Origin and evolution of magnetars

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ABSTRACT

We present a population synthesis study of the observed properties of the magnetars investigating the hypothesis that they are drawn from a population of progenitors that are more massive than those of the normal radio pulsars. We assume that the anomalous X-ray emission is caused by the decay of a toroidal or tangled up field that does not take part in the spin-down of the star. Our model assumes that the magnetic flux of the neutron star is distributed as a Gaussian in the logarithm about a mean value that is described by a power law \( \Phi = \Phi_0 \left( \frac{M_p}{45M_\odot} \right)^\gamma \) G cm\(^2\), where \( M_p \) is the mass of the progenitor. We find that we can explain the observed properties of the magnetars for a model with \( \Phi_0 = 2 \times 10^{25} \) G cm\(^2\) and \( \gamma = 5 \) if we suitably parametrize the time evolution of the anomalous X-ray luminosity as an exponentially decaying function of time. Our modelling suggests that magnetars arise from stars in the high-mass end \( (20M_\odot \leq M_p \leq 45M_\odot) \) of this distribution. The lower mass progenitors are assumed to give rise to the radio pulsars.

The high value of \( \gamma \) can be interpreted in one of two ways. It may indicate that the magnetic flux distribution on the main sequence is a strong function of mass and that this is reflected in the magnetic fluxes of the neutron stars that form from this mass range (the fossil field hypothesis). The recent evidence for magnetic fluxes similar to those of the magnetars in a high fraction \( (\sim 25\%) \) of massive O-type stars lends support to such a hypothesis. Another possibility is that the spin of the neutron star is a strong function of the progenitor mass, and it is only for stars that are more massive than \( \sim 20M_\odot \) that magnetar-type fields can be generated by the \( \alpha-\omega \) dynamo mechanism (the convective dynamo hypothesis). In either interpretation, it has to be assumed that all or a subset of stars in the mass range \( \sim 20-45M_\odot \), which on standard stellar evolution models lead to black holes via the formation of a fall-back disc, must give rise to magnetars.

Unlike with the radio pulsars, the magnetars only weakly constrain the birth spin period, due to their rapid spin-down. Our model predicts a birthrate of \( \sim 1.5-3 \times 10^{-3} \) yr\(^{-1}\) for the magnetars.

Key words: stars: early-type – stars: magnetic fields – stars: neutron – pulsars: general.

1 INTRODUCTION

The anomalous X-ray pulsars (AXPs) and Soft Gamma Repeaters (SGRs) have spin-down properties indicative of magnetic fields of \( \sim 10^{14-15} \) G which places them at the high end of the neutron star field distribution. The source of the quiescent X-ray luminosity in both the SGRs and the AXPs is unclear, but it is generally believed that it is associated with the decay of some component of the magnetic field.

The standard model of Duncan & Thompson (1992) assumes that the fields are generated at the time of formation of the neutron star by an efficient \( \alpha-\omega \) dynamo that operates at low Rossby numbers and requires millisecond birth periods. Neutron stars born with initial periods \( P_i \) are predicted to generate large-scale magnetic fields of \( 3 \times 10^{17} \) G \((1 \text{ ms}/P_i)\) under optimum conditions, which are more than adequate to explain the fields in magnetars.

A consequence of the rapid initial spin predicted for these models is that the supernova explosions that create the magnetars are expected to be an order of magnitude more energetic than ordinary core-collapse supernovae, if one makes the standard assumption that angular momentum is lost by magnetic braking and not by gravitational radiation or due to emission in a jet. However, the energetics of some well-studied supernova remnants associated with magnetars, appear to suggest that their formation may not always be accompanied by a hypernova explosion (Vink & Kuiper...
clustering study of Colpi, Geppert & Page 2000). Models of neutron stars with a heat source in the crust predict that cooling will occur initially at a nearly constant luminosity after which the luminosity will decay exponentially to negligible values (Kaminker et al. 2006), but there are no detailed models that investigate the dependence of decay rates on initial magnetic field and envelope composition. In the absence of such calculations, we have adopted the following parametrization to describe the decline of the crustal luminosity:

\[ L = L_0 \left( \frac{B_d}{10^{13} \text{G}} \right) e^{-\frac{t}{\tau_d}}, \]

where

\[ \tau_d = \tau_{d0} \left( \frac{10^{13} \text{G}}{B_d} \right)^\delta \text{ yr.} \]

Here, \( L_0 \) and \( \tau_{d0} \) are constants, and we have assumed that the birth crustal luminosity is proportional to the intrinsic dipolar field. We have also allowed for the possibility that the decay time is a function of the magnetar’s field strength \( B_d \) via the parameter \( \delta \).

