Abstract. We present new determination of the birth rate of AXPs and SGRs and their associated SNRs. We find a high birth rate of $1/(500 \text{ yr})$ to $1/(1000 \text{ yr})$ for AXPs/SGRs and their associated SNRs. These high rates suggest that all massive stars (greater than $\sim (23-32)M_\odot$) give rise to remnants with magnetar-like fields. Observations indicate a limited fraction of high magnetic fields in these progenitors thus our study necessarily implies magnetic field amplification. Dynamo mechanisms during the birth of the neutron stars require spin rates much faster than either observations or theory indicate. Here, we propose that neutron stars form with normal ($\sim 10^{12} \text{ G}$) magnetic fields, which are then amplified to $10^{14}$-$10^{15} \text{ G}$ after a delay of hundreds of years. The amplification is speculated to be a consequence of color ferromagnetism and to occur after the neutron star core reaches quark-deconfinement density. This delayed amplification alleviates many difficulties in interpreting simultaneously the high birth rate, high magnetic fields, and state of isolation of AXPs/SGRs and their link to massive stars.

Key words. stars: evolution — stars: neutron: SGRs/AXPs — supernovae: SNR
In this study we present an updated investigation of the birth rate of AXPs/SGRs and in addition, for the first time, the birth rate of associated SNRs is given. Since AXPs/SGRs ages rely on spin-down age estimates whereas SNRs ages are based on shock expansion models, this constitutes two independent estimates for birth rates. Both samples yield a high birth rate for AXPs/SGRs of \((1/5)-(1/10)\) of all core-collapse SNe, higher than previously appreciated. This high frequency of occurrence of AXPs/SGRs brings into focus issues related to the origin of the strong magnetic fields which we address here. This paper is presented as follows: §2 describes the methods and presents the birth rate results, and §3 discusses the implications. Our model, based on a delayed amplification of magnetic field, is presented in §4 before concluding in §5.

2. Birth rate based on spin-down and SNR ages

One can derive birth rates by fitting a linear trend to the observed cumulative number versus age relation. For SNRs, we take data from Marsden et al. (2001) and for spin-down ages we used \(P\) and \(\dot{P}\) from the Australia Telescope National Facility (ATNF) website. We supplemented the ATNF data with recent updates from the literature (see Table 1). The sample consists of 5 SGRs and 10 AXPs and 9 associations with SNRs. Of these objects AXP1E2259+586 and AXP4U0142+615 were omitted from our sample since these may have disks (Ertan et al. 2006; Gonzalez et al. 2007) which make the spin-down age unreliable. We note that including these objects did not change our estimates of birth rate from spin-down ages but resulted in worse fits. For the SNR age we adopted the geometric mean of the lower and upper ages given in Marsden et al. (2001).

The left panel of Figure 1 shows the cumulative number of associated SNRs \(N_{\text{SNR}}\) (diamonds and dot-dashed line) versus SNR age. To show the uncertainties in the ages we also plot the minimum and maximum ages for each SNR. The solid line is the expected number versus age relation for a constant birth rate of \(1/(1700 \text{ yr})\). In the right panel we show the cumulative number of SGRs/AXPs \(N_{\text{SD}}\) (circles and dashed line) versus spin-down age. The solid line is the expected number versus age relation for a constant birth rate of \(1/(500 \text{ yr})\). In the right panel we re-plot the cumulative number versus age relation for associated SNRs scaled up by a factor of 3 \((3N_{\text{SNR}}\text{, diamonds and dotted line)}\); the dot-dashed line re-plots the SNR birth rate of \(1/(1700 \text{ yr})\) from the left panel.

