Nuclear Instruments and Methods in Physics Research A 742 (2014) 237–240

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Anisotropy in cosmic rays from internal transitions in neutron stars

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ARTICLE INFO

Available online 11 November 2013

Keywords:
Cosmic ray
Nuclearite
Neutron star
Quark star
Dark matter

ABSTRACT

We discuss the possibility that some recently measured anisotropic cosmic ray components in the TeV–PeV energy range may be an indication of the ejection of a peculiar type of matter. We present a model where a neutron star internal transition with nuclear deconfinement of the quark content takes place. This catastrophic event may cause a mass ejection process seeding the insterstelar medium with droplets of quark matter, so called nuclearites. Neutralization of these droplets in molecular clouds may drive the anisotropy since quasi-rectilinear trajectories are allowed. Complementary information from current experimental settings on earth or magnetic spectrometers on the ISS may shed light on this exotic form of matter.

1. Introduction

Galactic cosmic rays (CRs) have an energy spectrum showing characteristic features [1]. In particular their astroparticle nature (electrical charge, mass or the ratio of them) has been pointed out as one of the key issues when trying to understand the sources where they may originate [2] and the emission processes itself. Additionally, this nature must determine, in turn, the mechanisms and feasibility to be accelerated to the high energies reported $E \sim 10^{20}$ eV. In this line there are some puzzling experimental measurements that are not yet fully understood. For example, several experiments have reported strong anisotropy measurements in the arrival direction distributions of Galactic CRs in the TeV to PeV energy range (Super-Kamiokande, Tibet III, Milagro, ARGO-YBJ, and IceCube [3,4]). The data reveal the presence of large scale anisotropies of amplitude $\sim 0.1\%$. Smaller scale anisotropies of size $\sim 10^\circ$–30° are also detected with amplitude a factor of a few lower. Milagro has reported the detection at significance $>12\sigma$ of two *hotspots* (regions with enhanced CR intensity) with amplitude $\approx 10^{-4}$, at a median energy of 1 TeV. ARGO-YBJ report similar excesses. IceCube observes localized regions of angular scale $\sim 15^\circ$ of excess and deficit in CR flux with significance $\sim 5\sigma$ around a median energy of 20 TeV [4].

The large scale anisotropy could be naturally explained by the diffusive transport of CRs within the Galactic magnetic fields [5,6]. Due to the charged nature of CRs at energies in TeV–PeV range their propagation is described by a gyroradius (Larmor radius) given by

$$r_L \approx \frac{E}{ZeB} \sim 1.08\ \mathrm{pc}\ Z^{-1}\left(\frac{E}{1\ \mathrm{PeV}}\right)\left(\frac{B}{1\ \mu\mathrm{G}}\right)^{-1}, \tag{1}$$

where Z is the charge of the particle in units of the electron charge e and the magnetic field strength of the Galaxy is assumed to be $B = 1\ \mu$G (see Ref. [7] for a review). For particles with $r_L \ll l_c$, where $l_c = 10-100$ pc is the coherence length of the Galactic magnetic field (e.g., Ref. [7]), the propagation will be totally diffusive over a distance $> l_c$. A number of previous works [6] have attempted to explain these phenomena invoking several mechanisms, however the situation remains largely uncertain.

In this contribution based in Ref. [8] we develop the possibility that the measured hotspots in the skymap are a manifestation of the peculiar nature of CRs. We propose that quark matter lumps, so-called *strangelets* or *nuclearites*, could be produced in the mass ejection process taking place in the nuclear deconfinement transition of a regular neutron star (NS) to a quark star (QS). This possibility has been proposed long ago [9,10] and revisited in later works [11,12]. Recently, new ideas concerning the triggering due to presence of a internal energy release from a dark matter component in a sort of *Trojan horse mechanism* have been considered [13,14]. Additional sources for these droplets may arise from high-density environments of merger events [15,16].

These slightly positively charged lumps of quark matter may suffer a diffusive trajectory and if molecular clouds (MCs) are near the sources this may drive the anisotropy. Possible processes in the cloud include electron capture, decay or even spallation [17]. In this way, for example, a change in the droplet incident state of charge, as a consequence of the interaction with the MC may neutralize the lump or it could decay with some fragments likely to be neutralized in the cloud.

