The XRF080109-SN2008D and a decade of GRB-Jet-SN connection

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Abstract

Last and nearest GRB-XRF 080109 has been an exceptional lesson on GRB nature. After a decade (since 25 April 08) we know that Supernovae may often contain a Jet. Its persistent activity may shine on axis as a GRBs. Such a persistent, thin beamed gamma jet may be powered by either a BH (Black Holes) or Pulsars. Late stages of these jets may lose the SN traces and appear as a short GRB or a long orphan GRB (depending on jet angular velocity and view angle). XRF are peripherical viewing of the jets. These precessing and spinning γ jet are originated by Inverse Compton and-or Synchrotron Radiation at pulsars or micro-quasars sources, by ultra-relativistic electrons. These Jets are most powerful at Supernova birth, blazing, once on axis, to us and flashing GRB detector. The trembling of the thin jet explains naturally the observed erratic multi-explosive structure of different GRBs. The jets are precessing (by binary companion or inner disk asymmetry) and decaying by power law \( t^{-\alpha} \) on time scales \( t_o \) a few hours, but they keep staying inside the observer cone view only a few seconds duration times (GRB); the jet is thinner in gamma and wider in X band. This explain the wider and longer X GRB afterglow duration and the rare presence of X-ray precursors.

1 A list of GRB puzzles

Why GRBs are so spread in their total energy, (above 8 orders of magnitude) and in their peak energy following the so-called Amati correlation[1]? Does the Amati law imply more and more new GRB families? Why, as shown below the GRB energy is not a constant but a growing function (almost quadratic) of the red-shift?

Why are the harder and more variable GRBs (4-5) found at higher redshifts contrary to expected Hubble law? Why does the output power of GRB vary in a
Figure 1: The GRB X-ray luminosity updated to 2008 included. The apparent
law luminosity-red-shift in a quadratic power, is mostly due, (in lower regions) to
the quadratic distance cut-off and (in higher regions) to the rarer beaming in axis
occurring mostly by largest samples and cosmic volumes.

range ([5]) of 8-9 orders of magnitudes with the most powerful events residing at the
cosmic edges ([6]), see Fig [7]. Why has it been possible to find in the local universe
(at distances 40-150 Mpc just a part over a million of cosmic space) at least two
nearby events (GRB980425 at $z = 0.008$ and recent GRB060218 at $z = 0.03$) while
most GRBs should be located at largest volumes, at $z \geq 1$ ([5])? Why are these
two nearby GRBs so much under-luminous ([5])? Why are their evolution times
so slow and smooth respect cosmic ones? Why do their afterglows show so many
bumps and re-brightening as the well-known third nearest event, GRB030329, if
they are one-shot explosive event? Indeed why do not many GRB curves show
monotonic decay (an obvious consequence of a one-shot explosive event), rather
they often show sudden re-brightening or bumpy afterglows at different time scales
and wavelengths ([7] [8]) - see e.g. GRB050502B [9]? Why have there been a few
GRBs and SGRs whose spectra and time structure are almost identical if their
origin is so different (beamed explosion for GRB versus isotropic magnetar) [5] [10].
How can a jetted fireball (with an opening angle of $5^\circ$-$10^\circ$ and solid angle as wide
as 0.1sr.) release an energy-power $10^{50}$ ergs$^{-1}$ nearly 6 orders of magnitude more
energetic than $10^{44}$ ergs$^{-1}$ the corresponding isotropic SN? Why there is not a more
democratic energy redistribution (or energy equipartition). How Fireball Jet Model
may fine tune multi-shells around a GRB in order to produce tuned shock explosions?
and re-brightening with no opacity within minutes, hours, days time-distances from the source([8])? How can some (∼6%) of the GRBs (or a few SGRs) survive the "tiny" (but still extremely powerful) pre-explosion of its precursor without any consequences for the source, and then explode catastrophically few minutes later? In such a scenario, how could the very recent GRB060124 (at redshift $z = 2.3$) be preceded by a 10 minutes precursor, and then being able to produce multiple bursts hundreds of times brighter? Why SGR1806-20 of 2004 Dec. 27th, shows no evidence of the loss of its period $P$ or its derivative $\dot{P}$ after the huge Magnetar eruption, while in this model its hypothetical magnetic energy reservoir (linearly proportional to $P \cdot \dot{P}$) must be largely exhausted? Why do SGR1806 radio afterglows show a mysterious two-bump radio curve implying additional energy injection many days later? In this connection why are the GRB021004 light curves (from X to radio) calling for an early and late energy injection? Why has the SGR1806-20 polarization curve been changing angle radically in short (∼days) timescale? Why is the short GRB050724 able to bump and re-bright a day after the main burst[11]? Why rarest GRB940217, highest energetic event, could held more than 500s??