We fit the data by a constant birth rate model: one set of fits assumes normal statistics and another set uses a robust estimator (e.g. §14 in Press et al. 1989). The robust estimator uses the sum of absolute values of differences rather than the sum of squares and thus gives less weight to outliers. The results assuming normal statistics give an SGR/AXP birth rate from spin-down of \(1/(500 \text{ yr})\) with a \(1\sigma\) range of \(1/(400 \text{ yr})\) to

\(^1\) An independent study by Gill&Heyl (2007), based on a population synthesis of AXPs detected in the ROSAT All-Sky Survey, yields a birth rate of \(~0.22\) per century.
Table 1. SGRs/AXPs data from Marsden et al. (2001), the atnf pulsar catalogue (Manchester et al. 2005), and Camilo (2007). Ages in years.

| Source            | $\tau_{SD}$ | $\tau_{SNR, lower}$ | $\tau_{SNR, upper}$ | $\tau_{SNR, mean}$ |
|-------------------|-------------|----------------------|----------------------|---------------------|
| SGR1806−20        | 281         | 3500                 | 30000                | 10300               |
| SGR1900+14        | 1050        | 9600                 | 30000                | 17000               |
| SGR0525−66        | 1960        | 5000                 | 16000                | 8940                |
| SGR1627−41        | N/A         | 2600                 | 30000                | 8830                |
| SGR1801−23        | N/A         | 2400                 | 30000                | 8490                |
| AXP1E1048−5937    | 2680        | 9800                 | 30000                | 17200               |
| AXP1E1841−045     | 4510        | 500                  | 2500                 | 1120                |
| AXP1845−0258      | N/A         | 600                  | 30000                | 4240                |
| AXPRXS1708−4009   | 8960        | N/A                  | N/A                  | N/A                 |
| TAXPXEJ18010−197  | 4260        | N/A                  | N/A                  | N/A                 |
| TAXPJ0100−7211    | 6760        | N/A                  | N/A                  | N/A                 |
| AXP1547−5408      | 1400        | N/A                  | N/A                  | N/A                 |
| AXP1E2259+586     | 228000      | 3000                 | 17000                | 7140                |
| AXP4U0142+615     | 70200       | N/A                  | N/A                  | N/A                 |

1/(570 yr), assuming a 50% uncertainty in spin-down age. For the robust estimator the best fit is 1/(525 yr) consistent with the above. For the associated SNRs, the resulting birth rate from the normal estimator is 1/(1600 yr) with a 1σ range of 1/(1500 yr) to 1/(1770 yr) while the robust estimator gave 1/(1770 yr). In all cases the $\chi^2$ values were acceptable indicating a constant birth rate fit is an acceptable model.

2.1. Birth rate comparison

The birth rate derived from associated SNRs is \( \sim 1/3 \) of the birth rate derived from spin-down ages. There are two effects that could account for such a discrepancy.

One effect is incompleteness of either sample, which would increase the birth rate of that sample; in this case incompleteness of the SNR sample could increase the birth rate to match the birth rate from spin-down. As can be seen from the right panel of Figure 1, if we increase the number of SNR by a factor of about 3 we obtain good agreement with the number versus age relation for AXPs/SGRs. It is worth pointing out that of the 15 AXPs/SGRs, 9 show associated SNRs. Since all AXPs/SGRs have been searched for associated SNRs, the SNRs are too faint to be seen. This is either due to: (i) the SNR is old; (ii) the SNR is not detected due to confusion; (iii) the SNR is young but the environment has low density. Either of the latter two situations suggests incompleteness, with a factor of about \( \sim 15/9 \), raising the birth rate estimate from associated SNRs to \( \sim 1/(1000 \text{ yr}) \); this is not enough to account for the difference in
Fig. 1. The left panel shows the cumulative age distribution for SNRs associated with AXP s and SGRs (diamonds and dot-dashed line). The solid line is the expected distribution for constant birth rate of $1/(1700 \text{ yr})$. The triangles indicate the upper and lower SNR age limits. The right panel shows the cumulative age distribution for AXP s/SGRs (circles and dashed line). The solid line is the expected distribution for constant birth rate of $1/(500 \text{ yr})$. The diamonds and dotted line is the cumulative distribution for associated SNRs (from left panel) scaled up by a factor of 3. To better illustrate this scaling, the $1/(1700 \text{ yr})$ line is re-plotted (dot-dashed line).

birth rates. For SGRs/AXPs birth rate if there is incompleteness in the sample then the birth rate increases above $1/(500 \text{ yr})$. However, these objects are fairly bright in X-rays so only transient SGRs/AXPs would contribute to incompleteness. The high birth rate we derived indicate that there cannot be very many transients. Thus the incompleteness cannot be an important factor otherwise we overproduce AXP s/SGRs compared to the total SN rate in the Galaxy.

