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Pulsar scintillation patterns and strangelets

M. Ángeles Pérez-García [a,*], Joseph Silk [b,c,d], Ue-Li Pen [e]

[a] Department of Fundamental Physics and IUFFyM, University of Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain
[b] Institut d'Astrophysique, UMR 7095, CNRS, Université Pierre et Marie Curie, 98bis Blvd Arago, 75014 Paris, France
[c] Department of Physics and Astronomy, Johns Hopkins University, Homewood Campus, Baltimore MD 21218, USA
[d] Beecroft Institute of Particle Astrophysics and Cosmology, Department of Physics, University of Oxford, Oxford OX1 3RH, UK
[e] Canadian Institute for Theoretical Astrophysics, University of Toronto, 0N M5S 3H8, Canada

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ABSTRACT

We propose that interstellar extreme scattering events, usually observed as pulsar scintillations, may be caused by a coherent agent rather than the usually assumed turbulence of H_2 clouds. We find that the penetration of a flux of ionizing, positively charged strangelets or quark nuggets into a dense interstellar hydrogen cloud may produce ionization trails. Depending on the specific nature and energy of the incoming droplets, diffusive propagation or even capture in the cloud are possible. As a result, enhanced electron densities may form and constitute a lens-like scattering screen for radio pulsars and possibly for quasars.

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A variety of scintillation phenomena observed from pulsars and quasars require interstellar scattering screens that contain compact regions of high electron density. These include quasar Extreme Scattering Events (ESE) [1,2], pulsar parabolic arcs [3,4] and Galactic Center scattering of OH maser sources [5,6]. Many of these phenomena, in particular the ESEs, require enhanced electron density regions of A.U. size ($\sim 1.5 \times 10^{13}$ cm). The overpressure $P/k_B \approx 10^6$–10^8 $\mathrm{K\,cm^{-3}}$, as estimated from typical temperatures $T \sim 10^4$ K and particle densities $n \sim 10^2$–10^4 $\mathrm{cm^{-3}}$, is difficult to explain in any conventional scattering screens embedded in dense molecular H_2 clouds. The only plausible environment where such pressures might be attained would be in the dense cloud cores (cf. the compact ionized cloud model developed by Walker [7,8]). The required source properties in this latter model require a significant mass in extremely dense cold gas clumps to source the ionized gas. The stability of such cold clumps is questionable, although exotic models have been proposed [9].

There is some direct evidence that the ionized clouds are highly elongated [10]. It is an already well-known fact that plasma lenses result from electron (over-) under-densities. Electron over-densities result in a faster phase velocity, corresponding to a concave (divergent) optical lens, while under-densities are associated with a convergent lens [11]. Quantitative lens models for the ESEs [7] estimate electron column densities $N_e \sim 10^{15}$ $\mathrm{cm^{-2}}$.

Here we are interested in estimating the effect of the enhancement of the electron column density on A.U. scales as a result of the formation of ionized trails in H_2 (molecular) and HI (atomic) hydrogen clouds caused by an external agent. We propose a mechanism that provides an alternative to postulating the existence of controversial clumps of dense molecular hydrogen, and naturally generates pervasive ionized trails in dense interstellar cloud cores. Our model invokes strangelets [12] (also known as *nuclearites*), finite droplets of quark matter with non-zero strangeness fraction and slightly charged. They are currently being searched for on earth [13] as final products in heavy ion collisions, with the ALICE experiment at the LHC, in the CDMSII, under the form of light ionizing particles, or in the AMS-02 mission. It is expected that these quark droplets can be naturally generated by a series of different astrophysical events where a nucleon-quark deconfinement transition may take place, e.g. neutron star (NS) collisions, NS or black hole combined binary mergers or in NS to quark star (QS) conversions. This latter process may be induced by internal heating due to dark matter annihilations [14] (under the assumption of a Majorana particle candidate) and even leave observable traces in the pulsar distribution [15] or in the emission of very short gamma ray bursts (GRBs) with typical time scales $T_{90} \lesssim 0.1$ s [16] detectable with modern projected missions [17]. Due to the large gravitational and nuclear binding energies released in the transitioning process, a mass ejection episode is expected, possibly seeding the interstellar medium with a fraction of strangeness-carrying lumps of matter formed during the phase of nucleon deconfinement. Energetics show that the measured short GRBs isotropic equivalent photon emission value $E_{\gamma\,iso} \sim 10^{48}$–$10^{52}$ erg is compatible with relativistic mass ejecta $M_{\rm ej} \lesssim 10^{-4} M_\odot$ able to consistently produce

* Corresponding author.
E-mail addresses: mperezga@usal.es (M.Á. Pérez-García), silk@iap.fr (J. Silk), pen@cita.utoronto.ca (U.-L. Pen).

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observable gamma rays. It has been actually proposed that quark matter droplets might partially populate cosmic ray (CR) primaries (see e.g. [18–20]).