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http://dx.doi.org/10.1016/j.nima.2013.11.007

2. Strangelets

These lumps would be formed after the metastable *ud* matter decays by weak interaction, $u+d \rightarrow u+s$, to form more stable *uds* matter [9,10]. They are expected to be highly bound $m_A \lesssim A m_N$. Typical values of strangelet binding energy are currently uncertain but supposed to be $E/A \sim \text{MeV}-\text{GeV}$ energies. Either on earth (accelerators) or on the ISS (with the AMS-02 spectrometer) direct searches are being conducted to experimentally detect this (so far) elusive type of astroparticles.

The lowest energy state in a strangelet is not subject to the constraint of being neutral, and therefore it is energetically allowed to have stable $Z/A > 0$, $Z/A \ll 1$ massive strangelets [18], where A is the baryonic number. There is, however, a constraint on the minimum value of $A \sim 10-600$ [19]. Several models of strangelets exist that lead to various Z/A dependencies. For example, for ordinary strangelets, $Z \sim A^{1/3}$, while for CFL (color-flavour-locked) strangelets $Z \simeq 0.3 A^{2/3}$ [18]. Even smaller charge-to-mass ratios are allowed $Z/A \sim 10^{-7}/10^{-2}$. Regarding charge, experiments such as CREAM and AMS-02 will have the ability to perform a direct measurement, and infer estimates of Z/A [20] with the RICH instrument.

If strangelets were responsible for the observed hotspots, they should produce detectable air-showers. There is a general belief that these should manifest as slowly moving droplets providing an enhanced photon production as they cross the water based telescopes [21]. In turn, this is possible if the kinetic energy per nucleon content, K_N, satisfies $K_N = K_{\text{tot}}/A > 1$ GeV. Measurements indicate a total kinetic energy of particles in hotspots, $K_{\text{tot}} \sim E \sim \text{TeV}-\text{PeV}$, which implies $A \lesssim 10^2 - 10^4$.

Fig. 1 represents the droplet Larmor radius as a function of the baryonic number A for strangelets with $Z/A \sim 10^{-6}$ and kinetic energy contours $K = 10^{12}, 10^{13}, 10^{14}, 10^{15}$ eV. Typically a diffusive behavior is expected, since it is required that $Z > 1$. If, instead, charge could be fractionary then quasi-rectilinear regimes would be possible.

3. Astroparticle sources

Neutron stars have been suggested as possible sources of injection of strangelets [22]. Strangelets could be produced for instance in the course of a NS to QS transition [23]. In such events, a fraction f_{ej} of the gravitational energy released can be injected into the expelled outer crust, leading to total kinetic energies $E_{\text{ej}} \sim 4 \times 10^{50} (f_{\text{ej}}/10^{-3})$ erg for standard NS mass and radius. The Lorentz factor Γ of the ejected mass can be of order

$$\Gamma \sim 22 \left(\frac{f_{\text{ej}}}{10^{-3}}\right) \left(\frac{12\ \text{km}}{R_*}\right) \left(\frac{M_*}{1.5 M_\odot}\right)^2 \left(\frac{10^{-5} M_\odot}{M_{\text{ej}}}\right), \tag{2}$$

for NS mass M_*, radius R_*, and ejected mass M_{ej} [24]. Particles of mass number A could then gain energies of order $K_{\text{acc}} \sim 21 (A/10^3)(\Gamma/22)$ TeV, the typical energy observed in hot-spots. It has been shown [24] that typical ejection fractions depend on the characteristics of the transition and, in particular, this may generate a multi-wavelength signal to help discriminate this catastrophic astrophysical event. A short hard $E_\gamma \gtrsim 100$ keV spike in gamma rays is predicted to appear.

