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LETTERS

The supernova remnant CTB 37B and its associated magnetar CXOU J171405.7–381031: evidence for a magnetar-driven remnant

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Abstract We discuss the association between the candidate magnetar CXOU J171405.7–381031 and the supernova remnant CTB 37B. The recent detection of the period derivative of the object allowed an estimation of a young characteristic age of only $\sim 1000\,$yr. This value is too small to be compatible even with the minimum radius of the remnant being $\geq 10\,\mathrm{pc}$, the value corresponding to the lower limit of the estimated distance of $10.2 \pm 3.5\,\mathrm{kpc}$, unless the true distance happens to be even smaller than the lower limit. We argue that a consistent scenario for the remnant's origin, in which the latter is powered by the energy injected by a young magnetar, is indeed more accurate to explain the young age, and demonstrates its non-standard (i.e. magnetar-driven) nature.

Key words: stars: supernova — stars: neutron

1 INTRODUCTION

Firmly placed inside the population of young neutron stars, the sub-class of high-B field sources, currently composed of the Anomalous X-ray Pulsars and the Soft-Gamma Repeaters, has been well identified and intensively studied over the last decades (Woods & Thompson 2006). However, there are many puzzles concerning their progenitors and birth events. Given their short characteristic ages ($\tau = \frac{P}{2\dot{P}}$), they should still be associated with supernova remnants (SNRs). Based on positional coincidence, similarity of ages and other observable features, only a few associations remain undisputed (Gaensler et al. 2001; Ankay et al. 2001; Marsden et al. 2001; Allen & Horvath 2004). This topic may hide clues for a proper understanding of their nature and evolution, towards an explanation of the apparent high value of the magnetar magnetic fields.

While the evolution of conventional SNRs has been widely discussed in the literature (for instance, see Truelove & McKee 1999), it has been argued that the very formation of a highly magnetized object on short timescales should lead to a dynamical behavior of the remnant, hereby termed magnetar-driven SNR. This modified dynamics, in turn, has implications for the proposed associations and should be taken into account for a consistent picture. We shall review the fundamental ideas in Section 2 and, for the sake of definiteness, apply them to the recently proposed candidate CXOU J171405.7–381031 in CTB 37B, which is identified as a magnetar by two different groups

(Sato et al. 2010; Halpern & Gotthelf 2010a). We will argue that a short derived characteristic age of $\sim 1000\,\mathrm{yr}$ for the magnetar poses problems for a "standard" model (i.e. not driven by energy injection of the magnetar), and actually supports the magnetar-driven picture.

2 ENERGY INJECTION IN MAGNETAR-DRIVEN SNRS

In spite of several decades of work, the problem of gravitational collapse-driven explosions has not been solved (Burrows & Nordhaus 2009). The sequence of events in the collapse process has been well established, but substantial difficulties remain concerning the detailed mechanism(s) of the explosion, and the role (if any) of the formed compact object. Several studies of the expansion of remnants in different interstellar media (ISMs) were performed over the years, just assuming that the explosion is successful, and an energy of $\sim 10^{51}$ erg (Hamuy 2003) is released in a point-like region. Of course, if the central object is to become decoupled from the outgoing gas, this approach makes sense. However, such vision was first challenged by Ostriker & Gunn (1971) when they postulated that the rotation energy of a central pulsar may drive supernovae. Later it became clear that this phenomenon is too slow to power explosions, but many of its features still remain in the so-called magnetodynamical mechanisms (Moiseenko et al. 2010). A recent work addressing the issues of lightcurves and energetics for the specific case of magnetars can be found in Woosley (2010).

The discovery of superstrong magnetic fields posed yet another problem related to the explosion scenario. If the field had to be amplified from an initial seed, then the pre-supernova progenitors had to possess a suitable distribution of both magnetic field and angular momentum. If the initial rotation is not fast enough, the amplification would be quenched (Thompson et al. 2004). This leads to an idea that fast rotating magnetars should be born, for their fields to grow by the α-Ω dynamo, and their braking is then efficient in the aftermath following their birth. Thus, if a magnetar is in turn formed inside the remnant immediately after the explosion by dynamo amplification, the injection of energy (much in the same way as Ostriker & Gunn 1971 envisioned) is inevitable, and an initial energy loss

