, $d^{\text{NS}} = 140$ – 150 pc and $V_r^{\text{NS}} = 60$ – 210 km s^{-1} . In both cases, the values of the closest separations are well above their corresponding association threshold (~ 15 pc). Moreover, the estimated OC ages of ~ 0.3 and ~ 0.5 Gyr (Dias et al. 2002) would be much larger than the inferred NS dynamical age τ_{dyn} of 0.1–0.3 Myr and that of its putative massive progenitor (30–60 Myr). Thus, we ruled out the possible associations with NGC 6475 and ASCC 99. Similarly, we found possible associations with the Upper Scorpius, Upper Cen Lupus and Lower Cen Crux OB associations. For the Upper Cen Lupus association, the closest approach separation $\Delta r \sim 55$ pc, for $\tau_{\text{dyn}} = 0.3$ – 0.5 Myr, $d^{\text{NS}} = 110$ – 150 pc and $V_r^{\text{NS}} = 50$ – 180 km s^{-1} , while for the Lower Cen Crux association, we derived $\Delta r \sim 95$ pc for $\tau_{\text{dyn}} = 0.3$ – 0.4 Myr, $d^{\text{NS}} = 90$ – 110 pc and $V_r^{\text{NS}} = 90$ – 190 km s^{-1} . However, only for the Upper Scorpius association the closest approach distance is below the corresponding association threshold (~ 25 pc). We note that this value is dominated by the size of the OB association (de Zeeuw et al. 1999) rather than by the uncertainty on its orbit extrapolation, which is quite low, thanks to the small uncertainties on the proper motion, distance and radial velocity derived by *Hipparcos* (see Table 2). In particular, for the Upper Scorpius association, we obtained $\Delta r = 5$ – 25 pc for $\tau_{\text{dyn}} = 0.3$ – 0.5 Myr, $d^{\text{NS}} = 120$ – 150 pc and $V_r^{\text{NS}} = 50$ – 150 km s^{-1} . The inferred range of values for the NS present-time distance is consistent with that derived from the parallax measurement of Walter et al. (2010), $d_{\pi}^{\text{NS}} = 123^{+11}_{-15}$ pc. Conversely, fixing the NS present-time distance to this value would yield $\tau_{\text{dyn}} = 0.42 \pm 0.08$ Myr, $V_r^{\text{NS}} = 67 \pm 13 \text{ km s}^{-1}$ and a closest approach separation $\Delta r = 17 \pm 8$ pc, after accounting for the uncertainty on the parallactic distance. Thus, we deem the Upper Scorpius OB association as the putative parental cluster for RX J1856.5–3754.

Table 2. Names, coordinates, right ascension and declination proper motions (μ_α ; μ_δ), distances d , and radial velocities V_r for the OC and OB associations in the Dias et al. (2002) and de Zeeuw et al. (1999) catalogues which are potential birthplaces for RX J1856.5–3754 (see Section 3). Values of the closest approach Δr and the corresponding NS dynamical age (τ_{dyn}), distance (d^{NS}) and radial velocity (V_r^{NS}) are given in the last four columns.

Name	RA (h m s)	Dec. ($^\circ$ ' '')	μ_α (mas yr $^{-1}$)	μ_δ (mas yr $^{-1}$)	d (pc)	V_r (km s $^{-1}$)	Δr (pc)	τ_{dyn} (Myr)	d^{NS} (pc)	V_r^{NS} (km s $^{-1}$)
NGC 6475	17 53 51	−34 47 36	+1.67 ± 0.20	−3.60 ± 0.20	301	−15.53 ± 1.04	160–170	0.1–0.3	140–150	60–180
ASCC 99	18 49 50	−18 43 48	+6.90 ± 0.64	−2.50 ± 0.49	280	−31.29 ± 0.40	150–160	0.1–0.2	140–150	60–210
Upper Scorpius	16 12 03	−23 25 09	+11.04 ± 0.01	−23.32 ± 0.14	145 ± 2	−4.6 ± 0.92	5–25	0.3–0.5	120–150	50–150
Upper Cen Lupus	15 08 12	−43 45 06	+21.30 ± 0.35	−23.13 ± 0.14	140 ± 2	+4.9 ± 0.98	55	0.3–0.5	110–150	50–180
Lower Cen Crux	12 18 52	−57 05 29	+33.50 ± 0.11	−8.90 ± 0.09	118 ± 2	+12.0 ± 2.4	95	0.3–0.4	90–110	90–190