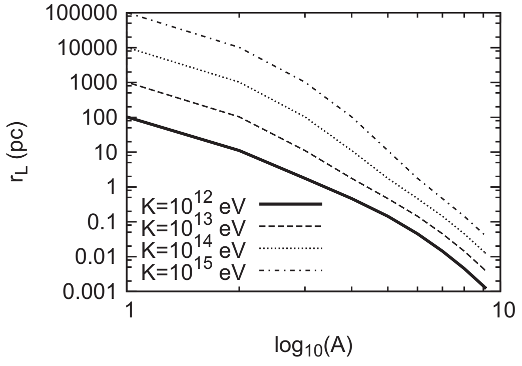

Fig. 1. Larmor radius as a function of A for strangelets with $Z/A \sim 10^{-6}$ and energies in the ~TeV–PeV range.

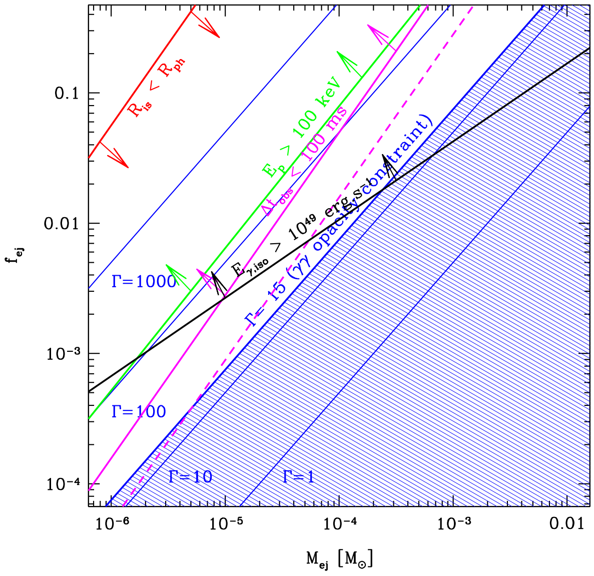

Fig. 2. Efficiency of the energy injection in the crust f_{ej} in a NS transition versus ejected outer crust M_{ej} from [24]. See text for details. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

In Fig. 2 we plot the efficiency of the energy injection in the crust f_{ej} in a NS transition versus ejected outer crust M_{ej} as appears in Ref. [24]. Lines of constant Lorentz factor Γ are plotted in blue for $\Gamma = 1$ (non-relativistic limit), 10, 15, 100 and 1000.

The limit $\Gamma \simeq 15$ obtained from the compactness argument limits the forbidden shaded region where a gamma ray burst emission is not visible from kinematical constraints. Time and peak energy, isotropic equivalent gamma-ray energy observability limits are shown in magenta, green and black respectively. Astrophysical radii constraints are depicted in red.

Accelerated strangelets may experience energy losses by interacting with the radiation field close to the NS, and with the baryonic and radiative backgrounds of the supernova (SN) envelope. Ref. [25] concluded that there is room for the escape of accelerated particles. Besides, if the ejection happens when there are no SN envelope (since the NS may have traveled far after the initial birth) in a transition of a NS to a QS then ejection may be more efficient.

4. Interaction in the MC and induced anisotropies

Charged strangelets will have a diffusive trajectory due to the magnetized interstellar medium (ISM). Typical timescales are

$$\Delta t = \frac{d_s^2}{2D} \sim 6 \times 10^5\, Z^{1/3} \left(\frac{d_s}{1\ \text{kpc}}\right)^2 \left(\frac{E}{20\ \text{TeV}}\right)^{-1/3} \text{yr}, \tag{3}$$

where d_s is the rectilinear distance to the source and the diffusion coefficient is $D(E) = 1.33 \times 10^{28} H_{\text{kpc}} [E/(3Z\ \text{GeV})]^{1/3}\ \text{cm}^2\ \text{s}^{-1}$, with $H_{\text{kpc}} \equiv H/(1\ \text{kpc})$ the height of the Galactic halo [26]. The ionization and the spallation timescales in the ISM (of average density $n_{\text{ISM}} = 0.5\ \text{cm}^{-3}$) read respectively $\tau_{\text{ion}} \sim 7 \times 10^{12}\, Z^{-2} (E/20\ \text{TeV})$ yr, and $\tau_{\text{spall}} \sim 4 \times 10^5 (A/10^3)^{-2/3} (n_{\text{ISM}}/0.5\ \text{cm}^{-3})^{-1}$ yr [18],