Once these major questions are addressed and (in our opinion) mostly solved by our precessing gamma jet model, a final question still remains, calling for a radical assumption on the thin precessing gamma jet: how can an ultra-relativistic electron beam (in any kind of Jet models) survive the SN background and dense matter layers and escape in the outer space while remaining collimated? Such questions are ignored in most Fireball models that try to fit the very different GRB afterglow light curves with shock waves on tuned shells and polynomial ad-hoc curves around the GRB event. Their solution forces us more and more toward a unified precessing Gamma Jet model fed by the PeV-TeV lepton showering (about UHE showering beam see analogous ones[13, 14]) into $\gamma$ discussed below. As we will show, the thin gamma precessing jet is indeed made by a chain of primary processes (PeV muon pair bundles decaying into electrons and then radiating via synchrotron radiation), requiring an inner ultra-relativistic jet inside the source.

## 2 Blazing Spinning and Precessing jets in GRBs

The huge GRBs luminosity (up to $10^{54}$ erg s$^{-1}$) may be due to a high collimated on-axis blazing jet, powered by a Supernova output; the gamma jet is made by relativistic synchrotron radiation and the inner the jet the harder and the denser is its output. The harder the photon energy, the thinner is the jet opening angle. The hardest and shortest core Gamma event occur at maximal apparent luminosity once the jet is beamed in inner axis. The jets whole lifetime, while decaying in output, could survive as long as thousands of years, linking huge GRB-SN jet apparent Luminosity to more modest SGR relic Jets (at corresponding X-Ray pulsar output). Therefore long-life SGR (linked to anomalous X-ray AXPs) may be repeating; if they are around our galaxy they might be observed again as the few known ones and the few rare extragalactic XRFs. The orientation of the beam respect to the line of sight plays a key role in differentiating the wide GRB morphology. The
relativistic cone is as small as the inverse of the electron progenitor Lorentz factor. To observe the inner beamed GRB events, one needs the widest SN sample and the largest cosmic volumes. Therefore the most far away are usually the brightest. On the contrary, the nearest ones, within tens Mpc distances, are mostly observable on the cone jet periphery, a bit off-axis. Their consequent large impact crossing angle leads to longest anomalous SN-GRB duration, with lowest fluency and the softest spectra, as in earliest GRB98425 and in particular recent GRB060218 signature. A majority of GRB jet blazing much later (weeks, months after their SN) may hide their progenitor explosive after-glow and therefore they are called orphan GRB. Conical shape of few nebulae and the precessing jet of few known micro-quasar, describe in space the model signature as well as famous Cygnus nebulae. Recent outstanding episode of X-ray precursor, ten minutes before the main GRB event, cannot be understood otherwise.

In our model to make GRB-SN in nearly energy equipartition the jet must be very collimated \( \frac{\Delta \Omega}{\Omega_0} \simeq 10^8 \cdot 10^{10} \) \cite{[15, 5, 16]} explaining why apparent (but beamed) GRB luminosity \( \dot{E}_{GR-jet} \simeq 10^{53} \cdot 10^{54} \text{erg s}^{-1} \) coexist on the same place and similar epochs with lower (isotropic) SN powers \( \dot{E}_{SN} \simeq 10^{44} \cdot 10^{45} \text{ergs}^{-1} \). In order to fit the statistics between GRB-SN rates, the jet must have a decaying activity \( (\dot{L} \simeq (\frac{\dot{L}}{t})^{-\alpha}, \alpha \simeq 1) \): it must survive not just for the observed GRB duration but for a much longer timescale, possibly thousands of time longer \( t_o \simeq 10^4 \text{s} \). The late stages of the GRBs (within the same decaying power law) would appear as a SGRs: indeed the same law for GRB output at late time (thousand years) is still valid for SGRs. SGRs are not Magnetar fire-ball explosion but blazing jets.

