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UNIVERSALITY IN MAGNETOEMISSION OF COMPACT ASTROPHYSICAL OBJECTS

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ABSTRACT. Magnetodynamics of inhomogeneous crusty nuclear matter is considered accounting for quantum fluctuations and ferromagnetic coupling. We show that anomalies in nuclide magnetic moments give rise to erratic jumps in magnetotransport of neutron star crusts. Universal properties of such a noise are favorably compared with statistical and temporal features of Soft Gamma Repeating bursts.

Keywords: Soft gamma repeaters. – neutron stars: magnetic field.

1. Introduction

The pioneering evidence for ultramagnetized astrophysical objects (“magnetars”) is associated with the discovery Mazets et.al (1979) of March 5, 1979 event from SGR 0526-66. The magnetar concept (e.g., Kondratyev, 2002; Svinkin et al., 2015) and refs. therein) is strongly corroborated by further observations of soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). The observed SGR properties indicate (Kondratyev, 2002; Svinkin et al., 2015) significant higher multipole magnetic fields being substantially larger than the corresponding dipole component $B_{\mathrm{dip}} \sim 10^{15}$ G. Assuming a noticeable contribution of magnetic pressure in a balance of crust forces in neutron star (NS) we write

$$\mathrm{dB_n}^2/\mathrm{d}R \sim 8\pi\ \mathrm{GM}\ n(R)/R^2\ , \qquad (1)$$

where the gravitational constant G, and the star mass M(R) within radius R is related to the matter density $n(R)$ as $4\pi R^2\ n(R) = \mathrm{dM}/\mathrm{d}R$. Substituting this relation into Eq. (1) and integrating over NS crust area, we obtain for the field strength $\mathrm{B}{\sim}10^{1.5}$TeraTesla $(\mathrm{M}/\mathrm{M_o})(10\mathrm{km}/\mathrm{R})^2$,with the solar mass $\mathrm{M_o}$. Thus field torroidal components can reach tens teratesla (TT) that is consistent with estimates (Kondratyev, 2014) based on the supernova explosion energy. Such fields (ie, in excess of 0.1 TT) can affect the structure and properties of atomic nuclei (see. (Kondratyev, 2002; 2014) and refs. therein), In this contribution the randomly jumping interacting moments (RJIM) model (Kondratyev, 2002) is further extended for an analysis of SGR burts.

2. Modeling NS Crust Magnetodynamics

The RJIM model for magnetodynamics simulations in NS crust has already been described in(Kondratyev 2002) and refs. therein. We briefly remind that in simulations of demagnetization dynamics we use a very general form for magnetic moments m of atomic nuclei $m = \mu \sum_n v_n \theta(b - b_n) = Ig$ with the nucleon magneton μ, spin I and nuclear g-factor g, as well as step function $\theta(x)$ depending on a local magnetic field b. Atomic nuclei occupied a volume V_{D} contribute to the magnetization $P = m / V_D$. Taking $g = 3$ for nuclear component of magnetic induction we get

$$P = 1.5\ \mathrm{TG}\ In\ /(10^{13}\ \mathrm{g/cm^3}), \qquad (2)$$

In a case of comparable sizes for nucleus and occupied volume V_{D} (i.e., $n \sim 10^{13,5}$ g/cm^3) internuclear interaction is ferromagnetic (Kondratyev&Lutz, 1999; Kondratyev, 2002). Taking for magnetic coupling strength between nearest-neighbor (nn) elements the value J total Hamiltonian H for atomic nuclei array in a field H can be expressed as follows:

$$\mathrm{H} = -\sum_i m_i b_i \qquad (3)$$

through an interaction of magnetic moment m_i with a local field $b_i = H(t) + J\sum_{j \subset nn} P_j + h_i$. Here the sum runs over *nn* elements and random fields h_i with Gaussian distribution with a width R, called the disorder (Kondratyev, 1994; 2002), which allow to take into account the inhomogeneity, disorder and fluctuations.

3. RJIM model Implications in SGR-Burst Activity

Let us consider adiabatically changing in time crust magnetic field H. When the local field value b_i of a certain NS crust domain becomes less than certain value b_i magnetization is changing stepwise. Due to the ferromagnetic interaction moment hopping may be triggered for the nearest neighbors, which in turn may cause some discontinuity point for their neighbors, and so forth, producing, thereby, avalanches. The linear speed c_{m} of the avalanche propagation is determined by the ratio of a lattice constant a ~20 fm and the relaxation time $t_{\mathrm{N}} \sim 10^{220.5}$ s for nuclear

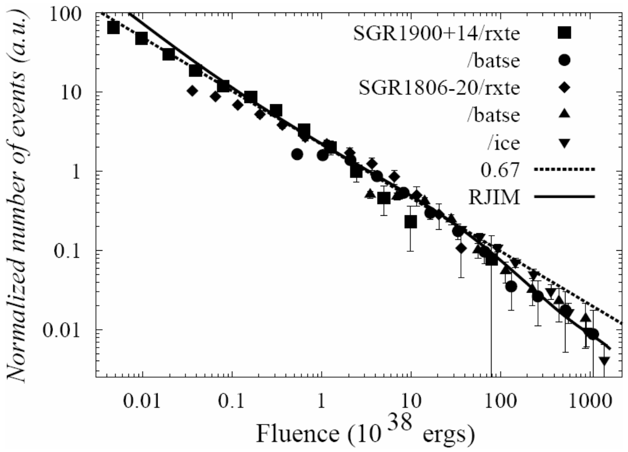

Figure 1: Normalized cumulative energy distributions of SGR-bursts are compared with the results of RJIM for the cubic lattice of a size $(150)^3$ represented by the solid line. The data of the RXTE and BATSE observations for SGR 1900+14 from (Gogus et al., 1999) are shown by squares and circles, respectively. RXTE (diamonds), BATSE (up-triangles), and ICE (down-triangles) data for SGR 1806-20 are from (Gogus et al., 2000). The dashed line denotes the power law distribution.

