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PULSARS, SUPERNOVAE, AND ULTRAHIGH ENERGY COSMIC RAYS

K. Kotera[1], K. Fang[2], A. V. Olinto[2] and E. S. Phinney[3]

Abstract. The acceleration of ultrahigh energy nuclei in fast spinning newborn pulsars can explain the observed spectrum of ultrahigh energy cosmic rays and the trend towards heavier nuclei for energies above 10^{19} eV as indicated by air shower studies reported by the Auger Observatory. By assuming a normal distribution of pulsar birth periods centered at 300 ms, we show that the contribution of extragalactic pulsar births to the ultrahigh energy cosmic ray spectrum naturally gives rise to a contribution to very high energy cosmic rays (VHECRs, between 10^{16} and 10^{18} eV) by Galactic pulsar births. The required injected composition to fit the observed spectrum depends on the absolute energy scale, differing considerably between the energy scale used by Auger and that used by the Telescope Array. Depending on the composition of the cosmic rays that escape the supernova remnant and the diffusion behavior of VHECRs in the Galaxy, the contribution of Galactic pulsar births can also bridge the gap between predictions for cosmic ray acceleration in supernova remnants and the observed spectrum below the ankle. Fast spinning newborn pulsars that could produce UHECRs would be born in supernovae that could present interesting specific radiative features, due to the interaction of the pulsar wind with the surrounding ejecta. The resulting supernova lightcurves could present a high luminosity plateau over a few years, and a bright X-ray and gamma-ray peak around one or two years after the onset of the explosion. If such signatures were observed, they could have important implications both for UHECR astrophysics and for the understanding of core-collapse supernovae.

Keywords: ultrahigh energy cosmic rays, neutron star, pulsar, supernova

1 Introduction

The origin of cosmic rays continues to challenge our understanding after a century of observations. Observatories on the ground have studied extensive air showers from energies 10^{15} eV up to 10^{20} eV. The bulk of the cosmic ray flux is believed to be accelerated in Galactic supernova remnants (SNR) (Baade & Zwicky 1934; Bell 1978; Blandford & Ostriker 1978). This long held notion fits well the observed spectrum up to 10^{16} eV Blasi & Amato (2012). Above these energies a new component is needed to explain the spectrum and observed composition. This new component may be Galactic, as suggested in Hillas (2006); Ptuskin et al. (2010), or extragalactic as proposed in Berezinsky et al. (2005); Lemoine (2005). The transition from Galactic to extragalactic is expected to occur well below 10^{19} eV, with models spanning the very high energy (VHE) range between 10^{16} eV and 10^{18} eV with "dip" models around 10^{17} eV (Berezinsky et al. 2005; Lemoine 2005) and "ankle" transition models around 10^{18} eV (see, e.g., Allard et al. 2005).

The study of ultrahigh energy cosmic rays (UHECRs), from 10^{18} eV to 10^{20} eV, has progressed significantly with the advent of giant airshower observatories such as the Pierre Auger Observatory (Abraham et al. 2004) and Telescope Array (TA) in Utah, USA (Tokuno et al. 2012). The spectrum, sky distribution of arrival directions, and composition indicators are well measured over a large range of energies. Differences in reports from the two major observatories include a 20% shift in absolute energy scale ($E_{\rm Auger} \simeq 0.8 E_{\rm TA}$) and the differing trends of composition indicators at higher energies. Currently the most extensive dataset on composition indicators, such as the average and the RMS of the depth of shower maximum ($X_{\rm max}$), has been published by the Auger

[1] Institut d'Astrophysique de Paris, UMR 7095 - CNRS, Université Pierre & Marie Curie, 98 bis boulevard Arago, 75014, Paris, France
[2] Department of Astronomy & Astrophysics, Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, IL 60637, USA.
[3] Theoretical Astrophysics, California Institute of Technology, 1200 E California Blvd., M/C 350-17, Pasadena, CA 91125, USA

