Cosmic Rays from Pulsars and Magnetars

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ABSTRACT

We compare the expected abundance of cosmic-ray electrons and positrons from pulsars and magnetars. We assume that the distribution of infant pulsars and magnetars follows that of high-mass stars in the Milky Way and that the production rate of cosmic rays is proportional to the spin-down and magnetic-decay power of pulsars and magnetars, respectively. In combination with primary and secondary cosmic-ray leptons from other sources (especially supernova remnants), we find that both magnetars and pulsars can easily account for the observed cosmic-ray spectrum, in particular the dip seen by HESS at several TeV and the increase in positron fraction found by PAMELA.

Key words: stars: neutron : cosmic rays

1 INTRODUCTION

Recent measurements of cosmic rays from energies of one GeV to one TeV have shown a spectrum (Chang et al. 2008; Aharonian et al. 2008) and abundance of positrons (Adriani et al. 2009) that are difficult to reconcile with astrophysical sources. These observations have naturally stirred up great interest among the particle physics community and especially people who study dark matter (e.g. Hooper 2009). Essentially the problem is that the observed spectrum is much harder than that expected to be produced by astrophysical sources such as supernova shocks or pulsars, so it is quite natural to look at more exotic possibilities, including decaying dark matter. On the other hand, several works have also examined the question of whether or not astrophysical sources can account for the observed spectrum and positron abundance by including a reasonable model for the diffusion of cosmic rays through the Galaxy. In this Letter we consider the expected abundance of cosmic-ray electrons and positrons (hereafter referred to as cosmic rays) produced by magnetars and pulsars.

Magnetars are ultramagnetized neutron stars with fields $B_\ast \sim 10^{14} - 10^{16}$ G, fueled by either magnetic field decay (Thompson & Duncan 1993) or residual thermal energy (Hevl & Kulkarni 1998). Magnetars are thought to produce copious numbers of electron-positron pairs both in bursts (Thompson & Duncan 1995; Hevl & Hernquist 2005) and in quiescence (Hevl & Hernquist 2008). Moreover, the local radiation from these pairs is thought to power the bursts from soft-gamma repeaters (Thompson & Duncan 1993) as well as the recently discovered non-thermal emission from soft-gamma repeaters and anomalous x-ray pulsars in quiescence (Mereghetti et al. 2003; Kuiper et al. 2006). Consequently, magnetars seem a natural candidate to make an important contribution to the observed abundance of electrons and positrons observed at Earth.

Profumo (2008) presented a detailed calculation of the expected spectrum of cosmic rays in various models for their production from pulsars. His calculation focused on the population of gamma-ray pulsars. The situation for magnetars is somewhat different because these objects are much rarer than gamma-ray pulsars; the birth rate for magnetars is roughly ten times smaller than that of pulsars. Consequently, the cosmic ray flux that we observe can come both from the magnetars that are active today as well as from more ordinary looking objects that may have been active magnetars in the past such as RXJ 0720.4-3125 (Hevl & Hernquist 1998; Hevl & Kulkarni 1998). To calculate the expected abundances of cosmic rays from magnetars, we generate a Monte Carlo simulation of the magnetar population over the past ten million years and compare it with a similar simulation of the pulsar population over the past million years.

2 THE MODELS

2.1 Emission

To model the cosmic ray emission from pulsars we assume a production rate always proportional to the spin-down power by magnetic dipole emission. In contrast to Profumo (2008),
we do not make any distinction between objects that we expect to be gamma-ray pulsars versus the rest of the pulsar population. To specify the model, we assume that all the pulsars are born with a period of 49 milliseconds and spin down to one second by the time we observe them. For the magnetars, we take the cosmic ray emission to be proportional to the magnetic field decay power. We use the calculations of Heyl & Kulkarni (1998) to follow the evolution of the magnetic field starting at $10^{16}$ G at the pole on the surface. We assume that only the energy in the external magnetic field is converted into cosmic rays and that the external field is strictly dipolar (if the internal field is uniform, there is a factor of fifty more energy within the star). For ease of comparison, the initial spin period of the pulsar population is chosen such that the total spin-down energy in the pulsars equals the total magnetic field energy of the magnetars. The magnetars and pulsars may inject high-energy electrons and positrons into interstellar space. We assume that the fraction of the magnetic field or spin-down energy converted to pairs is given by $\epsilon_e$ and $\epsilon_p$, respectively. These are determined by insisting that total electron-positron cosmic-ray abundance from other expected sources (Delahaye et al. 2010) when combined with either the magnetars or pulsars does not exceed that observed by Fermi around 300 GeV.

