HIGH ENERGY COSMIC RAYS, GAMMA RAYS AND NEUTRINOS FROM JETTED GRBs

ARNON DAR
Theory Division, CERN, CH-1211 Geneva 23, Switzerland
and
Department of Physics and Space Research Institute
Israel Institute of Technology, Haifa 32000, Israel

ABSTRACT

Recent observations suggest that gamma ray bursts (GRBs) and their afterglows are produced in star formation regions in distant galaxies by highly relativistic jets that happen to point in our direction. Relativistic beaming collimates the emission from the highly relativistic jets into small solid angles along the jet direction. It implies that we are seeing only a small fraction of the events that produce GRBs. The observed GRB rate then requires an event rate which is comparable to the birth rate of neutron stars (NS). The highly relativistic jets 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. With an event rate comparable to the NS birth rate, such events in our Galaxy may be the main source of Galactic cosmic rays at all energies. Internal interactions and/or external interactions of these jets with high column density matter and/or radiation at their production sites or along their trajectories can produce high energy gamma rays and neutrinos that are highly beamed along the jet direction. Jetted GRBs, like blazars, may be much more fluent in high energy gamma rays and neutrinos than in MeV gamma rays. But, TeV gamma rays from large cosmological distances are unobservable because of their attenuation by electron-positron pair creation on the intergalactic infrared background radiation. However, high energy neutrinos from distant GRBs may be observed with large surface/volume telescopes which are under construction. TeV gamma rays and high energy neutrinos may also be detected from relatively nearby GRBs by the existing moderate size detectors, but with a much smaller rate.

1. The Energy Crisis Of Spherical GRBs

Thanks to the precise and prompt localization by the Italian-Dutch satellite, BeppoSAX (see, e.g., Costa et al. 1997), long lived GRB afterglows spanning the wavelength range from X-ray to radio have now been detected in more than a dozen GRBs. They led to the redshift measurements, z=0.69, 0.835, 3.42, 1.096, 0.966, 1.61, 1.62 of GRBs 970228 (Kulkarni et al. 1999) 970508 (Metzger et al. 1997), 971214 (Kulkarni et al 1998), 980329, 980613 (Djorgovski et al 1999), 980703 (Djorgovski et al. 1998), 990123 (Anderson et al. 1999; Kulkarni et al. 1999), 990510 (Vreeswijk et al. 1999), respectively, from absorption lines in their optical afterglows and/or emission lines from their host galaxies. In addition, strong suppression has been observed with the Hubble Space Telescope in the spectrum of the host galaxies of GRBs 970228 and 980329 at wavelengths below 700 nm. If it is due to absorption in the Lyα forest

(Fruchter 1999), then their redshifts are near z$\sim$ 5. These measured/estimated redshifts indicate that most GRBs take place at very large cosmological distances. For instance, assuming a zero cosmological constant ($\Omega_\Lambda = 0$), the luminosity distance with

$$D_L = \frac{c}{H}\frac{2[2-\Omega_M(1-z)-(2-\Omega_M)\sqrt{1+\Omega_M z}]}{\Omega_M^2}, \quad (1)$$

the present canonical values for the cosmological parameters, H = 65 km cm^{-1}Mpc^{-1} and $\Omega_M = 0.2$ (which will be assumed in this paper), yield $D_L \sim 5 \times 10^{28}$ cm for z=2. The typical observed GRB fluence ($F_\gamma \sim 10^{-5}$ erg cm^{-2}) and their large distances imply enormous energy release in gamma rays,

$$E_\gamma = \frac{4\pi D_L^2 F_\gamma}{(1+z)} \sim 10^{53} \text{ erg}, \quad (2)$$

if their energy release is isotropic as used to be assumed/advocated by the standard fireball models of GRBs and GRB afterglows (e.g., Piran 1999 and references therein). In particular, the large fluence $F_\gamma \approx 5.1 \times 10^{-4}$ erg cm^{-2} (Kippen et al. 1999) and redshift z=1.61 of GRB 990123 yield $E_\gamma \approx 3.4 \times 10^{54}$ erg. Such enormous energy release in gamma rays alone, implies an "energy crisis" for spherical GRBs (Dar 1998): The short duration and the very large energy release in GRBs indicate that they are powered by gravitational collapse of compact stars. But, the energy release in such events fall short of that required to power GRBs like 971214, 980329 and 990123, 990510 if they were isotropic. Furthermore, all the known luminous sources of gamma rays (quasars, radio galaxies, active galactic nuclei, accreting binaries, pulsars, supernova explosions, supernova remnants) exhibit rather a modest efficiency, $\eta < 10^{-4}$, in converting gravitational, kinetic or thermonuclear energy into gamma rays. If GRBs have a similar efficiency for converting the energy release from their central engine to gamma rays, then the energy crisis is common to most GRBs.

