Cosmic Rays and Gamma Ray Bursts From Microblazars

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Abstract

Highly relativistic jets from merger and accretion induced collapse of compact stellar objects, which may produce the cosmological gamma ray bursts (GRBs), are also very efficient and powerful cosmic ray accelerators. The expected luminosity, energy spectrum and chemical composition of cosmic rays from Galactic GRBs, most of which do not point in our direction, can explain the observed properties of Galactic cosmic rays.

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The origin of high energy cosmic rays (CR), which were first discovered by V. Hess in 1912, is still a complete mystery [1]. Their approximate broken power-law spectrum, $dn/dE \sim E^{-\alpha}$ with $\alpha \sim 2.7$ below the so called CR knee around $10^{15.5}$ eV, $\alpha \sim 3.0$ above the knee and $\alpha \sim 2.6$ beyond the so called CR ankle around $10^{19.5}$ eV, suggests different origins of CR with such energies. It is generally believed that CR with energy below the knee are Galactic in origin [2], those with energy above the knee can be either Galactic or extragalactic [3], and those beyond the ankle are extragalactic [4].

If the CR accelerators are Galactic, they must replenish for the escape of CR from the Galaxy in order to sustain the observed Galactic CR intensity. Their total luminosity in CR must therefore satisfy, $L_{MW}[CR] = \int \tau^{-1}(Edn/dE)dEdV$, where $\tau(E)$ is the mean residence time of CR with energy $E$ in the Galaxy. It can be estimated from the mean column density, $X = \int \rho dx$, of gas in the interstellar medium (ISM) that Galactic CR with energy $E$ have traversed. From the the secondary to primary abundance ratios of Galactic CR it was inferred that [5] $X = \bar{\rho} c\tau \approx 6.9(E[GeV]/20Z)^{-0.6} g cm^{-2}$, where $\bar{\rho}$ is the mean density of interstellar gas along their path. The mean energy density of CR and the total mass of gas in the Milky Way (MW), that have been inferred from the diffuse Galactic $\gamma$-ray, X-ray and radio emissions are [1], $\epsilon = \int E(dn/dE)dE \sim 1$ eV cm$^{-3}$ and [6] $M_{gas} = \int \rho dV \sim 4.8 \times 10^9 M_\odot$, respectively. Hence [7],

$$L_{MW}[CR] \sim M_{gas} \int \frac{cEdn/dE}{X}dE \sim 1.5 \times 10^{41} \text{ erg s}^{-1}. \quad (1)$$

The only known Galactic sources which can supply this CR luminosity [8] are supernova explosions [9] and gamma ray bursts [10]. Approximately, $E_K \sim 10^{51}$ erg is released in supernova explosions (SNe) as nonrelativistic kinetic energy of ejecta at a rate $R_{MW}[SNe] \sim 1/30$ y$^{-1}$. If a fraction $\eta \sim 15\%$ of this energy is converted into CR energy by collisionless shocks in the supernova remnants (SNR), then the total SNe luminosity in CR is,

$$L_{MW}[CR] \approx \eta R_{MW}[SNe] E_K[SNe] \sim 1.5 \times 10^{41} \text{ erg s}^{-1}, \quad (2)$$

as required by eq. (1). The non thermal X-ray emission from SNR 1006 observed by ASCA and ROSAT [11], the GeV $\gamma$-ray emission from several nearby SNRs observed by EGRET
[12], and the recent detection of SNR 1006 in TeV $\gamma$-rays by the CANGAROO telescope [13], were all used to argue that SNRs are the source of galactic CR. However, the TeV $\gamma$ rays from SNRs can be explained by inverse Compton scattering of microwave background photons by multi-TeV electrons whose synchrotron emission explains their hard lineless X-ray radiation [11]. Furthermore, the mean lifetime of strong shocks in SNRs limits the acceleration of CR nuclei in SNRs to energies less than $\sim Z \times 0.1\text{PeV}$ and cannot explain the origin of CR with much higher energies. In fact, most nearby SNRs in the Northern hemisphere have not been detected in TeV $\gamma$-rays [15]. Moreover, the Galactic distribution of SNRs differs significantly from that required to explain the observed Galactic emission of high energy ($>100\text{MeV}$) $\gamma$-rays by cosmic ray interactions in the Galactic ISM [16]. All these suggest that, perhaps, SNRs are not the main accelerators of Galactic CR.

