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Jetted GRBs, afterglows and SGRs from quark stars birth

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1. Introduction

Recent studies suggest that when cold nuclear matter is compressed to high nuclear densities, diquarks with spin zero and antisymmetric color wave function Bose-condensate into a superfluid/superconducting state that is several times as dense (e.g., Rapp et al. 1998; Wilczek 1998). Various astrophysical phenomena may be explained by gravitational collapse of neutron stars (NSs) to (di)quark stars (QSs) as a result of a first order phase transition in NSs within $\sim 10^4$ years after their birth in supernova explosions, when they cooled and spun down sufficiently (by magnetic braking?). The gravitational energy release drives an explosion which may eject both highly relativistic narrowly collimated jets and a mildly relativistic "spherical" shell. The jets can produce the observed gamma ray bursts (GRBs) and their afterglows in distant galaxies when they happen to point in our direction. The spherical ejecta produces additional supernova like afterglow. The slow contraction/cooling of the remnant QSs can power soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs), without invoking a huge magnetic energy storage. The jets distort the original supernova remnant (SNR), sweep up ambient matter along their trajectories, accelerate it to cosmic ray (CR) energies and disperse it in hot spots which they form when they stop in the galactic halo. Such events in our Galaxy may be the main source of Galactic cosmic rays at all energies (Dar & Plaga 1999).

2. Soft gamma ray repeaters

SGRs are slowly rotating ($P \sim 5 - 8$ s) pulsars that produce multiple bursts of soft γ-rays, often at super-Eddington luminosities (see, e.g., Hurley, Kouveliotou, these proceedings). Four of these objects have been discovered. The inferred ages and velocities of SGRs and AXPs suggest that their characteristic spin-down ages are not their true ages. For instance, the period, $P = 5.16$ s, and the period derivative, $\dot{P} = 1.1\ 10^{-10}$, of SGR 1900+14 (Hurley et al. 1998c and references therein) yield a characteristic age $\tau = P/2\dot{P} \approx 750$ y, much younger than the age of its nearby supernova remnant (SNR) G42.8+0.6. Moreover, if the characteristic age of SGR 1900+14 represents its true age and if it was born at the center of the SNR, it must have moved with perpendicular velocity $v_\perp \sim 40000\ (D/5.7$ kpc) km s^{-1} to its present location (Hurley et al. 1998a,b). A similar "age/separation crisis" seems to exist for other SGRs. I propose that the characteristic age of SGR is the age of the (di)quark star (QS) born by a first order phase transition in a neutron star (NS) that has cooled and spun down sufficiently. Its typical velocity is that of ordinary pulsars, $v \sim 500$ km s^{-1}, much larger than the typical velocities, (~ 100 km s^{-1}), of young pulsars produced in SNe, such as the Crab pulsar (Caraveo & Mignani 1999) and the Vela pulsar (Nasuti et al. 1997), and of all millisecond pulsars (Toscano et al. 1998). Because of their large natal velocities, SGRs are not expected to be found in binaries. The quiescent thermal X-ray emission from the cooling QSs (SGRs and AXPs) may be used to verify that their radii are significantly smaller than those of millisecond pulsars. After cooling by X-ray and wind emission, the QSs become the slowly rotating normal radio pulsars.

3. Jetted GRBs from NS collapse

Relativistic jets seem to be emitted when mass is accreted at a high rate onto black holes and neutron stars. They have been resolved by VLA radio observations (Rodriguez & Mirabel 1998) into highly magnetized clouds of plasma (plasmoids) that are emitted in injection episodes which are correlated with sudden removal of the accretion disk material. After initial expansion these plasmoids seem to retain a constant radius ($R_{\rm p} \sim 2\ 10^{15}$ cm) until they slow down and spread. Their formation is not well understood yet. But, it seems very likely that highly relativistic jets are also ejected in NS collapse because the accretion rates and the magnetic fields in NS collapse are much larger. If momentum imbalance in the ejection of two opposite relativistic jets is responsible for the large mean velocity ($V_{\rm NS} \approx 450 \pm 90$ km s^{-1}; Lyne & Lorimer 1994) of slowly spinning pulsars (presumably QSs), then momentum conservation implies that the kinetic energy of the jets satisfies

$$E_{\rm jet} \geq cP_{\rm NS} \sim cM_{\rm NS}V_{\rm NS} \sim 4\ 10^{51}\ {\rm erg}. \tag{1}$$

Thus, the total jet energy may be $E_{\rm jet} \sim 10^{52}$ erg. Such highly relativistic jets/plasmoids are strong emitters of beamed γ-rays through synchrotron emission, inverse Compton scattering and resonance scattering of interstellar light. When they point in our direction in external galaxies, they produce the observed GRBs and their afterglows (e.g. Shaviv & Dar 1995; Dar 1998a). If the true rate of GRBs is comparable to the birth rate of NSs, $\dot N_{\rm NS} \simeq 2\ 10^{-2}$ y^{-1} in galaxies like our own (van den Bergh & Tamman 1991), then the inferred rate of observable GRBs in galaxies like our own, $\dot N_{\rm GRB} \sim 10^{-8}$ y^{-1} (Wijers et al. 1997), implies that the GRBs must be narrowly beamed into a solid angle

$$\Delta\Omega \simeq 2\pi \dot N_{\rm GRB}/\dot N_{\rm NS} \simeq \pi\ 10^{-6}. \tag{2}$$

Emission from narrow jets with bulk motion Lorentz factor $\Gamma = 10^3$ is beamed into $\Delta\Omega \sim \pi/\Gamma^2 \simeq \pi\ 10^{-6}$. Such strong beaming implies that we observe only a very small fraction of the events that produce GRBs.