2. Jetted GRBs

2.1. No Energy Crisis For Jetted GRBs

Various authors have pointed out that the energy crisis in isotropically emitting GRBs is avoided if GRBs are beamed into a small solid angle, $\Delta\Omega \ll 4\pi$ such that their total energy release in gamma rays is

$$E_\gamma = \frac{\Delta\Omega D_L^2 F_\gamma}{(1+z)}. \quad (3)$$

Beaming of gamma rays from GRBs is possible if the highly relativistic ejecta (Lorentz factor $\Gamma = 1/\sqrt{1-\beta^2} \gg 1$) that produces the GRB is beamed into a cone (conical

beaming) of solid angle $\Delta\Omega \ll 4\pi$, or if the ejecta is jetted - namely, if after initial expansion the ejected cloud/plasmoid maintains nearly a constant cross section. Conical beaming (e.g., Mochkovich 1993; Rhoads 1997) can solve the " energy crisis" of GRBs by reducing their inferred energies by the ratio $\Delta\Omega/4\pi \ll 1$. But, it suffers from other deficiencies of isotropically emitting GRBs (Dar 1998). Jetting the ejecta (e.g., Shaviv and Dar 1995, Dar 1998) solves the energy crisis and can also explain the short time variability of GRB light curves, the versatility of their afterglows, the absence of a simple scaling between them and their sudden decline in some GRBs (970508, 990123, 990510):

The emission from a highly relativistic plasmoid which is isotropic in its rest frame and has a power-law spectral shape, $F_{\nu'} = A\nu'^{-\alpha}$, is collimated in the lab frame to small emission angles $\theta \sim 1/\Gamma$ relative to its direction of motion, according to

$$F_\nu = \frac{2^{2+\alpha}\Gamma^{3+\alpha}}{(1+\Gamma^2\theta^2)^3} F_{\nu'=\nu(1+\Gamma^2\theta^2)/2\Gamma} \quad . \tag{4}$$

Thus, the observed flux from a plasmoid with a typical spectral index $\alpha \sim 0.7$ that moves with a Lorentz factor $\Gamma \sim 10^3$ at an angle $\theta < 1/\Gamma$ relative to the line of sight is amplified by approximately $\Gamma^{3+\alpha} \sim 10^{11}$. This amplification within a solid angle $\Delta\Omega \sim \pi/\Gamma^2$ can explain why highly relativistic jets with bulk motion Lorentz factors $\Gamma \sim 10^3$, total kinetic energy $E_k \sim 10^{52}$ erg, and conversion efficiency $\eta > 10^{-4}$ into gamma rays can produce GRBs with equivalent isotropic energy of $E_\gamma = \eta E_k 4\pi/\Delta\Omega > 4 \times 10^{54}$ erg, as observed for GRB 990123 (Kippen et al. 1999).

2.2. The Beaming Angle Of GRBs

The enormous release of energy in GRBs during a short time suggests that they are energized by collapse of compact stars (Blinnikov 1984, Paczynski 1986) due to mass accretion (Goodman, Dar and Nussinov 1987; Dar et al. 1992) or phase transition (e.g., Dar 1999a) If GRBs are produced, e.g., by gravitational collapse of neutron stars (NS) to quark stars (e.g., Dar 1999a; Dar and De Rújula 1999) when they cooled and spun down sufficiently, then the GRB rate is comparable to the NS birth-rate. The NS birth-rate is estimated to be $R_{NS} \sim 0.02$ y^{-1} in Milky Way like galaxies (van den Bergh and Tamman 1991). From the observed rate of GRBs, $R_{GRB}[UNIV] \sim 10^3$ y^{-1} in the whole Universe, it was estimated that the rate of observable GRBs in Milky Way like galaxies is $R_{GRB}[MW] \sim 10^{-8}$ y^{-1} (e.g., Wijers et al. 1997). The beaming angle of GRBs therefore must satisfy

$$R_{GRB}[MW] \approx 2(\Delta\Omega/4\pi)R_{NS}[MW] \tag{5}$$

where we assumed that two opposite jets are ejected in every NS collapse. Hence, $\Delta\Omega \simeq \pi/\Gamma^2 \sim \pi \times 10^{-6}$ which implies that their bulk motion Lorentz factor is $\Gamma \sim 10^3$. Such values have been inferred also from the absence of a break due to $\gamma\gamma \to e^+e^-$

in GRB spectra (e.g., Baring and Harding 1997), from the peak energy of GRBs and from GRB duration and substructure (e.g., Shaviv and Dar 1995). Such strong beaming implies that we observe only a very small fraction, $\sim 10^{-6}$, of the events that produce GRBs. I will call these events cosmological GRBs (CGRBs) if they occur in distant galaxies and "Galactic" GRBs (GGRBs) if they occur in our Milky Way (MW) galaxy.

2.3. The Jet Energy

Consider gravitational collapse that leads to the birth of a pulsar (e.g., gravitational collapse of NS to QS due to a phase transition of cold and highly compressed neutron matter to Bose condensate of diquark pairs (Dar 1999a, Dar and De Rújula 1999) or the birth of a pulsar in a supernova explosion (Cen 1999) and perhaps to the ejection of two opposite highly relativistic jets. If momentum imbalance in the ejection of the relativistic jets (and not asymmetric neutrino emission) is responsible for the observed large mean velocity (Lyne and Lorimer 1994), $v \approx 450 \pm 90$ km s^{-1}, of slowly spinning pulsars, then momentum conservation implies that the difference in the kinetic energy of the jets satisfies

$$\Delta E_{jet} \geq cP_{ns} \sim vM_{NS}c \sim 4 \times 10^{51} \text{ erg}, \tag{6}$$

where we used the typical observed mass of NSs, $M_{NS} \approx 1.4 M_\odot$. If $\Delta E_{jet} \ll E_{jet}$ the kinetic energy of the jets must be $E_{jet} \sim 10^{52}$ erg or larger. If $\Gamma \approx 10^3$ then the ejected jet (plasmoid) has a mass $M_{jet} \sim 1.5 \times 10^{-6} M_{NS} \sim 2.1 \times 10^{-6} M_\odot \sim 0.7 M_{Earth}$. Even if only a fraction $\eta \sim 10^{-4}$ of the jet kinetic energy is radiated in γ-rays, the inferred "isotropic" γ-ray emission in GRBs is $E_{isot} \simeq 4\eta\Gamma^2 E_{jet} \sim 4 \times 10^{54}$ erg, while the true γ-ray emission is only $E_\gamma \sim 10^{48}$ erg.