Gamma ray bursts (GRBs) have already been proposed as CR sources [17,18,10]. Photon acceleration of CR in isotropic GRBs is probably limited to energies below TeV [17]. Shock acceleration in GRBs may accelerate particles to ultrahigh energies [18]. However, because of the assumed spherical symmetry, the total energy release in GRBs was severely underestimated (see below). Consequently, it was concluded that extragalactic GRBs may be the source of the ultrahigh energy CR in the Galaxy but they cannot supply the bulk of the Galactic CR [18]. In fact, spherical fireballs from merger and/or accretion induced collapse (AIC) of compact stellar objects [19] cannot explain the observed properties of GRBs and their afterglows [20]: They cannot explain their complex light curves and short time scale variability [21]. They cannot explain the lack of scaling and the diversity of their afterglows [22]. They cannot explain their delayed GeV $\gamma$ ray emission [23]. In particular, isotropic emission implies enormous kinetic energy release in GRBs which cannot be supplied by merger/AIC of compact stellar objects [20]. Such release is necessary in order to sustain the long duration power-law fading of the observed afterglow of GRB 970228 [24]. It is also needed in order to produce the observed $\gamma$-ray fluence from GRBs 971214 and 980703 where the redshift $z$ of the host galaxy has recently been measured [25],
where $\Delta\Omega$ is the solid angle that the emission is beamed into and $d_L$ is their luminosity distance (we assuming a Friedmann Universe with $h \sim 0.65$, $\Omega_m \geq 0.2$ and $\Omega_m + \Omega_{\Lambda} \leq 1$).

However, if the relativistic ejecta is beamed into a narrow jet [26], most of the problems of the spherical fireball models can be avoided and the main observed properties of GRBs and their afterglows can be explained [20]. Moreover, in order to produce the same observed rate of GRBs, the number of jetted GRBs must be larger by a factor $4\pi/\Delta\Omega$ than the number of GRBs with isotropic emission. Thus, for a fixed energy release per event, the total kinetic energy release in GRBs is larger by a factor $4\pi/\Delta\Omega$ than that which was estimated [18] for spherical GRBs. Highly relativistic jets are also very efficient CR accelerators. Acceleration to CR energies can take place in the jets by diffusive shock acceleration or in front of the jets by the Fermi mechanism [27]. In this letter I show that jets from mergers/AIC of compact stellar objects may be the source of Galactic CR [10]. The predicted source luminosity, energy spectrum and chemical composition agree with those required by CR observations.

Highly relativistic jets seem to be emitted by all astrophysical systems where mass is accreted at a high rate from a disk onto a central black hole (BH). They are observed in galactic superluminal sources, such as the microquasars GRS 1915+105 [28] and GRO J1655-40 [29] where mass is accreted onto a stellar BH, and in many extragalactic blazars where mass is accreted onto a a supermassive BH. The emission of Doppler shifted Hydrogen Ly$\alpha$ and Iron K$\alpha$ lines from the relativistic jets of SS443 [30] 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 relativistic jets [31]. Highly relativistic jets may be the merger/AIC death throws of close binary systems containing compact stellar objects [10,20,26]. But, because the accretion rates and magnetic fields involved are enormously larger compared with normal quasars and microquasars, the bulk motion Lorentz factors of these jets perhaps are much higher, $\Gamma \sim 1000$ as inferred from
GRB observations. Such highly relativistic jets which point in (or precess into) our direction ('microblazars') can produce the cosmological GRBs and their afterglows [20]. Jetting the ejecta in merger/AIC of compact stellar objects can solve the energy crisis of GRBs [20,25] by reducing the total inferred energy release in GRBs by a factor $\Delta \Omega/4\pi$. If NS-NS and NS-BH mergers are the triggers of GRBs [32], then beaming angles $\Delta \Omega/4\pi \sim 10^{-2}$ are required in order to match the observed GRB rate [21] and the currently best estimates of the NS-NS and NS-BH merger rates in the Universe [33]. Such angles are typical of superluminal jets from blazars and microquasars. The estimated rate of AIC of white dwarfs (WD) and NS in the observable Universe is $\sim 1$ per second, i.e., larger than the estimated rate for NS-NS and NS-BH mergers [33] by about two orders of magnitude. Therefore, if GRBs are produced by jets from AIC of WD and NS then $\Delta \Omega/4\pi \sim 10^{-4}$. Note that either the ‘firing’ of many highly relativistic fragments into a small solid angle [20] or precessing jets [33] can produce the complex time structure of GRBs.