In this context, let us consider a cloud containing a mixture of H_2 and HI. Typical ionization reactions are of the form, $X + H_2 \to X + H_2^+ + e^-$, or $X + HI \to X + H^+ + e^-$, where X is the incoming charged strangelet. In addition, electron capture by the positively charged strangelet could be, in principle, possible [21]. The energy needed to ionize a hydrogen atom (molecule), initially in the ground state is I(HI) = 13.6 eV ($I(H_2) = 15.6$ eV). In astrophysical CGS units a more practical conversion factor 1 eV = 1.62×10^{-12} erg is used. The dimensions of the molecular cloud (MC) vary but the denser regions with $n \sim 10^{4\text{–}5}$ cm^{-3} are typically less than ~ 1 pc. Assuming for the cloud core $R_C \sim 0.1$ pc $\sim 3 \times 10^{17}$ cm, then the core volume is $V_C \approx 4\pi R_C^3/3 \simeq 1.1 \times 10^{53}$ cm^3. Taking in the cloud core $n_0 \sim 10^4$ cm^{-3}, the number of particle species (HI, protons, electrons) is accordingly given by $n_0 V_C \simeq 1.1 \times 10^{57}$. In addition, non-vanishing magnetic fields are expected in the MC and can be parametrized [22] as $B \sim 100(\frac{n}{10^4\ \text{cm}^{-3}})^{1/2}$ μG. In general, other ionizing agents, such as CRs can cause ionization of H_2 or HI with a rate $\xi^{HI} \sim 10^{-15}$ s^{-1} [23] or $\xi^{H_2} \sim 10^{-17}$ s^{-1} [24]. A more exotic flux of potentially ionizing electrically charged strangelets through the cloud will depend, on the one hand, on the time and spatial distribution of their astrophysical sources (besides a possible primordial background) and, on the other hand, on their peculiar nature.

We will consider a simplified model with emission of lumps of baryonic number A and mass $m_A \lesssim A m_N$, where m_N is the nucleon mass. The detailed mass formula can be obtained from existing calculations [21]. The strangelet number production rate in the astrophysical ith-process will be given by $dN_{A,i}/dt = \eta_i \dot{M}_{ej,i}/m_A$. $\dot{M}_{ej,i}$ is the mass rate and η_i is the efficiency of strangelet ejection for the ith-process involved, respectively. For example, for NS collisions it is expected that $M_{ej} \sim (10^{-5}\text{–}10^{-2})M_\odot$ while in a NS merger the mass ejection is $M_{ej} \sim (5 \times 10^{-4}\text{–}7 \times 10^{-3})M_\odot$ for equal-mass binaries with total mass $m = 2.7 M_\odot$ [25]. In a NS to QS transition capable of emitting a GRB, it is expected that $M_{ej} \lesssim 10^{-4} M_\odot$. According to [16] the rate of these transitions is $R_{NS\text{–}QS} \simeq (8 \times 10^{-4}\text{–}3 \times 10^{-3}) R_{SNtII}$ being $R_{SNtII} \simeq 10^{-2}$ yr^{-1} the rate of type II supernovae in our galaxy.

Having enumerated the possible processes that may constitute a source of the strangelet flux, for the rest of this work for practical purposes we will consider a *generic source* where the deconfinement transition can take place with galactic appearance rate $R = \bar{R} \simeq 10^{-5}$ yr^{-1} and ejected mass $M_{ej} = \bar{M}_{ej} \simeq 10^{-5} M_\odot$. The ejected mass rate is then $\dot{M}_{ej} = R M_{ej} \simeq 10^{-10} M_\odot$ yr^{-1}. Since the efficiency of strangelet production depends on the so far unknown details of the engine model, we will consider that only a small fraction $\eta \sim 10^{-2}$ is ejected in an exotic form [16]. Nevertheless, strangelets should be emitted with A-values larger than a critical stability value [26], $A > A_{min} \simeq 10^1\text{–}10^2$ so that they can possibly decay to the lightest energetically stable A_{min}-species.

The peculiar nature of the quark droplets is highly uncertain but it is usually assumed that their charge is small and distributed positively on the surface [18]. For ordinary strangelets $Z \simeq A^{1/3}$ [27] while for CFL (color-flavor-locked) strangelets $Z \simeq 0.3 A^{2/3}$. Even smaller charge-to-mass ratios are energetically possible for intermediate masses, $A \sim 10^2\text{–}10^{18}$, assuming a strong coupling $\alpha_S = 0.9$ [28]. For example, for $A \simeq 10^9$, $Z/A \simeq 10^{-4}$ while larger strangelets $A \simeq 10^{18}$ have $Z/A \simeq 10^{-7}\text{–}10^{-3}$ and even $Z/A < 0$. In this work we constrain strangelets to have $Z \geqslant 1$.