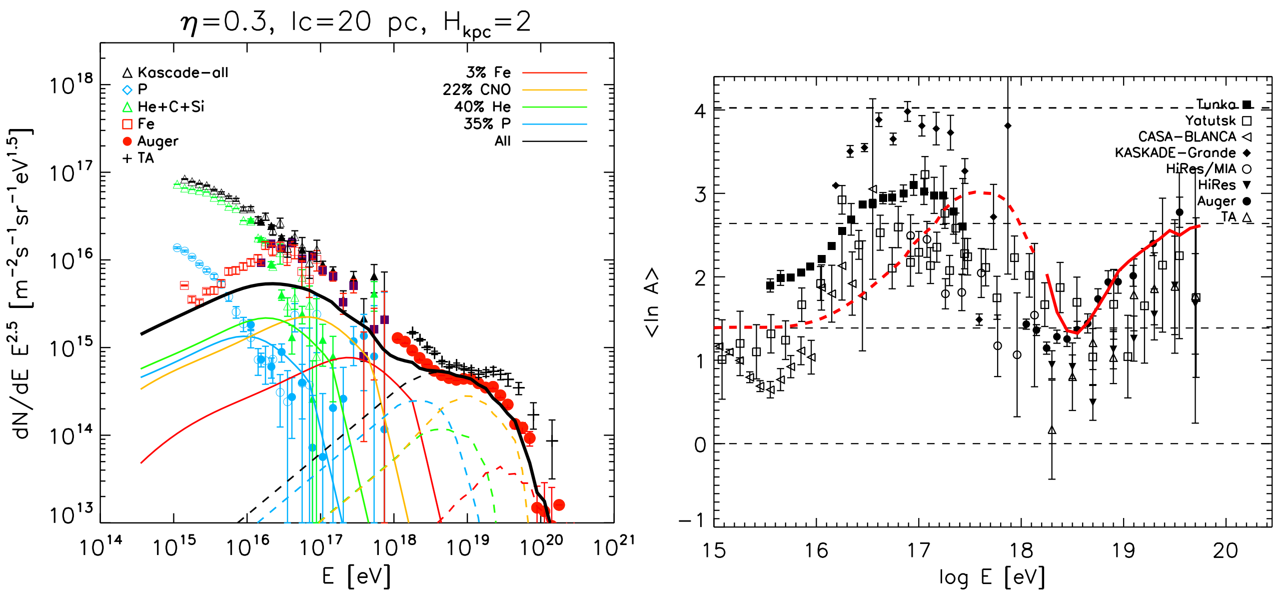

Fig. 1. Left: Total (thick solid line) UHECR spectrum produced by a population Galactic (solid) and extragalactic (dashed) pulsars with parameter distribution following Faucher-Giguère & Kaspi (2006), and with emissivity assumed to be constant over time, embedded in core-collapse SNe of ejecta mass 10 $M_\odot$ and energy 10^{51} erg. The contribution of various elements is indicated. The injection in the pulsar wind follows the ratio 35% Proton, 40% Helium, 22% CNO, and 3% Fe. **Right:** Average logarithmic mass of cosmic ray derived from Xmax measurements with non-imaging Cherenkov detectors (Tunka, Yakutsk, CASA-BLANCA) and fluorescence detectors (HiRes/MIA, HiRes, KASKADE-Grande Auger and TA) for hadronic interaction model EPOS compared with simulation predictions (red lines). Dashed lines indicate the energy range where pulsars have an underdominant contribution to the total flux and other Galactic sources, e.g., supernova remnants, also contribute.

collaboration and shows a departure from a composition consistent with lighter nuclei at 10^{18} eV to a trend towards heavier nuclei above 10^{19} eV (Abreu et al. 2011). TA reports shower behaviors consistent with protons Tameda et al. (2011). The discrepancies in composition reports and the difference in absolute energy scale make it difficult to constrain proposed models for the origin of UHECRs. Fortunately, a cross-experiment effort to understand these discrepancies is currently on-going.

