RELATIVISTIC ACCELERATION OF MONOPOLES IN NEUTRON STARS

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ABSTRACT

Monopole catalysis of nucleon decay inside neutron stars when combined with x-ray observations of radio pulsars, enables stringent bounds to be placed on the galactic monopole flux. However these bounds, occur only under certain conditions involving the neutron star magnetic field and the monopole mass. To a weaker extent it is also dependent on the neutron star's mass and radius. These conditions are usually not clarified. It turns out that for a magnetic field of $\sim 10^{12}$ gauss, the bounds on the monopole flux from neutron stars apply only for monopoles with energy $> 10^{15}$ GeV, or in the case of the millisecond pulsar for $E > 10^{11}$ GeV. Otherwise no catalysis occurs and the monopoles are relativistically accelerated away from the star. And even for monopoles of larger masses, whether they are trapped inside the neutron star, depends sensitively on the internal structure of the star, especially if it has a superconductivity core with the magnetic field permeating innumerable flux tubes. For pion superconductivity the London penetration length is very small, and the energy per unit length of the flux tube $> 10^{12}$ GeV/cm. Monopole energy losses due to collisions with electrons are an order of magnitude smaller, so that the net energy gain at the surface could be as high as $\sim 10^{15}$ GeV (relativistic) and the magnetic field will accelerate it out of the star on time scales too short for significant catalysis to take place.

1. INTRODUCTION

The existence of magnetic monopoles is an inevitable feature of a large class of grand unified theories of the fundamental forces of nature, apart from their existence providing a natural explanation for charge quantization. In many of these models, the monopole is very massive, with mass $\sim 10^{16}$ GeV, whereas in some other models it could be a few orders lower. Several attempts have been made to detect monopoles. In a superconducting detector the method of detection is based on the change in the macroscopic quantum state of a superconducting ring when a magnetic charge passes through it. This method is independent of the monopole mass, velocity, etc. For instance with a three loop detector continuously operated for 150 days no candidate events were seen[1] and this enables an upper limit of $\sim 3\times10^{-11}$ cm^{-2} S^{-1} Sr^{-1} to be put on cosmic ray monopoles of any mass and velocity passing through the Earth's surface, whereas the limit based on the existense of galactic magnetic fields[2] gives $F_M < 10^{-16}$ cm^{-2} S^{-1} Sr^{-1}, For the monopole flux. Much more stringent limits have been placed on the basis of another remarkable property of monopoles arising in GUT theories, i.e. their ability to catalyse proton or nucleon decay at rates comparable to those of strong interactions. In the presence of a monopole the cross-section for nucleon decay may be as large as a typical strong interaction C.S., i.e. $\sigma_{\Delta B} \simeq 10^{-27}$ cm^{-2} $\sim$ ~ 1 mb (mb is millibarn, ΔB denobes change in baryon no. in the monopole (M) induced proton decay, i.e. $P.M \rightarrow e^+ \pi^\circ M$). This prediction based on a study of the peculiar properties of the S-wave system of a fermion with a SU (2) monopole has been recently shown to also hold for SU (5) monopoles (also for Z (N)) where the effect is due to the anomaly is baryon number current due to the monopole's static magnetic field and the estimate of the C.S. for[3] catalysed p decay is $\sigma \approx (2\times10^{-3}/\beta)$ mb which again gives $\sim$ 1 mb and when these cross-sections are combined with the IMB data they imply a flux $F_M < 10^{-14}$ in the velocity range $10^{-4} < \beta < 10^{-2}$. As each nucleon decay releases about a nucleon rest mass energy $m_N c^2$ in the form of gamma photons, muons etc.[4] this large C.S. is of great astrophysical interest luminosity decay can be written as: $L_M \approx m_N c^2 n_N \sigma_{\Delta B} V \approx 1.6\times10^{-3}\, n_N\, \sigma/(1\,cm^2)\, V$ erg s^{-1} per monopole , where n_N is the nucleon number density and V_2 is the relative velocity. The C.S. can be parametrized as $\sigma \sim 10^{-27} \Lambda\, GeV^{-2}\, cm^{-2}$. It is assumed that the nucleon decay catalysis is a statistically independent process and thus a calculate the luminosity we have to multiply L_M by the total no. of monopoles present in the object (i.e. the number captured since its formation, given by $N = (2/3\,\pi)\, F_M \cdot A T_s$, where A and T_s are the area and age of the star respectively. The above formulae when applied to planetary objects such as Jupiter or Saturn and compared with the observed total luminosity from spacecraft measurements gave an F_M two orders less than the Parker limit. Again the observed heat flow from objects such as the Moon, (after allowing for radio-activity) enables the limit to be lowered further. Of course the most stringent limits arise from nucleon decay catalysis inside neutron stars (including the precursor main sequence star) with consequent emission of Kev x rays which after comparison with x ray space observations apparently imply $F_M < 10^{-26}\, cm^{-2}\, s^{-1}\, sr^{-1}$.