2.4. Jet Formation

The ejection of highly relativistic jets from accreting or collapsing compact stellar objects is not well understood. Therefore their properties must be inferred directly from observations and/or general considerations: Relativistic jets seem to be emitted by all astrophysical systems where mass is accreted at a high rate from a disk onto a central compact object. Highly relativistic jets were observed in galactic superluminal sources, such as the microquasars GRS 1915+105 (Mirabel and Rodriguez 1994; Mirabel and Rodriguez 1999) and GRO J165-40 (Tingay et al. 1995) where mass is accreted onto a stellar black hole (BH), and in many active galactic nuclei (AGN), where mass is accreted onto a supermassive BH. Mildly relativistic jets from mass accretion are seen both in AGN and in star binaries containing NS such as SS433 (e.g., Hjellming and Johnston 1988). High-resolution radio observation resolved the narrowly collimated relativistic jets of microquasars into blobs of plasma (plasmoids)

that are emitted in injection episodes which are correlated with sudden removal of the accretion disk material (Rodriguez and Mirabel 1998). After initial expansion, these plasmoids seem to reach a constant radius of $R_p \sim 10^{-3} pc$. The emission of Doppler shifted Hydrogen Lyα and Iron Kα lines from the relativistic jets of SS433 suggest that the jets are made predominantly of normal hadronic plasma. Moreover, simultaneous VLA radio observations and X-ray observations of the microquasar GRS 1915+105 indicate that the jet ejection episodes are correlated with sudden removal of accretion disk material into the relativistic jets (Mirabel and Rodriguez 1999). Highly relativistic jets, probably, are also ejected in the birth or collapse of NSs due to mass accretion or phase transition. But, because the accretion rates and magnetic fields involved are much larger compared with those in quasars and microquasars, the bulk motion Lorentz factors of these jets may be much higher, perhaps, $\Gamma \sim 10^3$ as implied by the above consideration and GRB observations. When these highly relativistic jets happen to point in our direction they produce the observed cosmological GRBs and their afterglows. They look like the Galactic micro copies of blazer ejections and therefore will be called "microblazers". In fact, when the light curves and energy spectra of blazar flares and of microquasar plasmoids are scaled according to the Lorentz factors expected for GRB ejecta, they look quite similar to GRBs (Dar 1999b).

The high collimation of relativistic jets over huge distances (up to tens of pc in microquasars and up to hundreds of kpc in AGN), the confinement of their highly relativistic particles, their emitted radiations and observed polarizations, all indicate that the jets are highly magnetized, probably with a strong helical magnetic field along their axis. Magnetic fields as strong as a few tens mili Gauss in the jet rest frame have been inferred from microquasar observations (Mirabel and Rodriguez 1999), while hundreds Gauss were inferred for GRB ejecta (assuming equipartition of energy between internal kinetic and magnetic energy). The UV light and the X-rays from the jets ionize the ISM in front of them. The jet material and the swept-up ionized ISM material in front of the jet can be accelerated by the Fermi mechanism to a power-law energy distribution that extends to very high energies, as inferred from the observed radiations from jets. The interactions of these high energy particles in the jet and/or their interactions with the external medium, produce the GRBs and their afterglows:

2.5. Jet Production of Gamma Rays

The GRB jets may consist of pure e^+e^- plasmoids or of normal hadronic gas/plasma clouds. The GRB can be produced by electron synchrotron emission. If the jet consist of a single plasmoid, then individual γ-ray pulses that combine to form the GRB light curve can be produced by internal instabilities or by interaction with inhomogeneous external medium. If the jets consist of multiple ejections of plasmoids, then

the GRB pulses may be produced when later ejected plasmoids collide with earlier ejected plasmoids that have slowed down by sweeping up the interstellar medium in front of them. But, such scenarios do not seem to provide a simple explanation why the GRB emission is peaked at $\sim$ MeV photon energies. Other GRB emission mechanisms, however, can provide such an explanation:

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

$$F_\gamma \simeq \frac{\sigma_T N \epsilon_\gamma}{\Gamma m_e c^2} \frac{E_{jet}(1+z)}{D^2 \Delta\Omega} \simeq \frac{10^{-5} z_2 N_{22} \Gamma_3 \epsilon_{ev} E_{52}}{D_{29}^2} \frac{erg}{cm^2} \tag{7}$$

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

If the plasmoid consists of normal crust material of neutron stars, (Doppler-shifted K_α iron line was detected from the jets of SS433), than photoabsorption of stellar light by partially ionized iron (Doppler-shifted to X-rays in the jet rest frame) and its reemission as γ rays (iron X-rays lines in the jet rest frame) yield ($\epsilon_\gamma \sim \Gamma\epsilon_x/(1+z) \sim$ MeV) in the observer frame and

$$F_\gamma \simeq \frac{\sigma_a N \epsilon_\gamma}{\Gamma M_{Fe} c^2} \frac{E_{jet}(1+z)}{D^2 \Delta\Omega} \simeq \frac{10^{-5} z_2 \sigma_{19} N_{22} \bar{\epsilon}_x \Gamma_3 E_{52}}{D_{29}^2} \frac{erg}{cm^2} \tag{8}$$