re-configuration associated with magnetic response, $c_m \sim a/t_N \sim 10^8$ cm/s (for more details see [3]). Then for outer crusts of a linear size, $l_{crust} \sim 100$ m, an estimate of the avalanche spanning time, $t_{av} \sim l_{crust} / c_m \sim 0.1$ ms, is consistent with the rising time for giant flares of SGR (Mazets et.al 1979, Kondratyev 2002, Svinkin et.al 2015). The field $H(t)$ remains almost constant on the time scale t_{av}, while the magnetization reduces sharply on a value proportional to the avalanche size. The corresponding excess of magnetic energy is released in the magnetosphere and estimated as

$$E = H\,\Delta P\,V_a = 10^{41}\ \text{Ergs}\ (H/\text{TT})\,(\Delta I\,n/\,10^{13}\ \text{g/cm}^3)\,(V_a/10^6\ \text{m}^3). \tag{4}$$

For a field strength $H \sim 3$TT, typical magnitar crust density $n \sim 10^{13,5}$ g/cm^3, and avalanche linear size of order of outer NS crust thickness, 100 m (i.e., V_a about 10^6 m^3) the amount of energy obtained from Eq. (3) is consistent with an energy of soft gamma-ray bursts.

Since the velocity of magnetoplasma waves (i.e., Alfvén waves) is close to the speed of light c, the linear size of the strongly excited magnetosphere region exceeds the value $R_{ex} \sim l_{crust}\, c/c_m \sim 10$ km, comparable to NS radius. Subsequent development and cooling of photon-electron-positron plasma via gamma-ray emission from this region generates a short-duration (~ 100 ms) SGR-burst event with rising and decaying fronts of light curve ~ 10 ms (Kondratyev 2002). Figure 1 represents the cumulative distributions of detected burst energy, i.e. the burst number with an energy exceeding certain value. We assume nearly isotropic emission accountimg for a source remoteness. The RJIM results are in a good agreement with observations for 7 periods of energy. The obtained event number dependence is well fitted by the power law with an exponent 0.67, which corresponds to the value 1.67 for the differential distribution and provides a signal of self-organized criticality in the burst statistics.

For a constant change rate $\dot{B}$ of the magnetic field the inter-avalanche field interval is proportional to the time interval (i.e. waiting time) between the induced bursts.

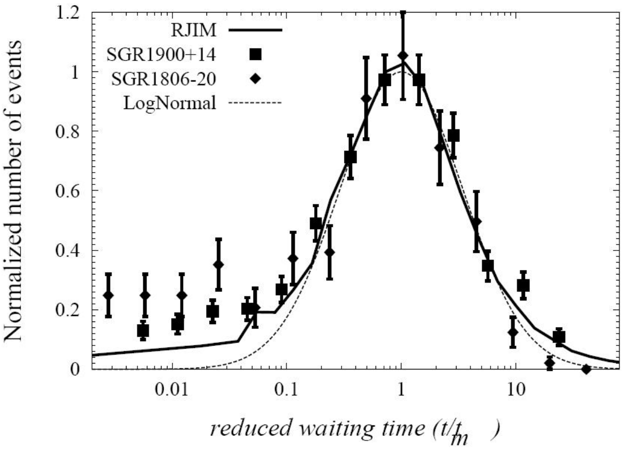

Figure 2: The reduced waiting time distribution between the successive RXTE/PCA bursts from SGR 1900+14 (squares) (Gogus et al., 1999) and SGR 1806-20 (diamonds) (Gogus et al., 2000) are compared with the waiting time distribution between avalanches (solid curve). The dashed line represents the fit to the lognormal distribution of the width 3.6.

Taking the respective normalized values, i.e. inter-burst time and inter-avalanche field, we compare the theoretical predictions with observations in Fig. 2. As seen in Fig. 2 for different SGRs the waiting time distributions as a function of the reduced time obey universal function. The data are well reproduced by simulations and fitted at a maximum by the lognormal function. Such a property points out the single time scale for SGR-burst triggering processes. Within RJIM model such a time-scale is determined by the ratio of the disorder parameter R and the field change rate $\tau = R / \dot{B}$. Therefore, the scaling with respective time leads to an universal function.

4. Conclusion

We considered magnetodynamics of inhomogeneous nuclear matter relevant for neutron star crusts. Accounting for inter-nuclide magnetic coupling, we show that quantum fluctuations in nuclear magnetic reactivity give rise to erratic jumps in magnetotransport of neutron star crusts. The resulting sharp energy releases lead to gamma-ray bursts. The properties of such a noise are favorably compared with burst statistics of Soft Gamma Repeaters. As is shown the predicted by RJIM model scaling properties for, e.g., the burst intensity and waiting time distributions, are in a good agreement with SGR observations supporting thereby the credibility of RJIM model.

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