To estimate the strangelet production number rate we are going to consider scintillation from a galactic emitting generic source located at a distance $d_{SO} \lesssim 10$ kpc from an observer. As an example, pulsar simulations yield a spatial distribution peaking about galactocentric radii ~ 5 kpc and vanishing beyond ~ 12 kpc [29]. We will also discuss the effect from a possibly nearby pulsating source [30,31] at $d_{SO} \sim 600$ pc. Then, the A-sized strangelet number galactic production rate at the generic source is given by

$$\frac{dN_A}{dt} = 2 \times 10^{45} \left(\frac{\eta}{0.01}\right)\left(\frac{\dot{M}_{ej}}{10^{-10} M_\odot\ \text{yr}^{-1}}\right)\frac{f_S(Z,\beta)}{A}\ \text{yr}^{-1}. \quad (1)$$

It is expected that a possible emission distribution function at the source $f_S(Z,\beta)$ can modulate this rate. We will not consider this refinement here, and in what follows we will assume $f_S(Z,\beta) \sim 1$.

Due to the fact that strangelets are electrically charged they will diffuse in the magnetized medium and the effective distance traveled over the rectilinear distance d_s, is obtained as $l(d_s) = d_s^2 c/(2D)$ in a corresponding diffusive time $t_{diff} \sim l(d_s)/c$. For the diffusion coefficient, D, in the galactic halo we take [32] $D(E) = 1.33 \times 10^{28} H_{kpc}[E/(3Z\ \text{GeV})]^{1/3}$ cm^2 s^{-1}, where $H_{kpc} \equiv H/(1\ \text{kpc})$ is its height. In the MC larger values of the magnetic field are assumed and following [33], we take $D_{MC}(E) \simeq 1.7 \times 10^{27}[E/(Z\ \text{GeV})]^{1/2}[B/10\ \mu\text{G}]^{-1/2}$ cm^2 s^{-1} with an averaged value over the MC of $B \sim 10$ μG.

Typically, the strangelet ejection energy at a transitioning source allows Lorentz factors bounded by a saturation value, $\gamma \lesssim \gamma_{sat}$ with $\gamma_{sat} \sim 20\text{–}1000$ [16]. Correspondingly, the kinetic energy is $T \sim (\gamma - 1)A$ GeV/c^2 so that we will assume $T \sim A T_0 \sim A$ TeV droplets with a moderate $A \gtrsim A_{min}$ and Z charge. In such scenario and in the universe lifetime, τ_u, $N_{\tau_u} \sim R\tau_u \sim 10^5$ sources could be expected at $d_{SO} \lesssim 10$ kpc. In that case the *unscreened* diffusive flux is $F \simeq F_0 N_{\tau_u}$ and

$$F_0 \simeq \frac{dN_A}{dt}\frac{1}{4\pi l(d_{SO})^2} \sim 2.3 \times 10^{-16} Z^{-2/3} A^{-1/3}\ \text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}. \quad (2)$$

We must note, however, that some sources may be closer than the assumed ~ 10 kpc. In the case that $d_{SO} \sim 600$ pc [30] then there are additional volume $\frac{V_{600\ pc}}{V_{10\ kpc}} \sim 2.1 \times 10^{-4}$ and distance $(\frac{l(10\ \text{kpc})}{l(600\ \text{pc})})^2 \sim 7.7 \times 10^4$ factors yielding an estimate one order of magnitude larger than previous value (we have roughly assumed an averaged source distribution in the halo).

As a comparison, for strangelets being currently searched in neutrino telescopes on earth, there is a lower limit $A \gtrsim 10^{13}$, our estimates yield in that case $F \sim 1.1 \times 10^{-15}$ cm^{-2} sr^{-1} s^{-1}. We will restrict to $Z = 1$, $A \sim 10^3$ droplets but larger A are allowed if they are less energetic remaining below observational CR bounds $\sim 10^{20}$ eV. If the source is nearby by chance there are presently competitive limits from experiments such as ANTARES [34], who report a testing capability flux $F_{ANTARES} \sim 2 \times 10^{-14}$ cm^{-2} sr^{-1} s^{-1} for $A \gtrsim 10^{13}$, or IceCube-22, who report $F_{IC22} \sim 10^{-18}$ cm^{-2} sr^{-1} s^{-1} for $A \gtrsim 10^{17}$ nuclearites [35]. It is however uncertain whether such large-A droplets can arrive on earth without suffering spallation or decay processes [20].

Once the nuclearites are produced it may happen that their diffusive trajectories intersect with a MC. These are accumulated in the midplane of the galactic disk although we suppose that may also be present at higher latitudes. If the Larmor radius is comparable to the typical coherence length of the galactic magnetic field, $r_L \lesssim l_c$, $l_c = 10\text{–}100$ pc [36], then a strangelet will suffer an accumulated deflection that can be estimated from the random walk approximation as,

$$\theta(T) \simeq 5.4^\circ \left(\frac{l_c}{100\ \text{pc}}\frac{d_{SC}}{10\ \text{kpc}}\right)^{1/2}\left(\frac{Z/A}{10^{-7}}\right)\left(\frac{B}{1\ \mu\text{G}}\right)\left(\frac{1\ \text{TeV}}{T}\right). \quad (3)$$

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