$$L_0 = 3.85 \times 10^{47} \left(\frac{B}{10^{14}\,\mathrm{G}} \right)^2 \left(\frac{1\,\mathrm{ms}}{P_0} \right)^4 \mathrm{erg\,s^{-1}}$$

and initial timescale for deceleration

$$\tau_0 \ = 0.6 \left(\frac{10^{14}\,\mathrm{G}}{B} \right)^2 \left(\frac{P_0}{1\,\mathrm{ms}} \right)^2 \mathrm{d}$$

can be defined for this process (Allen & Horvath 2004). These estimates are strictly valid for constant values of the magnetic field, whereas it is clear that the very phenomenon of field growth is operating here. However, in the absence of a fully detailed treatment, the expressions above may only be used to indicate the right order, but not high accurateness, of the expected injection.

Since the injected energy scales as B^{-2} and the initial ms periods are required for field amplification to operate, it follows that the timescale for a substantial energy injection (that is, an energy comparable to the kinetic energy of the explosion itself, adopted to be 10^{51} erg) is in fact very short, approximately on the order of hours (a "normal" pulsar would do so in $\sim 100 - 1000\,\mathrm{yr}$). Therefore, we may consider the injection as quite instantaneous by astronomical explosion standards. In short, the very formation of the magnetar leads us to expect that a large fraction of the kinetic energy of the remnant would, in fact, be provided by the injection (see also Woosley 2010), and thus results in a modified dynamical behavior at later times.

This injected energy would make a very young remnant expand more than the corresponding case without energy injection, making it look older in the free-expansion phase (lasting for just $\sim 100\,\mathrm{yr}$). The reason for that feature is the form of the injection term; later the same energy would affect the Sedov-Taylor phase, when the internal energy of the gas inside the cavity U picks up a term, becoming

$$U = E - \frac{9}{32} M \dot{R}^2 - \frac{L_0}{t^{-1} + {\tau_0}^{-1}}, \tag{1}$$

where R is the radius of the SNR and M is the mass in motion, and the last term represents the injected energy due to the magnetar formation.

The results of these considerations were shown and discussed in Allen & Horvath (2004). A variety of works dealing with standard SNR dynamics were then used to compare the results and point out the differences (e.g. Truelove & McKee 1999; Luz & Berry 1999; van der Swaluw et al. 2001). Besides the mentioned quicker expansion in the free-expansion phase, the Sedov-Taylor is also modified to last longer than the case without injection, ending after $\sim 2 \times 10^4 E_{51}^{3/14} n^{-4/7}$ yr in a first approximation (Allen & Horvath 2004), when the SNR enters a "snowplow" (radiative) phase, not very relevant to our problem because of the young ages expected. After recalling these main results, we believe there are good reasons to keep them in mind when SGR-AXP are tentatively associated with SNRs. A specific search for these effects was undertaken by Vink & Kuiper (2006), with negative results. In our view, this is not surprising: after $\sim 1000\,$yr the speed of the ejecta is essentially the same for models with or without energy injection (fig. 2 of Allen & Horvath 2004), making a kinematical identification more difficult. Therefore, it is only for very young remnants that a sensible difference could be found. There are reports in the literature (see Nomoto et al. 2010 and references therein) of highly energetic supernovae (termed "hypernovae") featuring $E_{\rm ej} \geq 10^{52}\,$erg, but these have been identified with the progenitors of GRBs, not necessarily the same events as the birth of magnetars (however, see Yu et al. 2010 for a unifying model). Even in the magnetar-birth events, there are reasons to believe that the total energy output is not large (Dall'Osso et al. 2009), and therefore the failure to identify hypernovae around SGR-AXP is, in principle, quite justified.

3 THE CTB 37B-CXOU J171405.7–381031 ASSOCIATION

The suggestion of the association of CXOU J171405.7–381031 with the remnant CTB 37B was made some time ago in Halpern & Gotthelf (2010b), and offers a new opportunity to understand the birth of magnetars and their supernovae. This association has now been confirmed by the measurements of the $\dot{P}$ that has been measured by Sato et al. (2010) and Halpern & Gotthelf (2010a), qualifying the central object as a magnetar. Moreover, the characteristic age is $\sim 1000\,$yr within a very small range, as found by the two groups. A full discussion of the CTB 37B SNR has been addressed in several works (Aharonian et al. 2008a,b; Halpern & Gotthelf 2010a). As in many other cases, the distance to the remnant is uncertain ($10.2 \pm 3.5\,$kpc; Caswell et al. 1975). It seems safe to assume, taking the angular diameter and the smallest value of the distance range, that $R > 10\,$pc, and possibly a figure as big as $20\,$pc represents the largest distance scale.