The energy release in merger/AIC of compact stellar objects is bounded by $E_b \sim M_{NS}c^2 \approx 2.5 \times 10^{54}$ erg, where $M_{NS} \sim 1.4M_\odot$ is the gravitational mass of a typical neutron star (NS). Then the typical kinetic energy release which is beamed into a solid angle $\Delta \Omega$ may be of the order $E_K[GRB] \sim 2.5 \times 10^{54}(\Delta \Omega/4\pi)$ erg. Such kinetic energy release was inferred from the optical afterglows of GRBs [20]. It is also follows from the energy release in $\gamma$-rays from GRBs with measured redshifts [25] if the conversion efficiency of jet kinetic energy into $\gamma$-ray energy is a few percent. The rate of SNe and cosmological GRBs that point in our direction were estimated to be [34] $R_{L^*}[SNe] \sim 0.02$ yr$^{-1}$ and [35] $R_{L^*}[GRB] \sim 2 \times 10^{-6}$ yr$^{-1}$, respectively, per $L^*$ galaxy. If SNe and GRBs have similar histories (evolution functions) then the rate of GRBs in the Milky Way that point in our direction is $R_{MW}[GRB] \sim 10^{-4}(4\pi/\Delta \Omega)R_{MW}[SNe]$. Thus, if most of the kinetic energy released in GRBs is converted into CR energy (see below) then the Galactic luminosity in CR due to Galactic GRBs is

$$L_{MW}[CR] \sim 10^{-4}R_{MW}[SNe]E_b \sim 1.5 \times 10^{11} \text{ erg s}^{-1},$$

(4)
where the unknown GRB beaming angle has been canceled out. Note the agreement between eq. (1) and eq. (4). However, the estimated ratio between the rates of SNe and GRBs is sensitive to the choice of cosmological model, even if their histories were identical. This is because SNe and GRB observations employ different techniques, have different sensitivities and consequently sample different volumes of the Universe. Therefore, I have estimated $L_{MW}[CR]$ in other independent ways. For instance, I have assumed that the ratio between the Galactic rate of GRBs and the global rate of GRBs is equal to the ratio between the Galactic broad band luminosity \[ L_{MW}[CR] \sim 2.3 \times 10^{10} L_\odot, \] and the luminosity of the whole Universe, \[ L_{UNIV} \sim \int (1 + z)^{-1} \rho_L(z) (dV_c/dz) dz \] where $\rho_L(z)$ is the comoving luminosity density and the factor $1/(1 + z)$ is due to the cosmic time dilation. If one assumes that most of the contribution to the volume integral comes from redshifts where $\rho_L(z)$ is well approximated by its measured value in the local universe \[ \rho_L \sim 1.8 h \times 10^8 L_\odot Mpc^{-3}, \] then

$$R_{MW}[GRB] \approx \frac{R_{UNIV}[GRB] L_{MW}}{\rho_L \int (1 + z)^{-1} (dV_c/dz) dz}. \quad (5)$$

For a Friedmann Universe with $\Omega = 1$ and $\Lambda = 0$, the volume integral yields

$$\int \frac{dV_c}{1 + z} = 16\pi \left( \frac{c}{H_0} \right)^3 \int_0^\infty \frac{(1 + z - \sqrt{1 + z})^2}{(1 + z)^{9/2}} dz = \frac{32\pi}{30} \left( \frac{c}{H_0} \right)^3. \quad (6)$$

Taking into consideration threshold and triggering effects, the estimated rate of cosmological GRBs which point in our direction from the BATSE observations \[ [21] \] is $\sim 5 \text{ day}^{-1}$. Consequently, for $h \sim 0.65$ eq. (5) yields $L_{MW}[CR] \sim 10^{41} \text{ erg s}^{-1}$, consistent with eq. (4). Moreover, if the ‘standard candle’ $E_K[GRB]$ is taken to be proportional to $\langle E_\gamma[GRB] \rangle$ as obtained from eq. (3), then the estimated CR luminosity becomes insensitive to the choice of the specific cosmology.