2.2 Parametrization of magnetic field

Recently, there have been detailed stellar evolution calculations for stars in the mass range \( 12 \, M_\odot \leq M_p \leq 35 \, M_\odot \) that have attempted to incorporate magnetic fields and rotation (Heger, Woosley & Spruit 2005). These calculations allowed for fields generated in the differentially rotating radiative regions of stars and their effect on the transport of angular momentum, on the assumption that a dynamo mechanism is in operation. However, the basic premise on which these calculations were made has recently been seriously challenged by Zahn, Brun & Mathis (2007). Therefore, the role played by magnetic fields and rotation in the evolution of stars still remains uncertain.

It is likely that the magnetic flux of the progenitor star, \( \Phi_p \), and to a lesser extent the initial angular momentum, both play an important role in determining the magnetic flux \( \Phi_{NS} \) of the nascent neutron star. In our modelling, we assume that the progenitor mass \( M_p \) is the primary variable that describes the birth magnetic flux of the neutron star.

Our modelling procedure is as discussed in FW, except for our treatment of the birth magnetic flux and birth spin period. Briefly, we begin with a dynamical model for the Galaxy, an initial mass function and an initial–final mass relationship for neutron stars. We then follow the spin evolution and motion of neutron stars, and calculate the properties of the currently observed population of magnetars allowing for X-ray selection effects.

In this study, we assume that the birth magnetic flux of the neutron star is distributed as a Gaussian about a mean that is given by a power law:

\[ \Phi_{NS} = \Phi_0 \left( \frac{M_p}{9 \, M_\odot} \right)^\gamma \text{ G cm}^2 \]

(8 \, M_\odot \leq M_p \leq 45 \, M_\odot \)

with dispersion \( \sigma_{\log \Phi_{NS}} \). For consistency with our previous study of radio pulsars, we assume \( \log \Phi_0 = 25.2 \) and deduce the exponent \( \gamma \) from the study of magnetars. The birth spin period is assumed to be given by a Gaussian distribution with mean \( P_s \) and dispersion \( \sigma_{P_s} \).

The birth magnetic field of the neutron stars is calculated from

\[ B_{NS} = \frac{\Phi}{\pi (R_{NS})^2} \text{ G}, \]

where...
where $R_{NS}$ is the radius of the neutron star in cm given by the mass–radius relationship for neutron stars which depend on the equation of state (see FW for further details).

### 2.3 Allowing for X-ray selection in the ROSAT survey

We have chosen to use the subset of magnetars discovered from the ROSAT All-Sky survey to constrain our models. In order to achieve this, we need to account for interstellar extinction and X-ray selection effects.

We have implemented the methodology laid out by Gill & Heyl (2007) for finding the percentage of the magnetars in our calculations that yield a ROSAT limiting count rate of 0.015 count s$^{-1}$ in the 0.1–2.4 keV energy range (Hünsch et al. 1999).

Our synthetic objects have been assigned a two-component model (power law and blackbody) modulated by interstellar absorption. Hence, as in Gill & Heyl (2007), the number of photons in the energy range $E - E + dE$ is given by

$$\frac{N(E)dE}{E} = \left[ \eta_1 \left( \frac{E}{1\text{keV}} \right)^{-\alpha} + \eta_2 \frac{8.1E^2}{k^4T^4(e^{E/kT} - 1)} \right] \times e^{-N_H\sigma(E)}dE. \quad (3)$$

Here, $\eta_1$ is the power-law normalization in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$, $\alpha$ is the power-law energy index, $kT$ is the temperature in keV and $\eta_2$ is the blackbody normalization in units of $L_{39}/D_{10}^2$, where $L_{39}$ is the luminosity in units of $10^{39}$ erg s$^{-1}$ and $D_{10}$ is the distance in units of 10 kpc. The neutral hydrogen column density $N_H$ is obtained using the Foster & Routledge (2003) model of the Galactic H I distribution. The photoelectric absorption cross-sections $\sigma(E)$ are from Balucinska-Church & McCammon (1992) used with the interstellar medium (ISM) abundances of Wilms, Allen & McCray (2000). In order to convert the absolute photon fluxes into the photon counts of the X-Ray telescope (XRT) detector, we have used the ROSAT calibration guidelines and the XRT effective area combined with the Position Sensitive Proportional Counter (PSPC) sensitivity.

In our modelling, the magnetars have been assigned a temperature and an energy index according to Gaussian distributions with means and spreads $kT = 0.5$, $\sigma_T = 0.1$ and $\alpha = 3.5$, $\sigma_\alpha = 0.5$, respectively. The relative contribution of the blackbody and power-law components to the total X-ray luminosity has been randomly assigned with values consistent with the observed distribution given by Perna et al. (2001).