3 The puzzle of a huge SGR1806-20 flare and the GRB-SGR connection

Indeed the puzzle (for one shot popular Magnetar-Fireball model\cite{[18]}) arises for the surprising giant flare from SGR 1806-20 that occurred on 2004 December 27th: if it has been radiated isotropically (as assumed by the Magnetar model\cite{[18]}), most of - if not all - the magnetic energy stored in the neutron star NS, should have been consumed at once. This should have been reflected into sudden angular velocity loss (and-or its derivative) which was never observed. On the contrary a thin collimated precessing jet \( \dot{E}_{SGR-jet} \simeq 10^{36} \cdot 10^{38} \text{erg s}^{-1} \), blazing on-axis, may be the source of such an apparently (the inverse of the solid beam angle \( \frac{\Delta \Omega}{\Omega_0} \simeq 10^8 \cdot 10^{10} \)) huge bursts \( \dot{E}_{SGR-Flare} \simeq 10^{38} \cdot \frac{\Omega_0}{\Delta \Omega} \simeq 10^{47} \text{erg s}^{-1} \) with a moderate steady jet output power (X-Pulsar, SS433). This explains the absence of any variation in the SGR1806-20 period and its time derivative, contrary to any obvious correlation with the dipole energy loss law.

In our model, the temporal evolution of the angle between the spinning (PSRs), precessing (binary, nutating) jet direction and the rotational axis of the NS, can be expressed as

\[ \theta_1(t) = \sqrt{\theta_x^2 + \theta_y^2} \]
where
\[ \theta_p(t) = \theta_a \cdot \sin \omega_0 t + \cos(\omega_0 t + \phi_b) + \theta_{psr} \cdot \cos(\omega_{psr} t + \phi_{psr}) \cdot |\sin(\omega_N t + \phi_N)| + \theta_s \cdot \cos(\omega_s t + \phi_s) + \theta_N \cdot \cos(\omega_N t + \phi_N) + \theta_y(0) \]
and a similar law express the \( \theta_e(t) \) evolution. The angular velocities and phase labels are self-explained\[16, 17\]. Lorentz factor \( \gamma \) of the jet’s relativistic particles, for the most powerful SGR1806-20 event, and other parameters adopted for the jet model represented in Fig. S are shown in the following Table S (16 17).

| \( \gamma \) = 10\(^0\) | \( \theta_a = 0.2 \) | \( \omega_a = 1.6 \cdot 10^{-8} \) rad/s |
| \( \theta_b = 1 \) | \( \theta_{psr} = 1.5 \cdot 10^7 / \gamma \) | \( \theta_N = 5 \cdot 10^7 / \gamma \) |
| \( \omega_b = 4.9 \cdot 10^{-4} \) rad/s | \( \omega_{psr} = 0.83 \) rad/s | \( \omega_N = 1.38 \cdot 10^{-2} \) rad/s |
| \( \phi_b = 2\pi - 0.44 \) | \( \phi_{psr} = \pi + \pi / 4 \) | \( \phi_N = 3.5 \pi / 2 + \pi / 3 \) |
| \( \phi_s \approx \phi_{psr} \) | \( \theta_s = 1.5 \cdot 10^6 / \gamma \) | \( \omega_s = 25 \) rad/s |