The second effect is that SNRs or AXPs/SGRs ages could be systematically off by a factor of $\sim 2$. In effect instead of shifting points vertically in Figure 1 the points are shifted horizontally. There is no reason why the SNR ages should be systematically too large by up to a factor of $\sim 2$. However there are reasons to believe that spin-down ages may systematically be off. The general spin-down formula for braking index $n$, $\dot{\Omega} = -K\Omega^n$ (where $K$ is a constant; e.g. Mészáros 1992), implies a spin-down age $\tau = P/((n - 1)\dot{P})$. Table 1 assumes the vacuum dipole case with $n = 3$. However the few pulsars with measured braking indices have values $n > 2$ with the exception of the Vela pulsar with $n = 1.4$ (Lyne et al. 1996). For $n = 2$ the spin-down age is twice that listed in Table 1: this can bring the spin-down derived birth rate down to $\sim 1/(1000 \text{ yr})$ in agreement with the SNR derived value corrected for incompleteness.

However, for 4 of the objects listed (SGR1806–20, SGR1900+14, SGR0525–66 and, AXP1E1048–5937) a doubled spin-down age is still not enough to remove the discrepancy between spin-down age and the lower limit to the SNR age. If the initial period of the
neutron star is below \( \sim 1\) ms, the moment of inertia decreases as it spins down (e.g. Berti\&Stergioulas, 2004). The spin-down formula given above assumes constant moment of inertia and thus a constant \( K \). Taking into account changes in the oblateness (moment of inertia) as the star spin-down from millisecond period leads to no more than 20-30\% increase in age estimate. This is not large enough to explain the discrepancy. On the other hand, spin-down ages assume constant magnetic field. Including magnetic field decay will decrease these ages and worsen the discrepancy.

To summarize this section, the AXPs/SGRs birth rate is about \( 1/(500 \text{ yr}) \) \( (n = 3) \) to \( 1/(1000 \text{ yr}) \) \( (n = 2) \). The latter is consistent with the SNR-derived rate corrected for incompleteness. We still need to explain a large discrepancy in age for the 4 cases mentioned above. We suggest a time delay from SNR explosion to the onset of spin-down to explain these cases (see section 4).

3. Implications

A birth rate of \( 1/(500 \text{ yr}) \) to \( 1/(1000 \text{ yr}) \) implies 1/5 to 1/10 of all core-collapse SNe lead to SGRs/AXPs. To interpret this we use a Scalo mass function, minimum and maximum SN progenitor masses of \( 9M_\odot \) and \( 60M_\odot \). For the 1/5 case, the SGR/AXP progenitor mass range is \( 23M_\odot \) to \( 60M_\odot \); for the 1/10 case, the SGR/AXP progenitor mass range is \( 32M_\odot \) to \( 60M_\odot \). The ranges can be shifted as long as they give the same fraction of SNe that lead to SGRs/AXPs (e.g. \( 20M_\odot \) to \( 40M_\odot \) for the 1/5 case).

An alternate possibility is that 1/5 to 1/10 of SNe for all progenitor masses produce AXPs/SGRs. However observations of associated SNRs indicate that SGRs/AXPs are associated with massive star progenitors (Gaensler 1999) so we favor 100\% production at the high-mass end with \( M > M_{\text{low}} = (23-32)M_\odot \).