2 Pulsars as sources of very high and ultrahigh energy cosmic rays

Here we show that the fast spinning pulsar birth model described in Blasi et al. (2000); Fang et al. (2012) can explain the observed spectrum (both the Auger and the TA spectra) and the composition trend described in Abreu et al. (2011). To fit these two observables we allow the freedom to vary the percentage of different elements that escape the supernova remnant divided into 4 groups: protons, Helium, Carbon group (CNO), and Iron. Although the surface of the rotating neutron star is a natural source of Iron, X-ray spectra of pulsars indicate that the top layers of their atmosphere is likely to be composed of Helium (Sanwal et al. 2002), or Carbon, Oxygen and Neon (Hailey & Mori 2002; Heinke & Ho 2010). At higher altitude, in the X-ray photosphere, one could find lighter ions (Zavlin & Pavlov 1998; Pavlov & Zavlin 2000) that could be also stripped off and accelerated in the wind. The source of UHECRs in our model are the rare, extremely fast spinning, young pulsars. The majority of pulsars will be born spinning slower and will therefore contribute to the flux of lower energy cosmic rays. The distribution of pulsar birth spin periods, $f(P = 2\pi/\Omega)$, is normal, centered at 300 ms, and with standard deviation of 150 ms, while that the initial magnetic field follows a log-normal distribution $f(\mu)$ with $\langle\log(B/\mathrm{G})\rangle \sim 12.65$ and $\sigma_{\log B} \sim 0.55$ (Faucher-Giguère & Kaspi 2006).

In order to estimate the observed spectrum of UHECRs, after their propagation through the extragalactic medium, we used the simulation output of Kotera et al. (2010) from 10^{18} eV up to the maximum accelerator energy, $E_{\rm max}$, and rescaled the result to the actual spectrum injected by single pulsars. The UHECR spectrum and composition ratios for a given pulsar, after escape through the surrounding supernova ejecta, were calculated in Fang et al. (2012). The normalization of the flux is set by the factor $n_{\rm Gal}\,\nu_{\rm m}\,f_{\rm s}$. On average, the pulsar birth rate is $\nu_{\rm s} \simeq 1.6\times10^{-4}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1} = 1/60\,{\rm yr}\,/{\rm Galaxy}$(Lorimer 2008), and the galaxy density $n_{\rm Gal} \simeq 0.02\,{\rm Mpc}^{-3}$. $f_{\rm s}$ is an overall factor used to fit the model prediction to the measured UHECR flux. In the pulsar model, $f_{\rm s} < 1$ can account for variations in the core-collapse geometry, poorer injection efficiency, or a particle density in the pulsar wind which is less than the Goldreich-Julian charge density.

The flux of cosmic rays accelerated by Galactic pulsars can be calculated as ${\rm d}N_{\rm Gal}/({\rm d}E\,{\rm d}t\,{\rm d}A\,{\rm d}\Omega) = ({\rm d}N_{\rm i}/{\rm d}E)(4\pi)^{-1}\,c\,\tau_{\rm esc}V_{\rm Gal}\,\nu_{\rm s}\,f_{\rm s}\,(1-e^{-\nu_{\rm s}\,\tau_{\rm esc}})$, where $V_{\rm Gal} = 10^{68}\,{\rm cm}^3$ is the volume of the Milky Way, $f_{\rm s}$ is the same scale factor introduced for the extragalactic component, and $\tau_{\rm esc}$ is the time a charged particle takes to escape the Galactic magnetic field. At energies above the knee ($\sim 10^{15}$ eV), nuclei spallation is negligible and the nuclei escape time can simply be estimated with the Leaky box model $\tau_{\rm esc}(E,Z,l_{\rm c}) = H^2/D$, where H is the height of the Galactic Halo Magnetic Field above (or below) the Galactic plane; typically $H \sim 2-8\,{\rm kpc}$ Mao et al. (2012). We take an empirical diffusion coefficient, D, as in Kotera & Lemoine (2008), assuming an azimuthal Galactic magnetic field of strength $3\,\mu$G, coherence length $l_c = 20\,{\rm pc}$, and scale height 2 kpc.

Assuming that cosmic rays injected in the ISM by Galactic pulsars have the same composition as those from EG pulsars, we can calculate the contribution of both Galactic and extragalactic pulsars (Fig.1). To fit the Auger spectrum a balanced ratio between proton, Helium, and CNO, with a minor presence of Iron suffices, while to fit the TA spectrum a higher percentage of Iron is needed since the spectrum extends to higher energies. The composition selected by the Auger spectrum also gives a good fit to the Auger average shower maximum ($\langle X_{\rm max}\rangle$) and the fluctuations around the mean (RMS($X_{\rm max}$)). Although the end of the Galactic spectrum is highly dependent on the Galactic diffusion parameters and the history of the most recent pulsar births in the Galaxy (such that the flux in the VHE region is time dependent), these two choices of energy scales give rise to significant differences in the predictions for the Galactic component. The Auger fit implies an under dominant contribution to the flux of VHECRs, while the TA fit would imply Galactic pulsars as the main contributors to VHECRs. See Fang et al. (in prep.) for more details.