An important difference between magnetars and pulsars is the evolution of cosmic ray generation with time. In the case of a pulsar the bulk of the cosmic rays are made during the very early life of the pulsar as it is spinning down most rapidly. On the other hand, we assume that magnetars generate cosmic rays from magnetic field decay, which is also thought to power thermal and nonthermal photon emission. The magnetic field decay timescale is typically several thousand years so the emission of cosmic rays from the magnetar is of longer duration. This difference shows up in the observed spectrum of cosmic rays from a nearby magnetar as compared to a nearby young pulsar (Fig. 1). In the case of a pulsar, one sees a relatively smooth spectrum up to the energy of the electrons or positrons that have had time to cool since the birth of the pulsar; at this energy there is a relatively sharp cut off. In the case of the magnetar the calculation this cut off is infinitely sharp. A magnetar releases its magnetic energy gradually, so the cosmic rays that we observe at Earth have a variety of ages, and the energy cut off is much less sharp. However, this is only a second-order effect in determining the shape of the spectrum from an ensemble of objects; the largest differences in the expected spectrum from a collection of magnetars versus pulsars owes to the relative ages of these two populations.

A second important issue is the spectrum of the cosmic rays where they are produced. In both cases we assume that the number of cosmic ray particles decreases as $\gamma^{-2.2}$ ($\gamma$ is the Lorentz factor of the cosmic ray), as suggested by observations of synchrotron emission from shocks (Salmonson et al. 2006). Furthermore, several strongly magnetized neutron stars appear to have emission similar to pulsar wind nebulae (Rea et al. 2009; Helland et al. 2004; Gonzalez & Safi-Harb 2002). The apparent absence of such structures around the classical magnetars (the soft-gamma repeaters and anomalous x-ray pulsars) may simply owe to the difficulty of detecting them at their relatively larger distances. Perhaps these nebulae are powered by pulsar spin-down; however, the efficiency of the conversion of spin-down energy to nebular emission appears to be higher than in typical pulsar wind nebulae, so magnetic field decay may play a role (Rea et al. 2009). Moreover, magnetars may be born with spin rates characteristic of typical pulsars (or even faster; Thompson & Duncan 1993) so in their youth they may emit pairs in a similar manner as pulsars (of course, the time evolution of the emission would differ but this only has a second-order effect on the observed spectra). Therefore, with supporting hints and without definite observational evidence to the contrary, we assume that the magnetars emit a similar spectrum to pulsars. This spectrum is softer than that adopted by Profumo (2008) who used $\propto \gamma^{-1.4}$ through $\gamma^{-2}$. The spectrum of particles produced is taken to extend from $\gamma = 1$ to $\gamma = 10^9$.

2.2 Diffusion

Like Profumo (2008), we use the model of Atoyan et al. (1995) to calculate the diffusion of cosmic rays through the Galaxy. We will briefly summarize previous results and the differences between our treatment and that of Profumo (2008).

Because of the Galactic magnetic field, cosmic rays cannot travel directly from their source to Earth. Rather, they diffuse through the Galaxy with higher energy particles having larger Larmor radii diffusing more quickly than lower energy particles. Meanwhile, as the particles gyrate about magnetic field lines, they also lose energy. If the region over which the particles diffuse is larger than the volume containing the important sources, it is appropriate to assume that the diffusion is spherically symmetric. This yields the following equation for the energy distribution of the cosmic rays (Atoyan et al. 1993; Profumo 2008),

$$\frac{\partial f}{\partial t} = \frac{D(\gamma)}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial f}{\partial r} + \frac{\partial (P(\gamma) f)}{\partial \gamma} + Q,$$

(1)

where $D(\gamma)$ is the diffusion coefficient, $P(\gamma)$ is the energy loss rate of the particles, and $Q$ is the source term. Ionization, bremsstrahlung, inverse Compton, and synchrotron radiation draw energy from the cosmic rays as they travel, but for cosmic rays younger than $10^7$ yr the final two processes dominate. In this regime we have

$$P(\gamma) = p_2 \gamma^2 \approx 5.2 \times 10^{-21} \gamma^2 \text{ s}^{-1}$$

(2)

and a simple solution to Eq. (1) follows for an instantaneous burst of cosmic rays at the origin,

$$f(r, t, \gamma) = \frac{N_0 \gamma^{-\alpha}}{\pi^{3/2} \Gamma(3/2) (1 - p_2 \gamma^2)^{\alpha/2} \left(\frac{r}{\gamma r_{\text{diff}}} \right)^3 e^{-\left(\frac{r}{\gamma r_{\text{diff}}} \right)^2}}$$

