HIGH ENERGY COSMIC RAY SIGNATURE OF QUARK NUGGETS

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It has been recently proposed (Witten, 1984) that dark matter in the Universe might consist of nuggets of quarks which could populate the "nuclear desert" between nucleons and neutron star matter. Witten further suggested that the "Centauro" events which could be the signature of particles with atomic mass A~100 and energy $E \sim 10^{15}$ eV (Bjorken and McLerran, 1979) might also be related to debris produced in the encounter of two neutron stars. In this paper, we examine a further consequence of Witten's proposal and show that the production of relativistic quark nuggets is accompanied by a substantial flux of potentially observable high energy neutrinos.

Witten (1984) noted that quark matter can exist in the form of droplets of finite size, "quark nuggets", and be more stable than nuclear matter, or at least metastable. If the hypothesis that quark matter is more stable than nuclear matter is correct, then the end-point of the evolution of a massive star will consist of core collapse following exhaustion of nuclear fuel and formation of a ~1 Mo quark star. When quark stars are disrupted by collisions or by tidal interactions, as would happen in the vicinity of a massive black hole, one might expect to find prolific production of quark nuggets. Even if the quark phase is only metastable then passage of a shock through a neutron star involved in a collision should also trigger formation of quark nuggets.

A plausible astrophysical scenario for the production of quark nuggets may readily be constructed. Strong evidence exists that there is a black hole of ~ 3 10^6 Mo at the center of our galaxy devouring matter at a rapid rate (Lo et al., 1985). This black hole most likely formed, as did other supermassive black holes in the nuclei of active galaxies and in quasars, by stellar collisions in dense galactic cores. Studies of the evolution of such cores suggest that dynamical relaxation occurs within a few 10^9 years to form exceedingly compact nuclei of stars surrounded by more diffuse halos. Within these nuclei, stars collide with one another. Collisions between ordinary stars will trigger the formation of neutron stars and one ends up with a compact central cluster of neutron stars. This cluster continues to evolve dynamically until the neutron stars collide and the debris aggregate to form a central black hole. This process is greatly accelerated by gravitational radiation towards the final stages (Shapiro and Teukolsky, 1985).

Once the massive black hole forms, neutron stars in eccentric orbits will occasionaly plunge within the Roche limit and be tidally disrupted. Occasional collisions will also occur, guaranteeing a continuing supply of fuel for the central black hole.

All of this falls within the more or less conventional scenarios for the evolution of a massive or supermassive black hole in the nucleus of a galaxy. According to computations of neutron star collisions (Gilden and Shapiro, 1984) approximately 30% of the neutron star mass may be heated and disrupted. In the case of collisions between two quark stars, we anticipate that the typical fragment size will have baryon number $A = 10^2$-10^3 or larger. We shall proceed on the hypothesis that the baryon number of surviving quark nuggets is of this order. In the case of tidal disruption, we expect a similar outcome.

We note first that the binding energy of quark matter is ~100 MeV per unit baryon number. Hence a shock in excess of this energy should suffice to cause disruption. This is precisely the energy that one would expect for shocks induced within a few gravitational radii of the central black hole. Post-shock heating will cause the temperature to exceed 100 MeV, and there will be prolific emission of $\nu\bar{\nu}$ pairs. We expect that the neutrino emission will amount to $E_\nu \sim 10^{53}$ erg per quark star disruption and that the spectrum of neutrino produced will peak near 100 MeV.

Now let us consider the fate of the quark nuggets, we shall assume that quark stars have many properties in common with pulsars, in particular a magnetic field $B_{12} = B/10^{12}$ g ~ 1, radius R_6 (in 10^6 cm units)~1 and a rotation period p (in sec)~1. Newly formed quark stars should have millisecond periods but quark stars that survive for more than a few 10^6 years before disruption will have a longer period.

We shall use the model of Goldreich and Julian (1969) to estimate the electrostatic acceleration of quark nuggets as they are disrupted from the rapidly spinning magnetic quark stars. In this simple model which assumes that the magnetic dipole moment is aligned with the rotation axis, charged particles escape along magnetic field lines that extend outside the light cylinder where they are electrostatically accelerated up to energies of $3\ 10^{12}\ Z\ R_6^2\ B_{12}/p^2$ eV. The typical charge of a quark nugget is $Z \approx 5\ A^{1/3}$ (Farhi and Jaffe, 1984) and we infer that the typical energy to which quark nuggets can be accelerated is $\varepsilon = 10^5\ A_{100}^{1/3}\ p^{-2}$ GeV .

How many of these relativistic nuggets would one expect ? Let us assume that we can tap the entire rotation energy $E_R \sim 10^{47}$ p^{-2} erg of the quark stars. Then we expect that $N \sim 10^{42}$ $A_{100}^{-1/3}$ relativistic quark nuggets of energy ε will be produced per quark star disruption. Note that this only amounts to a small fraction of ($\sim 10^{-11}$) of the quark star mass. Hence the acceleration process should be complete and the rotational energy reservoir depleted long before final disruption of the quark star occurs. A similar estimate could also apply to acceleration of Fe nuclei if they could survive neutron star disruption.

If the putative 3 10^6 M⊙ black hole at the galactic center formed over the past 10^9 years, it must have grown on the average by 1 M⊙ per 300 years. Let us suppose that it grew by quark star swallowing, involving either collisions or tidal disruption. The Larmor radius of a quark nugget exceeds that of a proton of the same energy by a factor 0.2 $A^{2/3} \sim 5$ $A_{100}^{2/3}$. Hence its Larmor radius will not exceed a few pc and we infer that relativistic quark nuggets will be well coupled to the galactic magnetic field. Hence they will accumulate throughout the cosmic ray confinement region usually taken to be the galactic halo, over a typical containment time of $\sim 10^8$ years. Assuming N nuggets per solar mass captured are emitted and retained in the galaxy for $\sim 10^8$ years we estimate the mean flux of relativistic quark nuggets of energy ε to be $\sim 10^{-10}$ $(N/10^{42})$ cm^{-2} sec^{-1} . We also predict a flux of 100 MeV neutrinos amounting to ~ 10 cm^{-2} sec^{-1}.

The observed anomalous high energy cosmic rays events (Jones, 1984) correspond to a flux of $\sim 10^{-9}$ cm^{-2} s^{-1} at an energy per event of $\sim 10^6$ GeV which agrees rather well with our estimates. Our calculated 100 MeV neutrino flux is also close to the cosmic flux of energetic neutrinos (>100 MeV)~ 11 cm^{-2} s^{-1} obtained from the 17 events/kiloton/year reported by the Kamiokande experimenters (Totusa, 1984) to be in excess of the atmospheric background events. Conservatively, we should regard this experiment as setting an upper limit on the background flux of 100 MeV neutrinos. Therefore the black hole in the center of our galaxy may generate both the Centauro events, interpreted as relativistic quark nuggets, and the high energy neutrino background flux that is consistent with current observations in proton-decay detectors.

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