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 of \textit{mGauss} in the jet rest frame have been inferred from microquasar observations \cite{28}, while hundreds of \textit{Gauss} were inferred for GRB ejecta. The UV light and the X-rays from the jet (and accretion disk) ionize the ISM in front of the jet. The swept up ISM/jet material can be accelerated by diffusive shock acceleration in the jet. Alternatively, the jet magnetic field can act as a magnetic mirror and accelerate the ionized ISM particles to high relativistic energies through the usual Fermi mechanism \cite{27}:

Let us denote by $M$ the total ejected mass in an ejection episode, by $\Gamma$ its initial bulk Lorentz factor and by $n_p m_p$ the total mass of ionized ISM that is accelerated by the jet. In the rest frame of ejecta with a bulk Lorentz factor $\gamma$, the charged ISM particles move towards the jet with energy $\gamma m_p c^2$ and are reflected back by the transverse magnetic field in the jet with the same energy. In the observer frame their energy is boosted to $E = \gamma^2 m_p c^2$. Moreover, each time such a charged particle is deflected by an external magnetic field (of the ISM or a star) back into the jet, its energy is boosted again by a factor $\gamma^2$. Thus, for $n$ reflections the energy of the accelerated particle can reach $E = \gamma^{2n} m_p c^2$ (neglecting radiation losses). Thus a GRB jet with $\Gamma \sim 10^3$ can accelerate ISM protons to energies up to $m_p c^2 \Gamma^2 \sim 10^{15}$ eV in a single reflection, while two reflections can impart to them energies up to $m_p c^2 \Gamma^4 \sim 10^{21}$ eV! For the sake of simplicity let us assume that the $n$ multiple reflections take place simultaneously (in practice $n \leq 2$), Let us also assume a pure hydrogenic composition (the generalization to an arbitrary composition is straightforward). If the jet loses most of its energy by acceleration of the ISM and not by hadronic collisions or radiation (because of the small hadronic cross sections for binary collisions and radiation processes), conservation of energy and momentum reads,

$$d(Mc^2\gamma) \approx -dn_pE; \quad E = m_p \gamma^2 n.$$ \hfill (7)

Consequently, for an ISM with a uniform composition

$$\frac{dn_p}{dE} \approx \frac{M}{m_p 2nm_pc^2} \left[ \frac{E}{m_pc^2} \right]^{-2+1/2n}; \quad E < \Gamma^{2n} mc^2.$$ \hfill (8)

Note that the power-law spectrum is independent of whether the ejecta is spherical, or conical or cylindrical. It is the same for ions and electrons as long as losses and escape are neglected.
It is also insensitive to variations in the ISM density along the radial direction. Under our assumed "ideal" conditions, the spectrum of accelerated particles approaches a \( dn/dE \sim E^{-2} \) shape. Efficient acceleration continues until either the jet becomes non-relativistic, or disperses, or the Larmor radius of the accelerated particles in the jet rest frame \( r_L \sim 3 \times 10^{15}(E[\text{EeV}]/\Gamma ZB[\text{Gauss}]) \text{ cm} \) becomes comparable to the radius of the jet. Moreover, the assumption of instantaneous acceleration is unjustified when the Larmor radius of the accelerated particles ceases to be small compared with the typical deceleration distance of the jet. Our simple analytical estimates can be tested in detailed Monte Carlo simulations. However, such simulations depend on too many unknown jet and ISM parameters. Instead, one may assume that the energy dependence of the escape probabilities of CR from their accelerators is similar to that for their escape from the Galaxy, i.e., \( \tau \sim (E/ZB)^{-0.6} \) is also valid for their escape from the CR accelerators. Then, Galactic CR are predicted to have a power-law spectrum with a power index \( \alpha = 2 - 1/2n + 2 \times 0.6 \), i.e.,

\[
\frac{dn}{dE} \sim C \left( \frac{E}{E_0} \right)^{-\alpha} \quad \text{with} \quad \alpha = \begin{cases} 
2.70, & E < E_0 \\
2.95, & E > E_0 
\end{cases}
\] (9)

where \( E_0 \sim m_p\Gamma^2 \sim A \text{ PeV} \), with \( A \) being the mass number of the CR nuclei. These predictions agree well with the cosmic ray observations. Because the jet emits enormous fluxes of beamed radiation in all relevant wave lengths, the ISM in front of it must be completely ionized, Since the escape probability of accelerated nuclei decreases like \( Z^{-0.6} \) the abundances of CR nuclei are expected to be enhanced by approximately a factor \( \sim Z^{0.6} \) compared with the ISM abundances. Ionization potential effects are expected to be washed out in the CR composition at high energy. If the origin of the CR knee is the transition from 'single' to 'double' reflections then there should be no change in cosmic ray composition around the CR knee, as claimed by recent measurements [36].

In conclusion, Galactic GRBs may be the main source of Galactic CR.
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