3 Signatures in the very early supernova lightcurve

While they spin down, pulsars release their rotational energy in the form of a relativistic magnetized wind. Kasen & Bildsten (2010); Dessart et al. (2012) discussed that magnetars, a sub-class of pulsars born with extremely high dipole magnetic fields of order $B \sim 10^{14-15}$ G and millisecond spin periods, could deposit their rotational energy into the surrounding supernova ejecta in a few days. This mechanism would brighten considerably the supernova, making them appear ultra-luminous. The potential candidate sources for UHECRs that we described

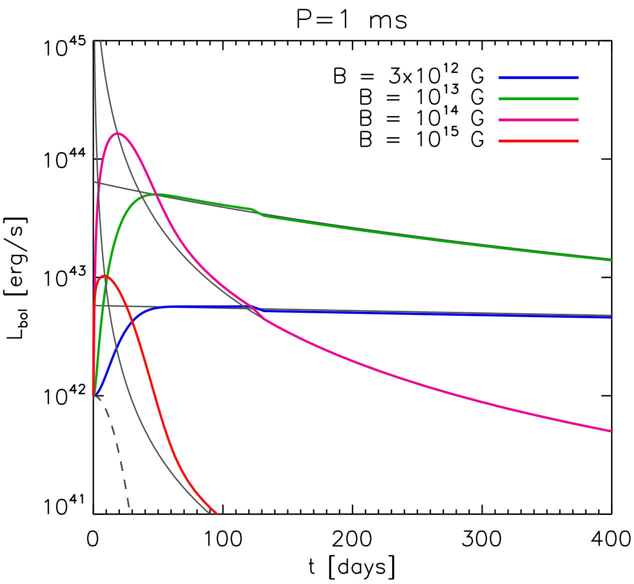

Fig. 2. Evolution of the bolometric radiated luminosity of the supernova as a function of time. The pulsar has a dipole magnetic field of increasing strength as indicated, and period $P_{\rm i} = 1\,{\rm ms}$. The supernova ejecta has $M_{\rm ej} = 5\,M_\odot$ and $E_{\rm ej} = 10^{51}$ erg. The gray lines give the evolution of the pulsar luminosity $L_{\rm p}$ for each initial spin period. The gray dashed lines are the contribution of the ordinary core-collapse supernova to the radiated luminosity $L_{\rm SN}$.

above and in Fang et al. (2012) are millisecond rotators at birth, and are mildly magnetized ($B \sim 10^{12-13}\,$G). Higher magnetization would imply indeed a fast spin-down, and hence that lower energy particles be produced when the supernova ejecta has become diluted enough to allow their escape. Such objects are expected to inject their equally tremendous rotational energy in the supernovae ejectas, but over longer times (of order of a few years). These early emissions have never been estimated.

Using simple radiative transfer arguments, one can calculate that supernovae embedding millisecond pulsars with mild magnetic fields of order $B \sim 10^{12-13}\,$G should present a high bolometric luminosity plateau over a few years (Fig. 2). More detailed calculations of the thermal and non thermal emissions, taking into account the opacity of the ejecta to the various radiations, we find that a bright X-ray or gamma-ray emission could also appear after one year from the acceleration of particles in the pulsar wind (Kotera et al. in prep.).

This study could have important implications for the understanding of core-collapse supernovae, revealing yet unidentified but highly constraining signatures. Note that direct constraints on the newly-formed remnant are scarce, epitomized by the case of SN1987A for which we do not even know the nature of the compact remnant. If this object is observable, and is actually observed by the following up of a large number of supernovae, it could be a ground-breaking discovery.

Because these objects present the ideal combination of parameters for successful production of UHECRs (Fang et al. 2012), the observation of such supernovae could be a further argument in favor of millisecond pulsars as sources of UHECRs, and a potential signature of an ongoing UHECR production.

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