### 3 Results and Discussion

We have computed a series of models for different values $M^*$, $\gamma$, $\Phi_0$, $\sigma_{\log\Phi_0}$, $P_0$, $\sigma_{P_0}$, $L_0$, $\tau_0$ and $\delta$ until a model is obtained that satisfies the following criteria: (i) the model must envelope and provide a reasonable representation of the observed period and period magnetic field distributions and (ii) the total number of observed magnetars must be less than the theoretically predicted number after X-ray selection effects are taken into consideration. Given the small number of magnetars and the unknown number of active, but currently dormant magnetars (e.g. objects such as SGR 1627–41 that has only recently reactivated after a nearly 10 yr long quiescent period Palmer et al. 2008), the real Galactic distributions are not well enough sampled to justify a more detailed modelling.

The total number of active magnetars in the Galaxy depends strongly on $M^*$ because of the rapidly declining initial mass function. Our calculations show that in addition to the initial mass function, the parameters $\gamma$, $\Phi_0$, $\sigma_{\log\Phi_0}$, $L_0$, $\tau_0$, and $\delta$ together determine the magnetic field, period and period derivative distributions.

Our results are rather insensitive to $P_0$ and $\sigma_{P_0}$ because of the rapid initial spin-down of magnetars. Hence, this study cannot exclude the possibility that magnetars are born at millisecond periods as required by some recent models (Geppert & Reinhardt 2006), or that the birth spin period may be a function of magnetic field as assumed in FW. For simplicity, in our models we have adopted $P_0 = 3$ and $\sigma_{P_0} = 1$ s, although the FW prescription with an upper initial period cut-off at 8 s is also acceptable.

We present in Fig. 1 our favoured model with $M^* = 20 M_\odot$, $\log\Phi_0 = 25.2$, $\sigma_{\log\Phi_0} = 0.4$, $L_0 = 10^{34}$, $\tau_0 = 5 \times 10^2$ yr and $\delta = 1.3$. The corresponding birth rate is $3 \times 10^{-3} \text{yr}^{-1}$. This model best envelopes the field, period, period derivative, characteristic age, luminosity and temperature distributions, and predicts 26 active magnetars after applying the ROSAT detectability criteria. We exclude the possibility of a significantly lower $M^*$ (e.g. $\lesssim 18 M_\odot$) on the grounds that it will lead to a conflict with the birth rate of radio pulsars which we assume arise from stars with $M \leq M^*$. On the other hand, the use of a significantly higher $M^*$ ($> 22 M_\odot$) leads to too few magnetars and inconsistencies with the observed distributions.

We have also constructed a $P - \dot{P}$ diagram which is shown in Fig. 2, where our ROSAT-selected objects are compared with the observations of all magnetars with known $P$. Thus, among the observed objects we have also included SGR 0526−66, which is located in the LMC, and CXOU J010043.7−721134, which is in the SMC, since their positions in the $P - \dot{P}$ diagram are unlikely to depend on which galaxy they reside.

The predicted number of active magnetars from our favoured model can be reconciled with the observed number of five ROSAT-detected sources if we assume that only $\sim 20$ per cent of magnetars were in an active state which brought them to a high enough luminosity to be detected by this satellite. In this case, the actual birth rate of magnetars would be $\sim 3 \times 10^{-3} \text{yr}^{-1}$, which of course depends on our basic assumption that all stars in the mass range 20–45 $M_\odot$ produce magnetars. However, we note that the total number of observed magnetars in the Galaxy is only 14. If no additional magnetars exist in our Galaxy, that is if all magnetars have already been discovered, this means that we have produced too many magnetars from progenitors in the mass range 20–45 $M_\odot$. This may suggest that some 50 per cent of stars in this mass range will produce black holes. If this is the case, the birth rate of magnetars would reduce to $\sim 1.5 \times 10^{-3} \text{yr}^{-1}$.

Studies of SGR bursts conducted by Kouveliotou et al. (1994) indicated that there cannot be more than seven active SGRs in the Galaxy and Kouveliotou et al. (1998) suggested that magnetars are born at a rate of about 0.1 per century. The recent study carried out by Gill & Heyl (2007) was based on a study of the five AXPs detected in the ROSAT All-Sky Survey, and indicated a birth rate of 0.22 per century with their progenitors being massive main-sequence stars. Both these estimates are generally consistent with the birth rate that we deduce. Another recent study carried out by Muno et al. (2008) who searched for magnetars in archival Chandra and XMM–Newton observations of the Galactic plane, yielded a birthrate in the range $3 \times 10^{-3} - 6 \times 10^{-2} \text{yr}^{-1}$. The upper end of this range is excluded by our calculations.