This raises the following questions:

1. How do all progenitors with \( M \geq M_{\text{low}} \) generate \( >10^{14} \) G fields in their compact remnants?
2. Why is there a sudden jump in the magnetic field strength between compact remnants from progenitors with mass greater than \( M_{\text{low}} \) (i.e. \( B \sim 10^{14} \) G) and those with mass less than \( M_{\text{low}} \) (\( B \sim 10^{12} \) G).
3. Why are all compact remnants from \( M \geq M_{\text{low}} \) progenitors isolated whereas the progenitors show a high binary fraction?

In regards to point 1 above, observations of OB stars (Petit et al. 2007) found 3 out of 8 with \( \sim \) kG fields and one out of two massive stars with \( \sim \) kG fields. Despite the paucity of data, this indicates that not all massive stars are strongly magnetic. The fossil field hypothesis (Ferrario & Wickramasinghe 2006) predicts even lower numbers of magnetic massive stars than observed. Our study implies that a magnetic field amplification mechanism is required to explain high fields in all compact remnants from
massive stars. One natural mechanism would be dynamo generation during neutron star formation (Thompson&Duncan 1993). However as shown by Vink&Kuiper (2006) the SNRs associated with SGRs and AXPs have normal explosion energy ($\sim 10^{51}$ erg) conservatively limiting the birth periods to $> 5$ ms. This provides a major challenge for the dynamo mechanism for the generation of SGR/AXP magnetic field strengths. Heger et al. (2005) also consider the spin periods of neutron stars at birth from massive stars using a stellar evolution code. They calculate the evolution of 12-35 $M_\odot$ progenitors including magnetic field and angular momentum transport. Their Table 4, gives results of $\sim 15$ ms (for 12$M_\odot$) to 3 ms (for 35$M_\odot$), many times slower than previously obtained in calculations ignoring magnetic torques. This in effect also argues against the dynamo mechanism, which requires sub-ms periods, to generate magnetar-like fields for stars of 35$M_\odot$ or less. This leaves us with the dilemma of how to account for the strong magnetic fields inferred for AXPs/SGRs (i.e. all descendants of stars more massive than $M_{\text{low}}$)?

Alpar (2001) instead suggests that all AXPs/SGRs have normal magnetic fields ($\sim 10^{12}$ G). The large spin-down rates of AXPs/SGRs are then explained by accretion (with propeller mechanism to give the large positive $\dot{P}$; Chatterjee et al. 2000) from a fall-back disk following the SN explosion. This would avoid the problem of generating strong magnetic fields in all stars with mass $> M_{\text{low}}$. Wang et al. (2006) find support for a debris disk around 4U0142+61 thus several destruction mechanisms such as radiation, magnetic propeller and flares which could limit the lifetime of fall-back disks, at least in this case are not effective. However, debris-disk models have difficulties explaining the large negative $\dot{P}$ (i.e. spin-up) occasionally observed in AXPs/SGRs.

Point 2 suggests some new physical mechanism for magnetic field amplification that sets in, independent of progenitor magnetic field, but dependent on progenitor mass. Finally, for point 3, the explosion of the progenitor in many cases leads to binary disruption. However, there still should remain a fraction of binary remnants. In our model, we suggest the second explosion (see below) further reduces the binary fraction.

4. Proposed explanation

We offer an alternate explanation which allows normal magnetic fields for neutron stars born from progenitors with mass $> M_{\text{low}}$, in addition to lower mass progenitors. In this picture, the magnetic field amplification occurs long after the neutron star formation, but only for neutron stars born from massive progenitors. The amplification occurs during the conversion from baryonic matter to quark matter which happens after the neutron star core reaches quark deconfinement density.