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

3. GRB Afterglows

The afterglows of GRBs may be synchrotron emission from the decelerating plasmoids (e.g., Chiang and Dermer 1997), and then they are highly beamed and may exhibit superluminal velocities ($c < v_\perp \leq \Gamma c$) during and right after the GRB. The deceleration of a mildly relativistic spherical ejecta from NS collapse to QS may also produce spherical supernova like light curve (many planetary nebulae, e.g., NGC 7009, NGC 6826, and some SNRs (including, perhaps, SNR 1987A) show antiparallel jets superimposed on a spherical explosion). When transformed to the rest frame of the decelerating plasmoid, the synchrotron spectra can be modeled 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 it yields spectral intensity (Dar 1998)

$$I_\nu \sim \nu^\alpha t^\beta \sim \nu^{-0.75\pm0.25} t^{-1.25\pm0.08}, \quad (9)$$

where $\alpha = -(p-1)/2$ and $\beta = -(p+5)/6$ and where I assumed $p = 2.5 \pm 0.5$ for Magnetic Fermi acceleration. This prediction is in agreement with observations of GRB afterglows. Moreover, the glows of microquasar plasmoids and radio quasar jets after ejection and of blazar jets after flares show the same universal behavior as 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 and 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 the jets begin to spread, the spectral index of their power-law time decline changes to $\beta' = 2.6 \pm 0.4$ (e.g., Mirabel and Rodriguez 1999). Thus, their over all time decline can be described approximately by $F \sim t^{-\beta}/[1 + (t/t_0)^{\beta'-\beta}]$ where t_0 is the time when the jets begins to spread. Indeed, such a behavior has been observed also in the afterglows of some GRBs (e.g., GRB 990510; Vreeswijk et al 1999).

4. Galactic GRBs - The Main Source of Cosmic Rays?

According to the current paradigm of cosmic rays (CRs) origin, CR nuclei with energies below $3 \cdot 10^{15}$ eV (the "knee") are accelerated in Galactic SNRs (Ginzburg 1957) and those above 3×10^{18} eV (the "ankle"), for which a disk origin is unlikely due to their isotropy, in sources far beyond our Galaxy (Burbidge 1964). However, recent observations suggest that, perhaps, SNRs are not be the main source of Galactic cosmic rays and that the CRs above the ankle are not extragalactic:

- Measurable fluxes of high energy gamma rays from interactions of cosmic ray nuclei in SNRs expected in models of SNR acceleration of CRs were not detected from nearby SNRs (Prosch et al. 1996; Hess et al. 1997; Buckley et al. 1998).

- The expected galactocentric gradient in the distribution of high energy gamma rays (> 100 MeV) from interactions of CRs from SNRs in the Galactic interstellar medium is significantly larger than observed by the EGRET detector on board CGRO (Hunter et al. 1997; Strong and Moskalenko 1998).

- Diffusive propagation of CRs from the observed Galactic distribution of SNRs yield anisotropies in the distribution of CRs above 100 TeV in excess of the observed value (Aglietta et al. 1995) by more than an order of magnitude (Ptuskin et al. 1997).

- The absence (Takeda 1998) of the "GZK cutoff" in the intensity of CRs at energies above $\sim 10^{20}$ eV due to interactions with the cosmic microwave radiation (Greisen 1996; Zatsepin & Kuz'min 1966) have brought into question (e.g., Hillas 1998) their hypothesized extragalactic origin.

Relativistic jets are efficient CRs accelerators (e.g., Dar 1998b). A modest fraction of the total energy injected into the MW in jets from Galactic GRBs at a rate similar to the NS birth/collapse rate in the MW, that is converted to CR energy, can supply, $\sim 1.5 \times 10^{41}\ erg\ s^{-1}$, the estimated Galactic luminosity in CR. Thus, Dar and Plaga (1999) have recently proposed that Galactic GRBs (GGRBs) are the main source of the CRs at all energies and that no GZK cutoff is expected in the CR spectrum:

The highly relativistic narrowly collimated jets/plasmoids from the birth or collapse of NSs in the disk of our Galaxy that are emitted with $E_{jet} \sim 10^{52}$ erg perpendicular to the Galactic disk, stop only in the Galactic halo, when the rest mass energy of the swept-up ambient material becomes $\geq$ their initial kinetic energy. Through the Fermi mechanism, they accelerate the swept-up ambient matter to CR energies and disperse it into the halo from the hot spots which they form when they finally stop in the Galactic halo (Fig.1).

