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Pulsars: a promising source for high and ultrahigh energy cosmic rays

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Abstract

Young pulsars have been scarcely discussed as sources of high and ultrahigh energy cosmic rays (UHECR) in the literature. However, the production of UHECRs in these objects could give a picture that is surprisingly consistent with the latest data measured with the Auger Observatory. Here we discuss the production of high and UHE cosmic rays in pulsars. We compare the propagated UHECR observables from the pulsar population with the available data. Finally, we discuss signatures of such a scenario, that one could find in the diffusive neutrino backgrounds and in the lightcurves of supernovae.

Keywords: `Cosmic rays, pulsars`

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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) [9, 13, 16]. This long held notion fits well the observed spectrum up to 10^{16} eV [17]. Above these energies a new component is needed to explain the spectrum and observed composition. This new component may be Galactic, as suggested in [27, 38], or extragalactic as proposed in [14, 33]. 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 [14, 33] and "ankle" transition models around 10^{18} eV (see, e.g., 6).

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 [3] and Telescope Array (TA) in Utah, USA [42]. 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 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 [5]. TA reports shower behaviors consistent with protons [41]. 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 ongoing.

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

The connection between high energy cosmic rays (around the knee region up to the ankle) and Galactic pulsars was suggested by a few authors in the decades

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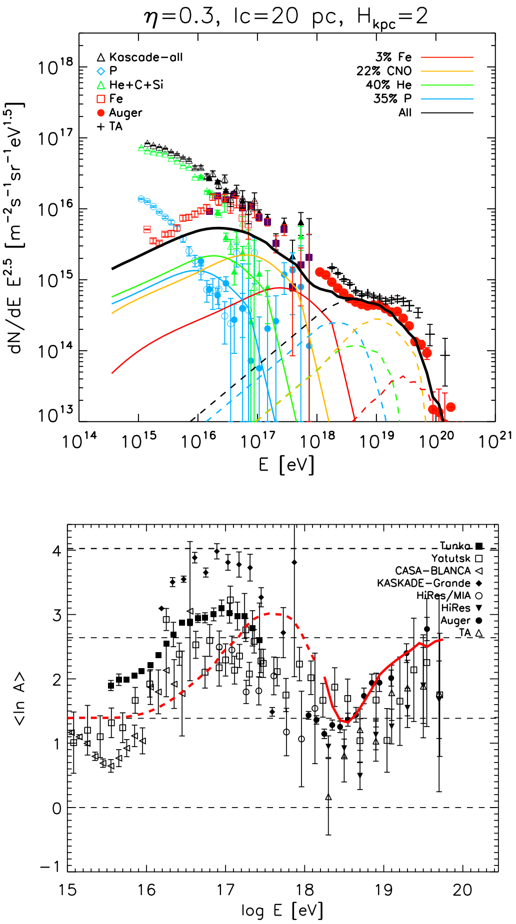

Figure 1: *Top:* Total (thick solid line) UHECR spectrum produced by a population Galactic (solid) and extragalactic (dashed) pulsars with parameter distribution following [23], and with emissivity assumed to be constant over time, embedded in core-collapse SNe of ejecta mass 10 $M_\odot$ and energy 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. *Bottom:* 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.

following the discovery of the first pulsar [28, 11, 12, 24, 10]. [18] proposed that iron nuclei accelerated in the fastest spinning young neutron stars could explain the observed cosmic rays above the ankle in a Galactic source scenario, building up on previous constraints by [43]. They assumed that the stripping of heavy nuclei from the surface of the star is a plausible seeding and derived a spectrum based on the spin down of young pulsars. [8] studied the birth of extragalactic magnetars (highly magnetized neutron stars) as the source of ultra-high energy protons, developing the acceleration mechanism in detail and assuming that the magnetar wind disrupts the supernova envelope to allow the escape of accelerated particles.

Most of the works conducted on this subject were made before the construction of the Auger Observatory. The [18] and [8] proposals for the origin of UHECRs were elaborated to explain the absence of the GZK cutoff in the observed spectrum reported by AGASA [40] without invoking the so-called top-down models (see, e.g., 15). An increase in the exposure at the ultra-high energies by the HiRes and Auger Observatories have shown that the UHECR spectrum is consistent with a GZK cutoff [2, 4]. Over the years, the pulsar model seemed to have been abandoned, likely because of one main feature: the unipolar induction process invoked by all these authors to accelerate particles in pulsars generates a hard spectrum that does not fit the observed UHECR spectrum. A detailed study of particle escape from the dense and radiative supernova ejecta surrounding the pulsar was also needed. The works cited above are essentially toy-models, that do not address detailed acceleration and escape issues. A decade ago, the chemical composition was also barely detectable at the highest energies while recent results suggest a puzzling trend toward heavier nuclei.

Here we show that the fast spinning pulsar birth model described in [18, 21] can explain the observed spectrum (both the Auger and the TA spectra) and the composition trend described in [5]. 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 [39], or Carbon, Oxygen and Neon [25, 26]. At higher altitude, in the X-ray photosphere, one could find lighter ions [44, 37] 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 $\sigma_{\log B} \sim 0.55$ [23].