2. INTERACTIONS OF MONOPOLES WITH NEUTRON STARS

When the above considerations were applied to a neutron star the point made was that monopoles hitting the star (with $\beta \approx 0.1$) would (Unlike the case of objects with normal density) be stopped in the surface layers itself and the energy released by the catalyzed nucleon decays would emerge in the form of KeV x rays. However this is not true for all ranges of monopole masses or neutron star magnetic fields. For instance at the surface of the neutron star (of mass M_{NS} and radius R_{NS}) the ratio of the gravitational force (f_G) to the magnetic force (f_B) acting on a monopole of charge g_{mo} and mass M_{mo} is $f_G/f_B = \frac{G M_{NS} M_{mo}}{\Phi_{NS} g_{mo}}$ where Φ_{NS} is the total magnetic flux contained in the neutron star; $\Phi_{NS} = B.R_{NS} \cdot R_{NS}$. If flux is conserved during stellar collapse and as stellar masses do not range over the large values, this ratio is remarkably constant for all stellar objects. Thus $f_G \sim 10\ (M_{mo})$ N; $f_B \sim 1 B$ N where N is newtons and M_{mo} is in units of $10^{16}\, GeV/c^2$ and B in units of 10^{12} Gauss SO for typical NS magnetic fields, if the monopole mass is less than 10^{15} GeV; the magnetic repulsion force acting on it can be greater even at the surface and it can accelerated away from the star rather than be deposited inside and catalyze nucleon decay. For the millisecond pulsars with much lower B ($\sim 10^8$ G), this acceleration would apply only for $M_{mo} < 10^{11}$ GeV. So it turns out that the much quoted stringent neutron star, x-ray, monopole limits do not apply if monopole masses are less than 10^{15} GeV. Monopoles of smaller masses are relativistically accelerated away from the star and no catalysis occurs. For white dwarfs the corresponding B values are $\sim$ 10G and 10^5 G for the two monopole masses. Heavier monopoles can be trapped but here again their motion inside neutron star depends crucially on the interior structure of the star. Suppose the core is a type II superconductor, (The London penetration length is given by $\delta^2 = m_p/n_p e^2 \sim 5\times10^{-12}$ cm and the coherence length $\eta \sim \hbar^2 K_F/m_p \Delta$, Δ is energy gap, K_F fermi wave number, $\eta \sim 10^{-12}$ cm). Thus the magnetic field will permeate the region through a number of flux tubes(quantized vortices each carrying a flux quantum $\phi = hc/2e = 2\times10^{-7}$ G cm), the neutron star totally having $\sim R_{NS}^2\ (B/\phi) \simeq 10^{31}\ (B/10^{12} G) \sim$

flux tubes. The magnetic field in a vortex is $B_0 \sim \phi/\xi^2 \sim 5\times10^{15}$ G, giving $f_g/f_B \sim 10^{-3}$, (even for a 10^{16} GeV monopole) inside a flux tube; so that the monopole cannot enter any of these innumerable magnetic vortices permeating the interior of the neutron star. Only for a $\sim 10^{19}$ GeV monopole would the gravitational force be as large as the magnetic force in a flux tube, so that only such monopoles may penetrate inside! The proton superfludity with finite ξ is established when density $\rho > 3\times10^{14}$ gcm.$^{-3}$

3. MONOPOLE MOTION INSIDE THE NEUTRON STAR

If d is the distance separating the normal - superconductor boundary then from the equilibrium relation $\rho g d \sim B_0^2$, we have $d \sim \phi^2/8\pi^3 g \rho \xi^4 \sim 10^{-2}$ cm for sudden transition and the time required for the monopole to diffuse out of the star is ~ 10 years too small for effective catalysis, the bound being now barely more stringent than the Parker bound. At a few times nuclear density the neutron and proton chemical potential difference may become $\sim$ effective pion mass, so that pions would Bose condense to form a new superfluid which could fill substantial portion of the neutron star core. For the pion superconductor the flux quantum is 2ϕ and the penetration length δ, which is the reciprocal of the effective photon mass, is much smaller $\sim 10^{-13}$cm No. of quantized vortex lines (from $\nabla \times \langle v \rangle \simeq 2\Omega \simeq 2\Omega$) and $\oint v\, d\ell = \hbar/2m_n$) is $\sim 4\Omega m_p/\hbar \sim 10^5$ cm.$^{-2}$ The energy per unit length of vortex in the pion superconductor is $\sim (\phi/\delta)^2 \log(\delta/\eta) \sim 10^{12}$ GeV/cm. The monopole energy loss due to collisions with electrons is $\sim 10^{11}$ GeV/cm, i.e. at least an order of magnitude smaller, so that the net energy gain from the flux tube when the monopole emerges out is $\sim 10^{18}$ GeV (i.e. for $R_{NS} \sim 10^6$ cm.) which would make it $\sim 10^2$ $M_{mo}c^2$ even for 10^{16} GeV monopoles; which would imply a relativistic motion. Thus the magnetic field will accelerate even monopoles in this mass range out of the star on time scales too short for significant catalysis of nucleon decay inside the star to take place with subsequent emission of γ rays.

References

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