An alternate proposal by Dar&DeRújula (2000) involving normal magnetic field strength suggest a conversion to quark matter accompanied by a slow gravitational contraction to power the observed emission.
Amplification of the magnetic field up to $10^{15}$ G can be achieved as a result of color-ferromagnetism (Iwazaki 2005) during the phase transition. The magnetization here is unlike the case of a normal ferromagnet where spontaneous magnetization occurs as the temperature falls below the Curie temperature (there the order parameter is the spontaneous magnetization $M$ namely, the expectation value of spin over the sample, and an external field is required to impose domain alignment). Color-ferromagnetism instead is dictated by the Savvidy effect which is an instability of the vacuum due to infrared singularities (Savvidy 1977). In Color-Ferromagnetic quark matter (SU(2)), the color magnetic field is generated spontaneously not by alignment of quark color spins, but by the dynamics of the gluons (Iwazaki et al. 2005). Due to the nature of fractional quantum hall states, the color magnetic field can exist globally in the quark matter, without domain structure. This global uniform field is the minimum energy state (Iwazaki 2005 and references therein).

Staff et al. (2006) discuss the time delay from neutron star formation to deconfinement in the core and subsequent quark star formation (which occurs in an explosive manner, called a Quark-Nova or QN; Ouyed et al. 2002; Keränen&Ouyed 2003; Keränen et al. 2005). They found that neutron stars with, (i) mass greater than $\sim 1.5M_\odot$, (ii) initial periods less than $\sim 3$ ms and, (iii) magnetic fields less than $\sim 10^{12}$ G, experience deconfinement after several hundred years (see Table 2 and discussion in Staff et al. 2006). These numbers are interesting as they imply progenitors consistent with those we discussed above in the context of birth rates of AXPs/SGRs (i.e. $M > M_{\text{low}}$, $B \sim 10^{12}$ G and, periods of a few milliseconds). For more massive neutron stars (with progenitors mass around approximately $\sim 50-60M_\odot$) the delay is days rather than centuries leading to an energized SN instead (Leahy&Ouyed 2007). More massive progenitors lead to black holes.

To represent the idea of a delayed amplification of the magnetic field, we write the time since SN explosion as

$$\tau_{\text{SNR}} = \tau_{\text{NS}} + \tau_{\text{QS}},$$

where $\tau_{\text{NS}}$ and $\tau_{\text{QS}}$ are the time the compact object spends as a neutron star and quark star, respectively. In our model the magnetic field during the neutron star era ($\tau_{\text{NS}}$) is $\sim 10^{12}$ G thus spin-down is slow during this period. The delay time, $\tau_{\text{NS}}$, is defined by the time to reach deconfinement (Staff et al. 2006) plus a possible nucleation delay (Bombaci et al. 2004). However, after the QN the object’s magnetic field is strongly magnified leading to a fast spin-down. The result is that the spin-down age, $\tau_{\text{SD}}$, is given by $\tau_{\text{SD}} = \tau_{\text{QS}}$, which is determined by vortex expulsion and associated magnetic field decay (Ouyed et al. 2004; Ouyed et al. 2006; Niebergal et al. 2006; Niebergal et al. 2007). As shown in Ouyed et al. 2007a, the resulting spin-down age is $0.16P/\dot{P} \leq \tau_{\text{SD}} \leq 0.33P/\dot{P}$. This is reduced with respect to the standard value $P/(2\dot{P})$ by a factor of $\approx 1.5-3$. 

From Table 1, as noted above, 4 objects have spin-down ages much less than the minimum associated SNR age. The delayed amplification of magnetic field can alleviate this problem, i.e. $3000 \text{yr} < \tau_{NS} < 9000 \text{ yrs}$ and $200 \text{yr} < \tau_{SD} < 2000 \text{ yrs}$. The only object in Table 1 that has spin-down age reliably greater than SNR age is AXP1E1841$-$045: the reduced spin-down age in our model becomes consistent with the SNR age. In this case $\tau_{NS} < < \tau_{QS}$, thus no delay is required.