On the fossil field hypothesis, the high value indicated for the magnetic flux index $\gamma$ may simply reflect the intrinsic magnetic flux distribution on the main sequence.
Figure 1. Our model (solid line) overlaid on the magnetar data sample (dashed histograms) taken from http://www.physics.mcgill.ca/~pulsar/magnetar/main.html and with the addition of the recently confirmed member of the AXP class, 1E1547.0–5408 (=PSR J1550–5418) (Camilo et al. 2007).

Figure 2. Filled squares: observed magnetars (http://www.physics.mcgill.ca/~pulsar/magnetar/main.html) with the addition of 1E1547.0–5408 (Camilo et al. 2007); filled circles: magnetars as derived from our modelling (see the text). The solid line is an empirically determined boundary (a ‘magnetar death line’) given by $\log(\dot{P}) = 8.4 \log(P) - 20$.

Observations of main-sequence stars show that the maximum magnetic fluxes observed on the main-sequence map on to the magnetic fluxes of the highest field magnetic white dwarfs ($10^8–10^9$ G) and neutron stars ($10^{14}–10^{15}$ G) rather well. However, due to sensitivity limitations of polarimetric observations, only the upper end of the magnetic field distribution of main-sequence stars (the strongly magnetic stars) can be observed, so we only have a partial picture of magnetism on the main sequence. Unfortunately, most stars in the mass range 8–20$M_\odot$ that give rise to radio pulsars have magnetic fluxes well below the currently observed range on the main sequence so that the index $\gamma$ cannot be empirically estimated.

We note, however, that magnetic fluxes similar to those inferred in magnetars occur in $\sim 25$ per cent of massive B- and O-type stars.

If we somehow dismiss the close similarities between the magnetic fluxes of massive main-sequence stars and magnetars by putting them down to mere coincidence, alternatives to the fossil field hypothesis need to be explored. It is possible that the mass of the progenitor determines the spin of the nascent neutron star and thereby the strength of a dynamo-generated field. Support for this hypothesis comes from the calculations of Heger et al. (2005) which allow for angular momentum transport by magnetic fields generated by differential rotation during stellar evolution. These show that more massive stars tend to produce more rapidly spinning neutron stars. For a 35$M_\odot$ progenitor (the highest mass they considered), they predict that the neutron star will have a spin period of 3 ms which is rapid enough for the generation of a magnetar-type field by the $\alpha-\omega$ dynamo mechanism of Duncan & Thompson (1992).

However, for this to be a viable explanation of the magnetars, the $\alpha-\omega$ dynamo mechanism would need to be effective for neutron stars that arise from the progenitors with significantly lower masses ($\sim 20–22M_\odot$) or the derived birth rate of magnetars would be too low to explain the observations. Furthermore, since the calculations of Heger et al. (2005) have been seriously challenged by Zahn et al. (2007), it appears that we are still waiting for more stellar evolution calculations, that allow for both magnetic field and rotation, to show us whether or not millisecond rotation periods can result from massive stars. If such periods can be achieved, this would give support to the idea that the dynamo model is a viable alternative to the fossil field hypothesis, although it is likely that a fossil field could still play the role of a seed field.

It is relevant that we comment on the alternative to our basic hypothesis on spin evolution, namely that the field that decays is also the field that drives spin evolution during the magnetar phase. We have considered this possibility using ‘Avenue C’ of Colpi et al. (2000), but excluded it from our present considerations because it failed to populate the high-field end of the observed magnetar field distribution. It is conceivable that with the use of different field
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decay parameters for Avenue C, we may also be able to model the data, but we expect that such a model will need to have field characteristics during the magnetar phase that are so similar to those adopted in the present calculations that our major conclusions will remain largely unchanged.

In conclusion, we note that the origin of the crustal field component in magnetars remains unresolved. Zahn et al. (2007) have shown that the shearing of a poloidal field of fossil origin in a differentially rotating radiative region can lead to the generation of a toroidal field so that field complexity of the type that appears to be required in magnetars may arise naturally from stellar evolution, when the complex interplay between rotation and fossil magnetic fields is taken into consideration. On the other hand, since fall-back discs are expected to play a role in the evolution of stars in the mass range $\sim 20-45 M_\odot$, it is tempting to speculate that the crustal field component that characterizes the magnetars may have its origin in the interaction of the fall-back disc with the magnetic field of the stellar core, in cases where a magnetar is the outcome of stellar evolution. If this is the case, one would expect that most of the mass in the fall-back disc would be magnetically ejected.

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