The simplest way to produce the \( \gamma \) emission would be by IC of GeVs electron pairs onto thermal infra-red photons. Also electromagnetic showering of PeV electron pairs by synchrotron emission in galactic fields, \( (e^\pm \text{from muon decay}) \) may be the progenitor of the \( \gamma \) blazing jet. However, the main difficulty for a jet of GeV electrons is that their propagation through the SN radiation field is highly suppressed. UHE muons \( (E_\mu \geq \text{PeV}) \) instead are characterized by a longer interaction length either with the circum-stellar matter and the radiation field, thus they have the advantage to avoid the opacity of the star and escape the dense GRB-SN isotropic radiation field \[16\] \[17\]. We propose that also the emission of SGRs is due to a primary hadronic jet producing ultra relativistic \( e^\pm \) (1 - 10 PeV) from hundreds PeV pions, \( \pi \rightarrow \mu \rightarrow e \), (as well as EeV neutron decay in flight): primary protons can be accelerated by the large magnetic field of the NS up to EeV energy. The protons could in principle emit directly soft gamma rays via synchrotron radiation with the galactic magnetic field \( (E_\gamma \approx 10(E_\mu/EeV)^2(B/2.5 \cdot 10^{-6} G) \) keV), but the efficiency is poor because of the too small proton cross-section, too long timescale of proton synchrotron interactions. By interacting with the local galactic magnetic field relativistic pair electrons lose energy via synchrotron radiation: \( E_\gamma^{sync} = 4.2 \cdot 10^6 (E_\mu/\text{eV})^2(\frac{B}{2.5 \cdot 10^{-6} G}) eV \) with a characteristic timescale \( t^{sync} \approx 1.3 \cdot 10^{10}(\frac{E_\mu}{5 \cdot 10^3 \text{eV}})^{-1}(\frac{B}{2.5 \cdot 10^{-6} G})^{-2} s \). This mechanism would produce a few hundreds keV radiation as it is observed in the intense \( \gamma \)-ray flare from SGR 1806-20.

The Larmor radius is about two orders of magnitude smaller than the synchrotron interaction length and this may imply that the aperture of the showering jet is spread in a fan structure \[13\] \[14\] by the magnetic field, \( \frac{B}{c} \approx 4.1 \cdot 10^8 (\frac{E_\mu}{5 \cdot 10^3 \text{eV}})(\frac{B}{2.5 \cdot 10^{-6} G})^{-1} s \). Therefore the solid angle is here the inverse of the Lorentz factor \( (\sim \text{nsr}) \). In particular a thin \( (\Delta \Omega \approx 10^{-9} \cdot 10^{-10} \text{sr}) \) precessing jet from a pulsar may naturally explain the negligible variation of the spin frequency.
\[ \nu = 1/P \] after the giant flare \((\Delta \nu < 10^{-5} \text{ Hz})\). Indeed it seems quite unlucky that a huge \((E_{\text{flare}} \simeq 5 \cdot 10^{46} \text{ erg})\) explosive event, as the needed mini-fireball by a magnetar model\([18]\), is not leaving any trace in the rotational energy of the SGR 1806-20, \[ E_{\text{rot}} = \frac{1}{2} I N S \omega^2 \simeq 3.6 \cdot 10^{44} \left( \frac{P}{7.5 \text{ s}} \right)^{-2} \left( \frac{I_{10^{-15} \text{ g cm}^2}}{10^{45}} \right) \text{ erg}. \] The consequent fraction of energy lost after the flare is severely bounded by observations: \( \frac{\Delta(E_{\text{rot}})}{E_{\text{flare}}} \leq 10^{-6} \). More absurd in Magnetar-explosive model is the evidence of a brief precursor event (one-second SN output) taking place with no disturbance on SGR1806-20 two minutes before the hugest flare of 2004 Dec. 27th. The thin precessing Jet while being extremely collimated (solid angle \( \Delta \Omega \simeq 10^{-8} \text{ sr} \)) may blaze at different angles within a wide energy range (inverse of \( \Delta \Omega \simeq 10^{8} \text{ sr} \)). The output power may exceed \( \simeq 10^{8} \), explaining the extreme low observed output in GRB980425 - an off-axis event-, the long late off-axis gamma tail by GRB060218\([19]\), respect to the on-axis and more distant GRB990123 (as well as GRB050904).