If the highly relativistic plasmoid consists of a pure e$^+$e$^-$ plasma, then inverse Compton scattering of stellar light ($h\nu = \epsilon_{\rm ev} \times 1$ eV) by the plasmoid can explain the observed typical γ energy ($\epsilon_\gamma \sim 4\Gamma_3^2\epsilon_{\rm eV}/3(1+z)$ MeV), GRB duration ($T \sim R_{\rm SFR}/2c\Gamma^2 \sim 50$ s), pulse duration ($t_{\rm p} \sim R_{\rm p}/2c\Gamma^2 \sim 150$ ms), fluence ($F_\gamma \sim 10^{-5}$ erg cm^{-2}), light curve and spectral evolution of GRBs (Shaviv & Dar 1995; Shaviv 1996; Dar 1998). For instance,

$$F_\gamma \simeq \frac{\sigma_{\rm T} N \epsilon_\gamma}{\Gamma m_{\rm e} c^2}\frac{E_{\rm jet}(1+z)}{D^2\Delta\Omega} \simeq \frac{10^{-5} z_2 N_{22}\Gamma_3\epsilon_{\rm ev}E_{52}}{D_{29}^2}\frac{\rm erg}{\rm cm^2} \tag{3}$$

where $D = D_{29}\ 10^{29}$ cm is the luminosity distance of the GRB at redshift z, $z_2 = (1+z)/2$, $N = N_{22}\ 10^{22}$ cm^{-2} is the column density of photons along the jet trajectory in the star burst region, $\sigma_{\rm T} = 0.65\, 10^{-24}$ cm^2 is the Thomson cross section, $E_{\rm jet} = E_{52}\ 10^{52}$ erg and $\Gamma = \Gamma_3\ 10^3$.

If the plasmoid consists of normal NS crustal material, then photoabsorption of stellar light by partially ionized iron and its reemission as γ rays yield $\epsilon_\gamma \sim \Gamma\epsilon_{\rm x}/(1+z) \sim$ MeV in the observer frame (Shaviv 1996) and

$$F_\gamma \simeq \frac{\sigma_{\rm a} N \epsilon_\gamma}{\Gamma M_{\rm Fe} c^2}\frac{E_{\rm jet}(1+z)}{D^2\Delta\Omega} \simeq \frac{10^{-5} z_2 \sigma_{19} N_{22}\bar\epsilon_{\rm x}\Gamma_3 E_{52}}{D_{29}^2}\frac{\rm erg}{\rm cm^2} \tag{4}$$

where $\sigma_{\rm a} = \sigma_{19}\ 10^{-19}$ cm^2 is the mean photoabsorption cross section of X-rays by partially ionized iron.

4. GRB afterglows

In the plasmoid rest frame, the synchrotron emission from the decelerating plasmoid/jet can be modeled (e.g., Chiang & Dermer 1998) by convolving the typical electron energy spectrum (E^{-p} at low energies up to some "break energy" where it steepens to E^{-p-1} and cuts off exponentially at some higher energy due to synchrotron losses in magnetic acceleration) with the synchrotron Green's function (see, e.g., Meisenheimer et al. 1989). In the observer frame the beamed afterglow has a temporal and spectral behavior which can be interpolated by

$$I_\nu \sim \nu^{-\alpha}(t/t_0)^{-\beta}/[1+(t/t_0)^{\beta'-\beta}] \tag{5}$$

where t_0 is the time when the jet begins to spread, $\alpha \approx (p-1)/2$, $\beta \approx (p+5)/6$ and $\beta' \approx p$. For magnetic Fermi acceleration $p = 2.5 \pm 0.5$ and (Dar 1998a,b) $\alpha = 0.75 \pm 0.25$, $\beta = 1.25 \pm 0.08$, and $\beta' \approx 2.5 \pm 0.5$. The mildly relativistic spherical ejecta from the NS collapse produces additional unbeamed supernova-like afterglow, like that of GRB 980425/SN1998bw (many planetary nebulae and some SNRs appear to eject antiparallel jets from a spherical explosion). It is observable only if the jet is dim enough. A power-law afterglow + SN 1998bw like light curve better explains GRB afterglows like that of GRB 970228. Moreover, the glows of microquasar plasmoids and radio quasar jets after ejection and of blazar jets after flaring show behavior similar to that observed in GRBs afterglows. For instance, the glows of the ejected plasmoids from GRS 1915+105 on April 16, 1994 near the source had $\alpha = 0.8 \pm 0.1$ and $\beta = 1.3 \pm 0.2$ (Rodriguez & Mirabel 1998) identical to those observed for SS 433 (Hjellming & Johnston 1988) and for the inner regions of jets of some radio galaxies (e.g., Bridle & Perley 1984). When jets/plasmoids are attenuated and spread they decline with $\beta' \sim 2.4 \pm 0.3$ (Rodriguez & Mirabel 1998). Such a fast decline has been observed in the late afterglow of some GRBs.

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