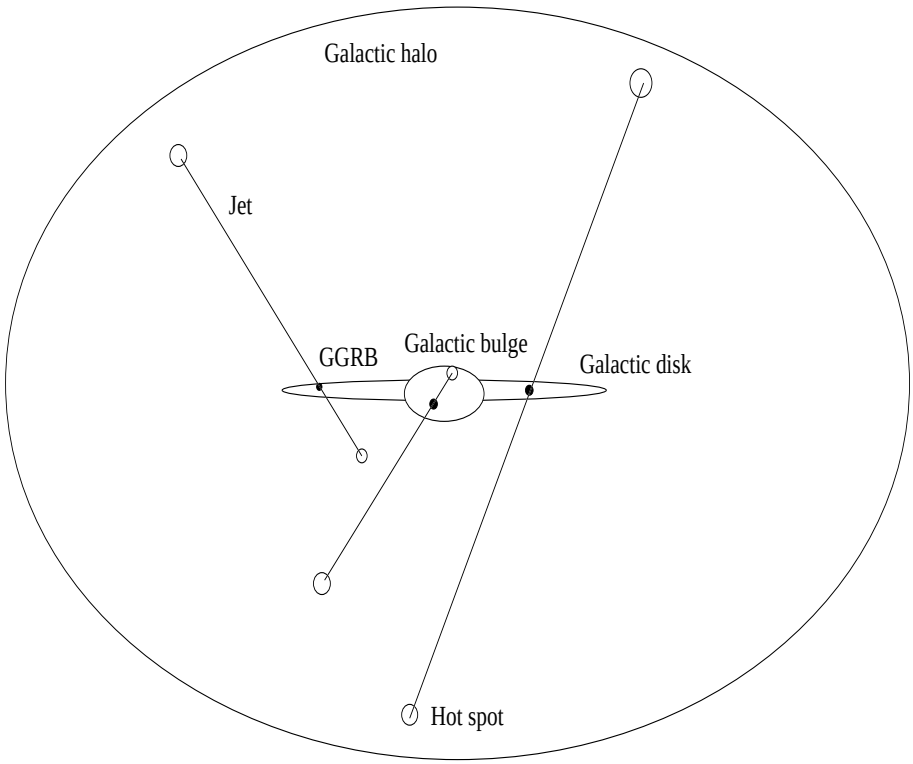

Fig. 1. *A highly schematic sketch of our paradigm. The birth or collapse of NSs in the disk of our Galaxy leads to an ejection of two opposite jets that produce "hot spots" when they stop in an extended Galactic halo.*

The typical equipartition magnetic fields in such hot spots may reach $B \sim$ $\sim (3E_{jet}/R_p^3)^{1/2} \sim 1$ G. Synchrotron losses cut off Fermi acceleration of CR nuclei with mass number A at $E \sim \Gamma A^2 Z^{-3/2} (B/G)^{-1/2} \times 10^{20}$ eV. Particle-escape cuts off Fermi acceleration when the Larmor radius of the accelerated particles in the plasmoid rest frame becomes comparable to the radius of the plasmoid, i.e., above

$E \simeq \Gamma Z(B/G)(R_p/0.1\ pc) \times 10^{20}$ eV. Consequently, CR with $E > Z \times 10^{20}$ eV can no longer be isotropized by acceleration or deflection in hot spots with $\Gamma \sim 1$.

Fermi acceleration in the highly relativistic jets from GRBs can produce a broken power-law spectrum, $dn/dE \sim E^{-\alpha}$, with $\beta \sim 2.2$ below a knee around $E_{knee} \sim A$ PeV and $\beta \sim 2.5$ above this energy (Dar 1998b). Spectral indices $\alpha \sim 2.2$ were obtained also in numerical simulation of relativistic shock acceleration (e.g., Bednarz and Ostrowski 1998) . Galactic magnetic confinement increases the density of Galactic CR by the ratio $c\tau_h/R_G$ where $\tau_h(E)$ is the mean residence time in the halo of Galactic CR with energy E, and $R_G \sim 50$ kpc is the radius of the Galactic magnetic-confinement region. With the standard choice for the energy dependence of the diffusion constant (observed, e.g., in solar-system plasmas) one gets: $\tau_h \propto (E/Z)^{-0.5}$. Consequently, the energy spectrum of CR is predicted to be

$$dn/dE \sim C(E/E_{knee})^{-p} \tag{10}$$

with $p \simeq \alpha + 0.5 \simeq 2.7$ ($\simeq 3$) below (above) the knee. This power-law continues as long as the Galactic magnetic field confines the CRs.

Part of the kinetic energy released by GGRBs is transported into the Galactic halo by the jets. Assuming equipartition of this energy, without large losses, between CR, gas and magnetic fields in the halo during the residence time of CR there, the magnetic field strength B_h in the halo is expected to be comparable to that of the disk $B_h \sim (2L_{MW}[CR]\tau_h/R_h^3)^{1/2} \simeq 3\ \mu G$ where $\tau_h \sim 5 \times 10^9$ y is the mean residence time of the bulk of the CR in the Galactic halo. Cosmic rays with Larmor radius larger than the coherence length λ of the halo magnetic fields, i.e., with energy above

$$E_{ankle} \sim 3 \times 10^{18}(ZB_h/3\mu G)(\lambda/kpc)\ eV, \tag{11}$$

escape Galactic trapping. Thus, the CR ankle is explained as the energy where the mean residence time $\tau_h(E)$ of CRs becomes comparable to the free escape time from the halo $\tau_{free} \sim 1.6(R_h/50\ kpc) \times 10^5$ years. Therefore, the spectrum of CRs with energies above the ankle, that do not suffer Galactic magnetic trapping, is the CRs spectrum produced by the jet, i.e.,

$$dn/dE \sim C(E_{ankle}/E_{knee})^{-3}(E/E_{ankle})^{-2.5};\ E > E_{ankle}. \tag{12}$$

Eqs. 10-12 describe well the overall CR energy spectrum.