4 Conclusion

The GRBs are not the most powerful explosions, but just the most collimated ones. Their birth rate is comparable to the SN ones (a few a second in the observable Universe), but their thin beaming \((10^{-8} \text{ sr})\) make them extremely rare \((10^{-8} \text{ s}^{-1})\) rate to point to us at their very birth. The persistent precessing (slow decay of scale time of hours) and moving beam span a wider angle with time and it encompass a larger solid angle increasing the rate by 3 order of magnitude to observed GRB rate; after a few hours \(\simeq 10^4 \text{ s}\), the beam may hit the Earth and appear as a GRB near coincident with a SN. The power law decay mode of the jet make it alive at smaller power days, months and year later, observable only at nearer and middle distance as a Short GRB or (at its jet periphery) as an XRF or in our galaxy as a SGRs. The link with SN is guaranteed in Long GRB, but the jet connection occurs also for Short GRBs whose explosive supernova is faded away months or years earlier. The presence of a huge population of active jets fit a wide spectrum of GRB morphology\([22]\). The nearest (tens-hundred Mpc) are observable mostly off-axis (because of probability arguments) the most distant ones are seen mostly on axis (because threshold cut at lowest fluxes). Now in our Universe thousands of GRBs are shining at SN peak power, but pointing else where. Only one a day might be blazing to us and captured at SWIFT threshold level. Thousand of billions are blazing (unobserved) as SGRs in the Universe. Short GRBs as well SGRs are born in SNRs location and might be revealed in nearby spaces. The GRB-GRS connection with XRay-Pulsars make a possible link to AXRay pulsar jets recently observed in most X-gamma sources as the famous Crab. The possible GRB-GRS link to X-gamma pulsar is a natural possibility to be considered as a grand unification of the model. Our prediction is that a lower threshold, as GLAST-Fermi satellite will induce a higher rate of GRBs both at nearer volumes (as GRB060218 and GRB 980425) and at largest red-shifts.
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Figure 2: The rare NGC 2770 twice SN within a week time: the XRF080109-SN2008D has deep meaning even for most sceptic theorist.

Figure 3: The long XRF luminosity imply a new object or just a SN-GRB jet whose precessing is observed much off-axis, nearly at widest angle.

Figure 4: The long light (B) luminosity imply either multi-explosive activity or just a SN-GRB jet, whose precessing is observed once in or off-axis, producing strong variability.
Figure 5: The long light (J) luminosity imply a SN-GRB jet blazing and precessing in or off-axis, producing strong variability.

Figure 6: The long light (R) luminosity imply new explosions or just a SN-GRB jet whose precessing is observed much off-axis, nearly at widest angle.

Figure 7: Left: The last GRB070616 long X-ray life; right: the puzzling ten-minute X-Ray precursor in GRB060124.
Figure 8: From the left to the right: A possible 3D structure view of the precessing jet obtained with a precessing and spinning, gamma jet; at its center the "explosive" SN-like source for a GRB (or a steady binary system, like Eta-Carina, for a SGRs) where an accretion disc around a compact object, powers a thin collimated precessing jet. In the two center figures, the 3D and the projected 2D of such similar precessing jet. In the right last panel we show an Herbig Haro-like object HH49, whose spiral jets are describing, in our opinion, at a lower energy scale, such precessing Jets as micro-quasars SS-433.

Figure 9: The possible simple beam track of a precessing jet to observer located at origin. On the left, observer stays in (0.00 ; 0.00); the progenitor electron pair jet (leading by IC[3] to a gamma jet) has here a Lorentz factor of a thousand and consequent solid angle at $\sim \mu$ sr. Its consequent blazing light curve corresponding to such a similar outcome observed in GRB041223.
Figure 10: Same as in Fig. 9 a precessing jet and its consequent light curve versus a similar outcome observed in GRB050219b.

Figure 11: The Egg Nebula whose shape might be explained as the conical section of a twin precessing jet interacting with the surrounding ejected gas cloud. Down: The similar observed structure of the outflows from the microquasar SS433. A kinematic model of the time evolution of two oppositely directed precessing jets is overlaid on the radio contours ([12]).