Conventional models of SNR expansion (Truelove & McKee 1999) run into trouble in explaining such radii for an age of only $1000\,$yr. Typically, a thousand-year old remnant will not enter the Sedov-Taylor phase before $\sim 1400\,$yr unless the ejected energy is larger than expected, but in any case this would have a small effect on the radius since the latter scales as $R_{\rm ST} = 15\,{\rm pc}(E_{\rm ej}/10^{51}\,{\rm erg})^{1/5}(n_{\rm ISM}/1\,{\rm cm}^{-3})^{-1/5}\,(t/10^4\,{\rm yr})^{2/3}$, with $n_{\rm ISM}$ being the particle density of the interstellar medium in which the SNR expands and t being its age. It follows that the remnant can be larger than $\sim 10\,$pc but only well after $1000\,$yr. This is at odds with the derived age of CXOU J171405.7–381031 unless the actual radius happens to be $\sim 5\,$pc because a factor of ≥ 2 in error in the distance, which seems unlikely.

Figure 1 displays the Radius-Age expected from SNRs for the two cases, a "standard" expansion and a "magnetar-driven" expansion, for the same energy $10^{51}\,$erg and assuming a value of $n_{\rm ISM} = 1\,{\rm cm}^{-3}$ for the particle density of the ISM.

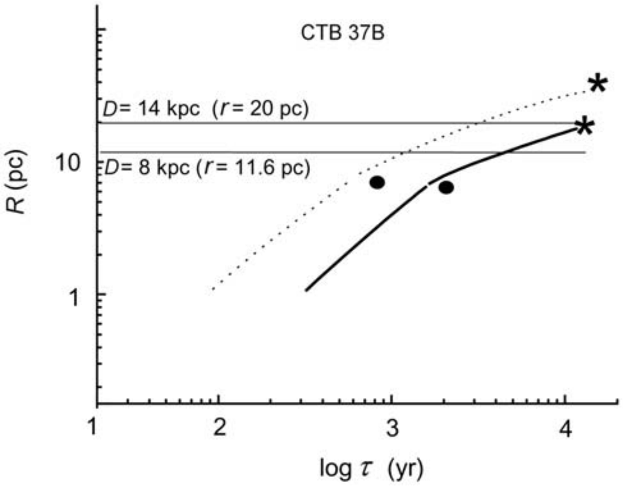

Fig. 1 As explained in the text "standard" (lower solid curve) and "magnetar-driven" (upper dotted curve) remnants. The two curves correspond to identical $E_{\rm ej} = 10^{51}\,$erg and external densities $n_{\rm ISM} = 1\,{\rm cm}^{-3}$. As explained in the text and in Allen & Horvath (2004), the difference in the solutions leads to enter earlier in the Sedov-Taylor phase in the magnetar- driven case, and therefore the remnants expand faster than in the standard case. The transition of the free-expansion to the Sedov-Taylor phase is marked with a black square on each curve. The end of the Sedov-Taylor phase happens at the points marked with an asterisk. This is important for matching the CTB 37B age with the derived $\tau = 1000\,$yr of the associated magnetar CXOU J171405.7–381031, which acts as a relative chronometer. It can be checked that the matching process is quite difficult for the "standard" expansion, or if the distance is closer to the extreme upper limit derived by Caswell et al. (1975) (horizontal lines, labeled). The upper curves were calculated for a magnetar injection energy of 2×10^{52} erg.

As can be checked from Figure 1, the new data (Sato et al. 2010; Halpern & Gotthelf 2010a) lead to a young age only for the "magnetar-driven" case (upper dotted curve), and in fact also favor the shorter of the estimated distances. Insistence on the "standard" expansion scenario would need a much shorter distance to the source, as stated above, and would also require the remnant to be in the free-expansion phase. Since there is information available about the density in the work of Aharonian et al. (2008b), reporting $n_{\rm ISM} \sim 0.5\,{\rm cm}^{-3}$ with a negligible shift in the curve (in fact, indistinguishable in a log plot), we believe it is fair to consider the upper curve of Figure 1 as accurate and conclude that a magnetar-driven scenario for the expansion is implied. In other words, a low density of the ISM cannot be invoked to explain the large radius of the remnant within a "standard" explosion, hence the solution of the quandary univocally points towards the dynamics.