4 DISCUSSION AND CONCLUSIONS

An association with Upper Scorpius was originally proposed, e.g. also by Kaplan et al. (2002) and Walter & Lattimer (2002), assuming their own measurements of the RX J1856.5–3754 parallactic distance and leaving its radial velocity unconstrained. Their inferred dynamical ages for RX J1856.5–3754 were $\tau_{\text{dyn}} \sim 0.4$ and ~ 0.5 Myr, respectively, close to the values inferred in this work. Our conclusion is also in line with the more recent results of Tetzlaff et al. (2010, 2011). In particular, for the same value of the NS distance $d_\pi^{\text{NS}} = 123^{+11}_{-15}$ pc (Walter et al. 2010) as assumed by Tetzlaff et al. (2011), the dynamical age that we derive for the NS ($\tau_{\text{dyn}} = 0.42 \pm 0.08$ Myr) is fully consistent with their estimate (0.46 ± 0.05 Myr). The NS radial velocity that we infer (67 ± 13 km s $^{-1}$), though, is larger than that derived by Tetzlaff et al. (2011), 6^{+19}_{-20} km s $^{-1}$, with any effect due to the difference in the assumed proper motion value being negligible. The difference in the inferred radial velocity (still below 3σ) is probably ascribed to the different approaches in selecting parameter values for the orbit simulation. Tetzlaff et al. (2011) sampled a uniform radial velocity distribution in the range -250 to 250 km s $^{-1}$, to consider also directions much closer to the LOS, as predicted by the ionization nebula model. Instead, by assuming the more likely bow-shock model (see footnote 2), we only sampled values in the range 50 – 200 km s $^{-1}$, according to the constraints on the bow-shock inclination angle along the LOS. The difference in the inferred radial velocity can, thus, explain a factor of 2 difference in the closest approach separation (for the same value of the NS distance). A similar result to ours has been obtained by Bignone et al. (in preparation) using a different orbit simulation code and a Monte Carlo approach to estimate the probability of a parental cluster association. They also find that Upper Scorpius is the only candidate with a non-negligible probability of being the RX J1856.5–3754 parent system and obtain a value of $\tau_{\text{dyn}} \sim 0.3$ Myr, compatible with ours. To summarize, the agreement between these three results rules out that the proposed association between RX J1856.5–3754 and the Upper Scorpius is affected by systematic effects and makes it statistically robust.

Identifying the Upper Scorpius OB association as the birthplace of RX J1856.5–3754 yields a robust value of the NS dynamical age $\tau_{\text{dyn}} = 0.42 \pm 0.08$ Myr, which is almost an order of magnitude lower than the spin-down age $\tau_{\text{sd}} = 3.8$ Myr. The dynamical age we derived is well compatible with the age, τ_{cool} , required to reproduce the observed source luminosity in standard cooling models (the minimal cooling scenario, Page et al. 2006, 2009). ‘Fast’ (or enhanced) cooling (e.g. Yakovlev, Levenfish & Shibano 1999, for a review) is not required to explain the observed properties of RX J1856.5–3754. The mismatch between the spin-down and the dynamical/cooling age implies that the characteristic braking index

of the source is $n \sim 2\tau_{\text{sd}}/\tau_{\text{dyn}} \approx 20$. Large and positive braking indices are routinely measured in radio pulsars (e.g. Johnston & Galloway 1999). However, assuming that such a large n represents the average (constant in time) value in the standard expression for spin-down $\dot{\nu} = -k\nu^n$, where ν is the star spin frequency and k a constant, would rule out any known form of braking torques. A possibility is to consider standard spin-down by magneto-dipole losses ($n = 3$ in the previous expression) but in the presence of a decaying magnetic field, which results in $k \propto B^2$ decreasing in time. Self-consistent models for the coupled magnetic and thermal evolution of a NS were recently presented by Pons, Miralles & Geppert (2009), to which we refer for details. Starting from a series of models with different mass M and initial surface dipolar field B_0 , we looked for values of M and B_0 which reproduce the present value of the luminosity L (two representative values 5×10^{31} and 10^{32} erg s $^{-1}$ were chosen) at an age equal to the dynamical age, 0.42 Myr. This is achieved by models with $B_0 \approx 10^{14}$ G and M in the range 1.1 – $1.7 M_\odot$. Further imposing that the period matches the observed one, $P \simeq 7$ s (Tiengo & Mereghetti 2007), restricts the mass to be $\gtrsim 1.3 M_\odot$. This further supports our conclusion that the true age of RX J1856.5–3754 is sensibly shorter than the spin-down age and well compatible with our inferred dynamical age. The lower limit on the star mass when combined with the estimate of the star radius obtained by Sartore et al. (2012) from the two-BB fit, $12.5 \lesssim R$ (km) $\lesssim 17.3$, is rather non-constraining for the NS equation of state; we remark also that these estimates of M and R are model-dependent and should be taken with caution. A further possibility to reconcile the dynamical and spin-down ages is that RX J1856.5–3754 was born with an uncommonly long period. Using the standard spin-down formula ($P^2 - P_0^2 \propto B^2 t$), it is easy to verify that to spin down the star at its present 7 s period in a time $t = \tau_{\text{dyn}} = 0.42$ Myr, an initial period $P_0 \sim 6.5$ s is required for $B \sim 1.5 \times 10^{13}$ G.