(3)

for $\gamma < \gamma_{\text{cut}} = (p_2 t)^{-1}$ (otherwise $f$ vanishes). In this equation $N_0$ is the total number of cosmic rays produced with a spectrum of $dN/d\gamma \propto \gamma^{-\alpha}$; here we take $\alpha = 2.2$. The diffusion length is given approximately by
Table 1. Parameters of the diffusion calculations for the two scenarios. $D_{10}$ is the value of the diffusion coefficient at 10 GeV, and $D_1$ is value at 1 GeV if one extrapolates power-law behavior to high energies to 1 GeV (for comparison with [Profumo, 2008]). Both are in units of cm$^2$/s. The pair-production efficiencies for pulsars is one-tenth that of magnetars in both cases.

| Scenario | $D_{10}$ | $D_1$ | $D_0$ | $\delta$ | $\epsilon_m$ |
|----------|----------|-------|-------|----------|------------|
| LOW      | $10^{28}$ | $2.1 \times 10^{27}$ | $4.1 \times 10^{27}$ | 0.6 | 0.1 |
| HIGH     | $7.5 \times 10^{28}$ | $2.1 \times 10^{28}$ | $3.6 \times 10^{28}$ | 0.5 | 0.3 |

Figure 1. The spectrum of cosmic rays from a single pulsar (green dashed curve), magnetar (red solid curve) or instantaneous burst (black dotted curve) at a distance of 200 pc and an age of 20,000 years under the “LOW” scenario. The total energy release is the same for the three models.

$$r_{\text{diff}}(\gamma, t) \simeq 2 \sqrt{\frac{D(\gamma)t}{1 - (1 - \gamma/\gamma_{\text{cut}})^{1 - \delta}}}.$$  

(4)

In contrast with [Profumo, 2008], we do not choose the diffusion coefficient $D(\gamma)$ to be a strict power law but assume rather that it saturates below several GeV (Atovan et al. 1995).

$$D(\gamma) = D_0 (1 + \gamma/\gamma_c)^\delta$$  

(5)

where we take $\gamma_c = (3\text{GeV})/m_e c^2$. In addition to giving the value of $D_0$, Table 1 presents the values of $D(\gamma)$ at 10 GeV as $D_{10}$ and the value at 1 GeV if one extrapolates the power-law behavior at high energy downward. The latter is for comparison with [Profumo, 2008], who uses a strict power-law relation.

### 2.3 Distribution

We adopt the analysis of Gill & Heyl (2007) to determine the expected spatial locations of magnetars and pulsars. This distribution has two components. One owes to the high mass stars throughout the Galaxy (Reed, 2000, 2005). This distribution decays exponentially from the center of the Galaxy with a scale length of 2.8 kpc and vertically away from the galactic disk with a scale height of 45 pc. The second component is the overabundance of high mass stars known as the Gould belt. Many of the nearby middle-aged neutron stars are probably associated with this recent star formation (Popov et al. 2003). Including this population is critical because nearby young sources can dominate the observed spectrum of cosmic rays. To determine the ages of the sources, we assume that the birthrate of pulsars and magnetars has been uniform in time throughout the Galaxy, so we simply choose 20,000 ages from a uniform distribution between zero and $10^5$ years for pulsars and $10^7$ years for magnetars.

Although we examine sources with ages up to $10^7$ years, the bulk of the emission emerges within the first 10,000 years for magnetars or shorter for pulsars. Therefore, even with a kick of up to 2,000 km/s, the sources move at most twenty parsecs from their birthplaces during their active phases. It is reasonable to neglect the motion of the sources through the Galaxy during their active period. This contrasts with [Profumo, 2008] who used present day positions of pulsars, which leads to a more diffuse distribution (e.g. more extended perpendicular to the Galactic disk) than when the sources were active because of natal kicks given to neutron stars.

### 3 RESULTS

There are two important questions to address. The first is whether the magnetic fields of the magnetars carry sufficient energy to account for the observed fluxes of cosmic rays. The second is whether or not magnetars can account for this observed spectrum of cosmic rays incident upon the Earth, given the assumed spectrum of cosmic ray production. We are interested in both the mean cosmic ray abundance over the realizations but also the range. Understanding the range is crucial because one or two nearby young sources can dominate the abundances, and we may simply be living in a somewhat special place at a somewhat special time. It is important to mention that our results even for pulsars do not agree with those of [Profumo, 2008] because of the aforementioned differences in modeling.

Fig. 3 shows the expected abundance of cosmic rays for pulsars and magnetars for the two different diffusion scenarios. Although the total energy reservoir is the same for a particular pulsar or magnetar, the magnetars are ten-times less numerous, so they are assigned a ten times larger efficiency so that the total cosmic-ray production is the same for the two models. The efficiency is set for the two diffusion scenarios by insisting that the model predictions agree with the Fermi data around 300 GeV (see Tab. 4). This also where the pulsar and magnetar models cross.