We have argued above that standard spin-down age estimates do not represent true ages. This affects the birth rate estimate for SGRs/AXPs given above in two ways. Firstly, the spin-down era is shorter by a factor of $\sim 1.5-3$ or an average of $2.25$. Secondly, the time since SN explosion is lengthened by the time delay to magnetic field amplification. In reality the delay time is different for each object depending on the neutron star’s initial period, magnetic field, and mass. As an approximation, we carried out fits with new age estimates using equation (1) with fixed $\tau_{NS}$, and with $\tau_{QS} = \tau_{SD}/2.25$. For $\tau_{NS} = 200, 500, 1000, 3000 \text{ yrs}$, the resulting birth rates were $1/(316 \text{ yr}), 1/(400 \text{ yr}), 1/(510 \text{ yr}), 1/(875 \text{ yr})$, respectively. Thus our previous estimates of $1/(500 \text{ yr})$ to $1/(1000 \text{ yr})$ is valid but the uncertainty is increased. This does not affect the main conclusion that about $1/5$ to $1/10$ of all core-collapse SN result in AXPs/SGRs.

4.1. AXPs 1E2259+586 and 4U0142+615

For these objects we found that their X-ray luminosity is determined by accretion from a torus$^3$ (Ouyed et al. 2007b). Thus their age as quark stars is $\tau_{QS} \neq \tau_{SD}$. This may explain the absurdly high spin-down age for 1E2259+586 compared to its associated SNR age. We have previously argued that the same situation applies to 4U0142+615 (see Figure 1 in Ouyed et al. 2007a).

The estimate of $\tau_{QS}$ is the time it takes to consume the torus or, $\tau_{QS} \sim m_t/\dot{m}_{t,q}$. The continuous (i.e. quiescent phase) accretion rate, $\dot{m}_{t,q}$ is given by eq.(20) in Ouyed et al. 2007b. We find

$$\tau_{QS} \simeq 16000 \text{ yrs} \frac{m_{t,-7} M_{Q,1.4}^4 \mu_{3.3}^3}{\eta_{0.1} R_{t,25}^3},$$

(2)

where: $m_{t,-7}$ and $R_{t,25}$ are the mass and radius of the torus in units of $10^{-7} M_\odot$ and 25 km, respectively; $M_{Q,1.4}$ is the mass of the quark star in units if 1.4$M_\odot$; $\mu_q \sim 3.3$ is the mean molecular weight of the torus atmosphere, and $\eta_{0.1}$ is the accretion efficiency in units of 0.1.

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$^3$ The QN ejects the neutron star crust which forms a highly degenerate Keplerian torus for rapidly spinning objects (Ouyed et al. 2007b). The torus densities are representative of neutron star crust matter and can easily survive the strong radiation.
5. Conclusion

Our study of the birth rate of AXPs and SGRS and their associated SNRs suggest that about 1/5 to 1/10 of all core-collapse SN lead to AXPs/SGRs. These high rates suggest that all massive stars (greater than $M_{\text{low}}$) give rise to remnants with magnetar-like fields.

This raises these issues: (i) how do all progenitors with $M \geq M_{\text{low}}$ generate $> 10^{14}$ G fields in their compact remnants?; (ii) why is there a dichotomy in magnetic field strength between compact remnants from progenitors with mass greater than $M_{\text{low}}$ (i.e. $B \sim 10^{14}$ G) and those with mass less than $\sim M_{\text{low}}$ ($B \sim 10^{12}$ G); (iii) why are all AXPs/SGRs isolated while many progenitors with $M > M_{\text{low}}$ are in binaries?

In this study, we introduce the notion of delayed magnetic field amplification to resolve these issues. We propose that neutron stars from progenitor masses $M > 9 M_{\odot}$ are born with normal ($\sim 10^{12}$ G) magnetic fields. A neutron star from a progenitor with an approximate mass range $M_{\text{low}} < M < 60 M_{\odot}$ will experience an explosive transition to a quark star (the QN) in which its magnetic field is amplified to $10^{14}$-$10^{15}$ G by color ferromagnetism (Iwazaki 2005). The second explosion (QN) and related mass loss helps to reduce the surviving compact binary fraction thus explaining the state of isolation of AXPs/SGRs. The transition occurs with a delay of several hundred years (Staff et al. 2006). This delayed amplification alleviates many difficulties in interpreting simultaneously the high birth rate and high magnetic fields of AXPs/SGRs and their link to massive stars.

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