If, as it seems likely, RX J1856.5–3754 originated ~ 0.4 Myr ago in the Upper Scorpius OB association, we can constrain the mass of the progenitor. The stellar population in Upper Scorpius has been extensively studied in the past (e.g. Preibisch et al. 2002, and references therein). The estimated age of the association is ≈ 5 Myr, according to mass estimates of Antares (an evolved M1 Ib supergiant, ≈ 20 – $25 M_\odot$) and of the runaway OB star ζ Oph ($\approx 20 M_\odot$). Hence, the putative progenitor of RX J1856.5–3754, which went supernova (SN) ≈ 0.4 Myr ago, must have had a mass of 20 – $60 M_\odot$, larger than usually expected for NS progenitors ($8 \lesssim M \lesssim 25 M_\odot$; Heger et al. 2003) and close to those invoked for magnetar progenitors (Muno et al. 2006). This, together with the high initial magnetic field required to reconcile the cooling and dynamical age in the framework of a decaying magnetic field, would then suggest that RX J1856.5–3754 might have been an active magnetar in

its youth. However, a recent re-assessment of the age of the Upper Scorpius association based on optical spectroscopy (Pecaut, Mamajek & Bubar 2012) suggests a more likely age of ≈ 11 Myr. Hence, the masses of all members of the association would be lower than previously estimated (e.g. the mass of Antares would be $\approx 17 M_{\odot}$) and the mass of the RX J1856.5–3754 progenitor would be ≈ 18 – $20 M_{\odot}$, i.e. still in the range expected for ‘normal’ NS progenitors. If one assumes that magnetars are indeed born from supermassive progenitors, this might suggest that RX J1856.5–3754 is not an evolved magnetar. However, any conclusion has to be taken with due care. First, the estimates on the Upper Scorpius age and on the mass of its members are still debated, which makes it difficult to precisely constrain the mass of the RX J1856.5–3754 progenitor. Secondly, any conclusion on the XDINS progenitors’ masses must be verified against other XDINS/cluster associations. The only other XDINS for which both the optical parallax and proper motions have been measured (Kaplan et al. 2007), and for which the Galactic orbit extrapolation can be reasonably well computed, is RX J0720.4–3125. The source has been associated with the Trumpler 10 OB association (Kaplan et al. 2007; Tetzlaff et al. 2011) for a dynamical age of 0.5–0.8 Myr. This would imply a progenitor no more massive than $\approx 20 M_{\odot}$, again close to that expected for ‘normal’ NS progenitors. However, owing to the lack of information on the NS radial velocity from a yet undetected bow shock, the association with Trumpler 10 is still tentative. The other way round, if one assumes that XDINSs are indeed evolved magnetars, the possible association of RX J1856.5–3754 with a relatively low-mass progenitor might suggest that not all magnetars are born from supermassive stars. Indeed, the proper motions of the magnetars XTE J1810–197 (Helfand et al. 2007), PSR J1550–5418 (Deller et al. 2012), SGR 1806–20 and SGR 1900+14 (Tendulkar, Cameron & Kulkarni 2012) imply transverse velocities $\lesssim 300 \text{ km s}^{-1}$, which would not require hyperenergetic SN explosions from supermassive progenitors.

To summarize, although it seems likely that the XDINS RX J1856.5–3754 was born ~ 0.4 Myr ago in the Upper Scorpius OB association, both the uncertainty on the age of the latter and the masses of its members make it difficult to draw firm conclusions on the actual mass of the NS progenitor, hence verify the possible evolutionary link between XDINSs and magnetars. Establishing parental cluster associations for a larger sample of XDINSs and magnetars, together with accurate studies of the cluster stellar population, is crucial to verify the connection between the properties of their progenitors and the evolutionary tracks followed by the NS after the SN explosion.

ACKNOWLEDGMENTS

We thank J. Pons for providing us with a set of his cooling models, T. de Zeeuw for useful discussions, and the anonymous referee, whose comments contributed to improve our manuscript. NS acknowledges the support of ASI/INAF through grant I/009/10/0.

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