5. High Energy Gamma Rays

The observed radiations from blazars, microquasars and GRBs indicate that their highly relativistic jets contain high energy charged particles with a power-law energy distribution $dn_p/dE \sim AE^{-\alpha}$ with $\alpha \sim 2.2$, that extends to very high energies. Such distributions can be formed in the highly relativistic jets through Fermi acceleration

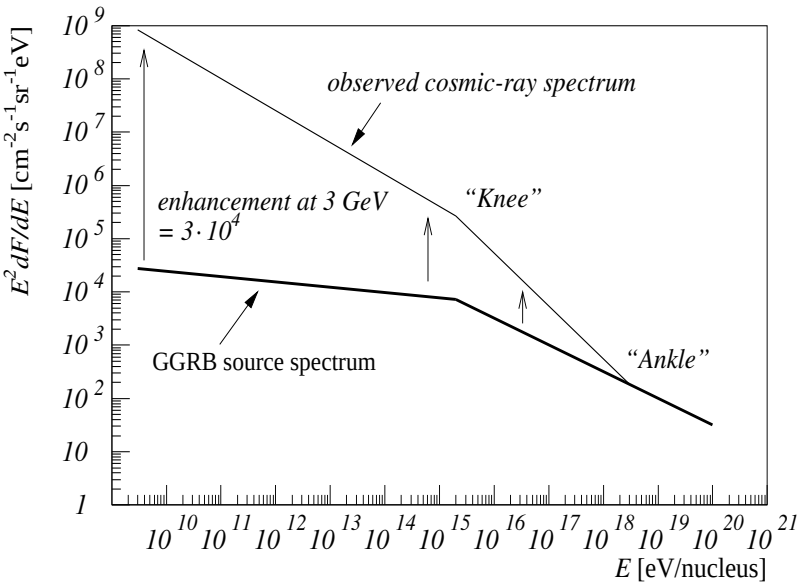

Fig. 2. *The observed flux of cosmic rays (thin line) as a function of primary energy E is well described by a power law that changes its slope sharply at only two energies the "knee" and the "ankle". At energies below the ankle it is enhanced (by a factor* $(E/E_{ankle})^{-0.5}$*) over the GGRB source spectrum (thick line, a power law with differential power law index of -2.2 below the knee and* $\simeq$ *-2.5 above it) by way of trapping in the Galactic halo magnetic fields.*

of swept up material. This power-law distribution of energetic protons is boosted and beamed into a solid angle $\Delta\Omega \approx \pi/\Gamma^2$ in the lab frame. GRB afterglows suggest that GRBs are produced in star formation regions, probably molecular clouds. The typical column density of such clouds is $N_p = 10^{24\pm1} cm^2$. The clouds must be highly ionized along the line of sight to the GRB by the enormous fluxes of beamed X-rays and UV radiations from the GRB. Interaction of the highly relativistic GRB jets with the high column density of this ionized gas (or with diffuse matter at their production sites) can produce high energy gamma rays through pp $\rightarrow \pi^0(\eta^0)$X; $\pi^0(\eta^0) \rightarrow 2\gamma$. The cross section for inclusive production of high energy γ-rays with a small transverse momentum, $\mathrm{cp_T = E_T} < 1$ GeV in pp collisions (e.g., Neuhoffer et al. 1971; Boggild and Ferbel 1972; Ferbel and Molzon 1974) is well represented by

$$\frac{\mathrm{E}}{\sigma_{\mathrm{in}}}\frac{\mathrm{d}^3\sigma}{\mathrm{d}^2\mathrm{p_T dE_\gamma}} \approx (1/2\pi\mathrm{p_T})\mathrm{e}^{-\mathrm{E_T/E_0}}\ \mathrm{f(x)}, \tag{13}$$

where E is the incident proton energy, $\sigma_{\mathrm{in}} \approx 35$ mb is the pp total inelastic cross section at TeV energies, $E_0 \approx 0.16\ GeV$ and $\mathrm{f(x)} \sim (1-\mathrm{x})^3/\sqrt{\mathrm{x}}$ is a function only of the Feynman variable $\mathrm{x} = \mathrm{E}_\gamma/\mathrm{E}$, and not of the separate values of the energies

of the incident proton and the produced γ-ray (Feynman scaling). The exponential dependence on E_T beams the γ-ray production into $\theta < E_T/E \sim 0.17/\Gamma$ along the incident proton direction. When integrated over transverse momentum the inclusive cross section becomes $\sigma_{in}^{-1} d\sigma/dx \approx f(x)$. If the incident protons have a power-law energy spectrum, $dn_p/dE \approx AE^{-\alpha}$, then, because of Feynman scaling, the produced γ-rays have the same power-law spectrum:

$$\frac{dn_\gamma}{dE_\gamma} \approx N_p \sigma_{in} \int_{E_\gamma}^{\infty} \frac{dn_p}{dE} \frac{d\sigma}{dE_\gamma} dE \approx N_p \sigma_{in} g_{p\gamma} A E_\gamma^{-\alpha}, \qquad (14)$$

where N_p is the column density of the target and $g_{p\gamma} = \int_0^1 x^{\alpha-1} f(x) dx \approx 0.092$ for $\alpha \approx 2.2$. Consequently, the collimated flux of high energy gamma rays produced by a GRB jet with initial kinetic energy $E = E_{52} \times 10^{52}$ erg that propagates through a molecular cloud of typical column density $N_p = N_{23} \times 10^{23}$ cm^{-2} is given by

$$\frac{dn_\gamma}{dE} \approx \frac{6 \times 10^{-6} E_{52} N_{23} \Gamma_3^2}{D_{29}^2} (1+z)^{2-\alpha} \left[\frac{E}{TeV}\right]^{-2.2} e^{-\tau(z,E)} \text{ cm}^{-2} \text{ TeV}^{-1}, \qquad (15)$$