For both diffusion scenarios and both populations the resulting cosmic ray abundance comes from nearby old objects and more distant young ones. The Galactic distribution of the sources goes from approximately three-dimensional to disk-like around a distance of 1 kpc. Given the abundance of pulsars and magnetars, the youngest source within this distance is typically $10^4$ yr or $10^5$ yr for pulsars or magnetars respectively. This yields cutoff energies of approximately 31 TeV and 3.1 TeV, roughly where the flux begins to decrease in the “LOW” scenario. Of course, the cutoff energy does not depend on the diffusion scenario. In the “LOW” scenario the diffusion length is about 1 kpc near the cutoff so there are few young sources to contribute to the flux at Earth at these energies, and the flux drops and recovers at high energies as the diffusion length increases.

On the other hand, in the “HIGH” scenario the diffusion length is a few kpc, so we receive cosmic rays from further in...
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Figure 2. Spectrum of cosmic rays from pulsars (green dashed curves) and magnetars (red solid curves) within the Galaxy under the “LOW” and “HIGH” diffusion scenarios. For each type of object, the shaded region gives one-standard deviation variation over the realisations. Furthermore, the bold curve gives the mean plus the results of Delahaye et al. (2010) excluding the contribution of pulsars. The solid triangles give the results from ATIC (Chang et al. 2008), the circles give the results from HESS (Aharonian et al. 2008) and the squares give the results from Fermi (Abdo et al. 2009). For each scenario the pair production efficiency is set so that the total cosmic-ray abundance does not exceed that observed by Fermi around 300 GeV.

Figure 3. The observed positron fraction of cosmic rays from pulsars (green dashed curves) or magnetars (red solid curves) combined with a standard model for cosmic-ray production and propagation exclusive of neutron stars from Delahaye et al. (2010) (given by the black curves) under the “LOW” and “HIGH” diffusion scenarios. For type of object, the shaded region gives one-standard deviation variation over the realisations. The solid squares give the results from PAMELA (Adriani et al. 2009).

the disk from younger sources even around the local cutoff — as the older, nearby sources cut out, the younger more distant sources seamlessly take over. The transition between these two populations leaves an imprint on the expected spectrum. The energy of this imprint depends on the details of the diffusion process and the age of the sources. As the diffusion becomes less rapid, and the objects become older, the transition energy decreases. For the magnetar population in the “LOW” scenario, this transition occurs tantalizingly close to the dip in the HESS data. Aharonian et al. (2009) interpret this dip as a large steepening in the power-law around 1 TeV consistent with the magnetar results. The pulsars do not follow the dip as sharply but they better fit the final HESS data point at about 5 TeV.

Fig. 3 shows the expected anti-matter fraction in electron-positron cosmic rays for the two different diffusion scenarios compared and combined with a model that excludes a contribution from either pulsars or magnetars (Delahaye et al. 2010). The contribution of pulsars or magnetars increases the expected positron fraction at all energies. The effect of magnetars is stronger at lower energies than pulsars because the positrons received from magnetars are typically older and less energetic than those from pulsars. The variation in the expected positron fraction over realisations is larger for the magnetars because the observed cosmic rays are produced by fewer dominant sources, so it is problematic to access which model does better with a statistical tests. At higher energies the pulsars predict a larger positron fraction than magnetars, although here the fractions agree within the expected variation. The disagreement with the observations below 10 GeV although statistically significant is probably not important because of solar modulation of the positron and electron flux at low energies that has not been modelled here.

4 CONCLUSIONS

We have derived the expected spectrum and composition of cosmic rays from magnetars under the reasonable assumptions that the decay of the external magnetic field powers the cosmic-ray production and that the birthrate of magnetars is about ten percent of that of pulsars. We assume that pulsar spin-down powers the cosmic-ray production from these more weakly magnetized neutron stars. We find that either the ensemble of magnetars or that of pulsars can reproduce many of the puzzling features of the spectrum of electron-positron cosmic rays recently discovered by ATIC and HESS. The differences in the appearance and location of these features in the cosmic-ray abundance between the models results mainly from the the relative rarity of magnetars. Although the relative heights of the two bumps in cosmic rays detected at Earth do depend on the the assumed power-law production spectrum, the location of the transition between them does not. On the other hand, the ensemble of pulsars cannot easily reproduce the sharp dip in abundance around
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2 TeV found by HESS – pulsars do reproduce the upturn at 5 TeV, so a combination of the two ensembles may explain both the dip and the upturn. Both pulsars and magnetars can account for the positron abundance in cosmic rays with energies of about one to one-hundred GeV. With additional modelling of the cosmic-ray diffusion, energy losses and production, even more detailed agreement with the observations can be achieved.

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