4 DISCUSSION AND CONCLUSIONS

We have discussed the association of the magnetar candidate CXOU J171405.7–381031 with the CTB 37B remnant, with the aim of contributing to the identification of the progenitor of these exotic objects, since the latter ones are still largely unknown. An initial expectation of high-mass progenitors ($> 30 - 40\,M_\odot$) was proposed by Gaensler et al. (2005), and later supported by the cluster analysis by Figer et al. (2005); Muno et al. (2006) and Bibby et al. (2008); which has recently been challenged by the identification of SGR 1900+14 by Davies et al. (2009) with the Cl 1900+14 cluster, implying there was a progenitor of $\leq 17\,M_\odot$ for the cluster magnetar. If the interpretation of these observations holds, the difference between the events producing pulsars and magnetars should not be related to the mass of the progenitor, but to some other physical/evolutionary feature(s).

Our view of the problem is that, given the difficulties for magnetic fields to grow to the $10^{14} - 10^{15}$G scale, the dynamo scenarios should operate. They lead in turn to predict a large energy injection from the central object into the remnant, and therefore a dynamical behavior of the SNR which has to be considered with care. In other words, due to the injection of energy by the central object (a combined effect of the high rotation and the growing field, as required by $\alpha - \Omega$ dynamos), we do not deal with ordinary remnants, but rather with a very special variety of them, the magnetar-driven ones. It is in this framework that the association needs to be analyzed, as reflected not only by the finding of an energetic magnetar inside, but also by the difficulties of a standard SNR expansion of only ~ 1000 yr to match the observed features. A self-consistency arises from the presence of employment of a magnetar born at the explosion: its presence reinforces employment of a modified dynamics and explains its size at a young age. The smaller size of the X-ray image and its asymmetry suggest that a young age could be matched to conventional models for a radius $\sim 1/2$ of the one adopted here. Note that this is achieved with the same total energy as a "standard" event, namely $10^{51}\,\mathrm{erg}$. If a larger scale is ever detected around a magnetar, its expansion would dramatically show effects of the modified dynamics, and would allow a refined test of this scenario.

Regarding the energy injection calculated to power the modified dynamics, it could be much smaller if, for example, the rapidly spinning object could get rid of its energy by gravitational radiation or another form of "invisible" (i.e not coupled to the remnant) emission. In spite that a quadrupole gravitational wave (GW) would not compete with dipole losses unless the oblateness happens to be extreme (Allen & Horvath 2004), and that it is now agreed that r-mode excitation is not important in these situations (Watts & Andersson 2002; Rezzolla et al. 2001), this possibility cannot be completely discarded. However, if this possibility occurs, we would learn that the birth of magnetars should be strong GW burst sources and the problem of how to amplify the magnetic field would again arise.

Using the same reasoning, we have previously inferred (Horvath & Allen 2010) a range of ages for CTB 37B much smaller than the values derived within conventional models. Now refining the broad interval to include an ISM density closer to usual values (as directly measured for CTB 37B by Aharonian et al. 2008b), the numbers for the ages are still low and would not change much unless the mass of the progenitor was 3–4 times the $10\,M_\odot$ value, but at the price of increasing the disagreement with the characteristic age of CXOU J171405.7–381031. Note the age also favors a "light" ($\sim 10\,M_\odot$) progenitor. Moreover, the new age is closer to the old estimation of $\sim 1500\,\mathrm{yr}$ by Clark & Stephenson (1975), but for quite different reasons. This new age allowed a prediction of the $\dot{P}$ value, $\dot{P} \sim 4 \times 10^{-11}\,\mathrm{s\,s^{-1}}$, which in turn predicted a magnetic field strength of $B = 4 \times 10^{14}\,\mathrm{G}$, before the actual discovery of CXOU J171405.7–381031. It is also interesting to note that younger objects ease the requirements for energizing the TeV scale, as observed by the HESS Collaboration (Aharonian et al. 2008b): electrons have to "live" less without being cooled (Halpern & Gotthelf 2010b) or even that the SNRs themselves contribute to the emission, because they are actually younger than they seem when their ages are erroneously estimated from conventional SNR expansion models.

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