where $D(z) = D_{29} \times 10^{29}$ cm, is the luminosity distance to the GRB and $\tau(z, E)$ is the optical depth to the GRB (redshift z) at energy E. The fluxes of high energy gamma rays from GRBs at $z \sim 2$ are attenuated strongly ($\tau > 1$) for E$>$ 20 GEV. For not very distant GRBs, e.g., z$<$ 0.5, the gamma ray flux is not attenuated strongly at energy E $<$ 100 GeV (Salomon and Stecker, 1998). GRBs with z$<$ 0.1 ($D_L < 500$Mpc can be visible in TeV gamma rays, but their expected rate is only

$$\sim R_{GRB}[L_*] \rho_L V_c(z < 0.1) \sim 0.1 \text{ y}^{-1}, \qquad (16)$$

where $R_{GRB}[L_*] \approx 2 \times 10^{-8}$ y^{-1} is the estimated mean rate of GRBs in an $L_* \approx 10^{10} L_\odot$ galaxy for z$<$ 0.1, $\rho_L \sim 1.2 \times 10^8 L_\odot$ Mpc^{-3} is the luminosity density in the local Universe and $V_c(z < 0.1) \approx 5 \times 10^8$Mpc^3 is the comoving volume within z$<$ 0.1. GeV gamma rays from very luminous 3 GRBs have been reported by the EGRET detector on board CGRO (Dingus et al 1994; Dingus 1995). They could have been produced by inverse Compton scattering of GRB photons from energetic electrons in the GRB jets. Only the detection of high energy neutrinos from GRBs can establish hadronic production of high energy photons in GRBs (and the hadronic nature of the GRB jets).

6. High Energy Neutrinos From GRBs

Hadronic production of photons in diffuse targets is accompanied by neutrino emission mainly through hadronic production of mesons that decay into neutrinos, e.g., $pp \rightarrow \pi^\pm \rightarrow \mu^\pm \nu_\mu$; $\mu^\pm \rightarrow e^\pm \nu_\mu \nu_e$ Analytical calculations (e.g., Dar 1983, 1984, Lipari 1993) show that a proton power-law spectrum, $dn_p/dE = AE^{-\alpha}$ with a power

index $\alpha \sim 2.2$, generates power-law spectra of γ-rays and ν_μ's that satisfy approximately, $\mathrm{dn}_\nu/\mathrm{dE} \approx 0.80\mathrm{dn}_\gamma/\mathrm{dE}$. Consequently,

$$\frac{\mathrm{dn}_\nu}{\mathrm{dE}} \approx \frac{5\times 10^{-6}\mathrm{E}_{52}\mathrm{N}_{23}\Gamma_3^2}{\mathrm{D}_{29}^2}(1+\mathrm{z})^{2-\alpha}\left[\frac{\mathrm{E}}{\mathrm{TeV}}\right]^{-2.2}\ \mathrm{cm}^{-2}\ \mathrm{TeV}^{-1}. \tag{17}$$

Thus, we predict that the high energy γ-ray emission from GRBs is accompanied by emission of high energy neutrinos with similar fluxes, light curves and energy spectra. The expected number of ν_μ events from a GRB in a deep underwater/ice ν_μ telescope is

$$\mathrm{N}_{\mathrm{events}} \approx \mathrm{SN}_\mathrm{A}\int \mathrm{R}_\mu \frac{\mathrm{d}\sigma_{\nu\mu}}{\mathrm{dE}_\mu}\frac{\mathrm{dn}_\nu}{\mathrm{dE}}\mathrm{dE}_\mu\mathrm{dE} \tag{18}$$

where S is the effective surface area of the telescope, $\mathrm{N_A}$ is Avogadro's number, $\sigma_{\nu\mu}$ is the inclusive cross section for $\nu_\mu \mathrm{p} \to \mu \mathrm{X}$, and R_μ is the range (in gm cm^{-2}) of muons with energy E_μ in water/ice. The number of events is not sensitive to the detector energy threshold if it is below 300 GeV, where both the muon range and production cross section increase linearly with energy and yield a detection probability in ice/water, which increases like $\approx 10^{-6}(\mathrm{E/TeV})^2$ below 300 GeV. Neglecting detector threshold effects, we predict that the number of neutrino events in deep underground ice/water neutrino telescopes per 1 km^2 is

$$\mathrm{N_e vents} \approx 1\times(1+\mathrm{z})^{-0.2}\frac{\mathrm{E}_{52}\mathrm{N}_{23}\Gamma_3^2}{\mathrm{D}_{29}^2}\ \mathrm{km}^{-2}\ . \tag{19}$$

Thus, a relatively nearby GRB (z=0.5) may generate $\sim 120\mathrm{E}_{52}\mathrm{N}_{23}$ upgoing muon events in underwater/ice telescope per 1 km^2 area and only 3 events if it is at z=2. The expected time length of these neutrino bursts from GRBs is typically, $\mathrm{t} \approx (\mathrm{R_{cl}}/\mathrm{c}\Gamma^2) \sim \mathrm{R}_{10}\times 10^3$ s, where R_{10} is the size of the molecular cloud in pc.

7. acknowledgements

Results presented here are based on an ongoing collaboration with A. De Rùjula and R. Plaga. This research was supported by the fund for the promotion of research at the Technion.

8. References

1) Aglietta, M. et al. 1995, ICRC 2, 800
2) Andersen, M. I. et al. 1999, Science, 283, 2075
3) Baring, M.G. & Harding, A.K. 1997, ApJ. 491, 663
4) Bednarz, J & Ostrowski, M. 1998, Phys. Rev. Lett. 80, 3911
5) Berezinskii, V. S. et al. 1990 *Astrophysics of cosmic rays* (North Holland, Amsterdam, 1990).

6) Blinnikov, S. I. et al. 1984, SvA. Lett. 10, 177
7) Boggild, H. & Ferbel, T. 1974, ARNS 24, 451
8) Bridle, A.H.& Perley, R. A. 1984, ARA&A 22, 319
9) Buckley, J. H. 1998, A&A, 329, 639
10) Burbidge, G. 1962, Prog. Theor. Phys. 27, 999
11) Cen, R. 1998, ApJL. in press (astro-ph/9809022)
12) Chiang, J. & Dermer, C.F. 1997, preprint astro-ph/9708035.
13) Costa, E. et al. 1997, Nature, 387, 783
14) Dar A. et al. 1983, Phys. Rev. Lett. 51, 227
15) Dar A. et al. 1984, Technion-Phys-84-41 (unpublished)
16) Dar A. et al. 1992, ApJ, 388, 164
17) Dar, A. 1997a, in *Very High Energy Phenomena In The Universe* (ed.Y. Giraud-Heraud & J. Tran Thanh Van, Editions Frontieres 1997) p. 69
18) Dar, A. 1998, ApJ. 500, L93
19) Dar, A. 1999a, A&A, in press (astro-ph/9902017)
20) Dar, A. 1999b, in preparation
21) Dar, A. and De Rújula, A. 1999, in preparation
22) Dar, A. and Plaga, R. 1999, A&A in press
23) Dar, A. & Shaviv, N. 1996, Astrop. Phys. 4, 343
24) Dermer, C. D. & Chiang, J. 1997, New Astronomy 3, 157
25) Dingus, B. et al. 1994, AIP Conf. Proc. 307, 22
26) Dingus, B. 1995, Ap. & Sp. Sc. 231, 195
27) Djorgovski, S.G. et al. 1998, ApJ. 508, L17
28) Djorgovski, S.G. et al. 1999, GCN Circ. No. 189
29) Drury, L. O'C, MarKiewicz, W. J. & Völk, W. J. 1989, A& A 225, 179
30) Ferbel, T. & Molzon, W.R. 1984, Rev. Mod. Phys. 56, 181
31) Fruchter, A. S. 1999 ApJ, 512, L1
32) Goodman, J., Dar, A. & Nussinov, S., 1987, ApJ, 314, L7
33) Ginzburg, V.L. 1957, Prog. Elem. Part. CR. Phys. 4, 339
34) Greisen, K. 1996, Phys. Rev. Lett. 16, 748
35) Hess, M. et al. 1997, ICRC 3, 229
36) Hillas, M. 1998, Nature 395, 15
37) Hjellming, R.M. & Johnston, K.J. 1988, ApJ. 328, 600
38) Hunter, S. D. et al. 1998, ApJ. 481, 205
39) Kippen, R. M. et al. 1999 GCN Circ. No. 224
40) Kulkarni, S. R. et al. 1998, Nature, 393, 35
41) Kulkarni, S. R. et al. 1999, Nature, 398, 389
42) Lipari, P., 1993, Astropar. Phys. 1, 195
43) Lyne, A.G. & Lorimer, D.R. 1994, Nature 369, 127
44) Mannheim, K. and Biermann, P.L. 1992, A&A 253, L21
45) Meisenheimer, K. et al. 1989, A&A, 219, 63

46) Metzger, M. R. et al. 1997, Nature, 387, 878
47) Mirabel, I. F. & Rodriguez, L. F. 1994, Nature, 371, 46
48) Mirabel, I. F. & Rodriguez, L. F. 1999, Preprint astro-ph/9902062
49) Mochkovich, R. et al. 1993, Nature, 361, 236
50) Neuhoffer, G., et al. Phys. Lett. 1971, 37B, 438
51) Paczynski, B. 1986, ApJ, 308, L43
52) Piran, T. 1999, Phys. Rep. in press
53) Prosh, C. et al, 1996, A&A 314, 275
54) Ptushkin, V. S. et al, 1997, A&A 321, 434
55) Rodriguez, L. F. & Mirabel, I.F. 1998, astro-ph/9808341
56) Rhoads, J. E. 1997, ApJ. 478, L1
57) Salomon, M. H. & Stecker, F.W. 1998, ApJ. 493, 547
58) Shaviv, N. J. 1996, Ph.D. Thesis (Technion Report 1996)
59) Shaviv, N. J. & Dar, A. 1995, ApJ. 447, 863
60) Shaviv, N. J. & Dar, A., 1997, in *Neutrinos, Dark Matter and The Universe*, eds. T. Stolarcyk et al. (Editions Frontieres 1997) p. 338.
61) Strong, A. W. & Moskalenko, I. V. 1999, ApJ, in press (preprint astro-ph/9807150)
62) Tingay, S. J. et al. 1995, Nature, 374, 141
63) Takeda, M. et al. 1998, PRL. 81, 1163
64) van den Bergh, S. & Tamman, G.A. 1991 ARA&A 29, 363
65) Vreeswijk, P. M. et al. 1999 GCN Circ. No. 324
66) Wijers, R.A.M.J. et al. 1997, MNRAS 294, L13
67) Zatsepin, G.T. & Kuz'min, V.A. 1996, JETP Lett. 4, 78