GRBs AND FRBs: SUPRAMASSIVE MAGNETAR AS A COMMON PROGENITOR?

Patrick Das Gupta,
Department of Physics and Astrophysics,
University of Delhi, Delhi - 110007

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GAMMA-RAY BURST SOURCES:

• **Long GRBs are associated with supernovae of type Ib/c $\Rightarrow$ Progenitors are likely to be massive Wolf-Rayet (WR) stars (i.e. stars that have lost their H envelope) $\Rightarrow$ Relatively small helium stars with size $\sim$ few $\times\, 10^{10}$ cm**

• **Long GRB rates are only $\sim 4 \times 10^{-3} - 10^{-2}$ times rates of SN Ib/c (Frail et al. 2001)**

• **Rate per volume of long GRBs has been estimated to be $\sim 10^2 - 10^3$ Gpc^{-3}yr^{-1}**

• **Prompt γ emission is along bi-polar narrow jets with $\Delta\Omega \sim$ 0.01 str (or, equivalently, $\theta_j \sim 0.1$ radian)**

High Lorentz factor of the jet, $\Gamma_j \sim 100 \quad \Rightarrow$ relativistic beaming, $\Delta\theta \sim 0.01 \quad \Rightarrow$ In the prompt emission phase, we see only a tiny fraction of the jet

• Short GRBs ($T_{90} < 2$ s) form only 30% of the total population (in this context, see Rezzolla and Kumar, 2015, for extended X-Ray emissions and magnetars)

FAST RADIO BURSTS:

• Flux density $\sim 0.1 - 10$ Jy at ~ 1 GHz, lasting for $\sim$ few ms

FRBs have been seen at ~ 800 MHz - ~ 2 GHz

• High dispersion measure (DM) $\sim 500 - 1200$ pc cm^{-3}

• **Many of them seen at high Galactic latitudes; FRB 131104 ($E_{rad} \sim 4 \times 10^{41}$ erg) has been identified with a GRB ($E_\gamma \sim 4 \times 10^{50}$ erg; DeLauney et al. 2016; Murase et al. 2017)**

• **If the measured DM is attributed to IGM then FRBs have $z \sim 0.45 - 1 \Rightarrow$ Radio luminosity $\sim 10^{41} - 10^{43}$ erg s^{-1} and radio energy $\sim 10^{38} - 10^{42}$ erg**

• **Only one FRB so far exhibits repeated bursts - FRB 121102.**

• **FRB 121102 is localized within a dwarf galaxy at $z \cong 0.193$ that contains a persistent compact radio-source (Chatterjee et al. 2017; Tendulkar et al. 2017)**

• **The persistent radio-source ($S_\nu \sim 200\ \mu$Jy) and FRB 121102 (flux densities at 1.7 GHz on different occasions range from ~ 0.1 Jy to ~ 4 Jy) are separated by a projected distance less than $\sim$ 40 pc (Marcote et al. 2017)**

• **Exploiting $t_{FF} \sim 1/\sqrt{G\rho_{nuc}} \sim 10^{-3}$ s, Falcke and Rezzolla (2014) have proposed a natural model for FRBs invoking collapse of initially rapidly rotating supra-neutron stars that get spun down due to magnetic braking:**

*** The supra-NS collapses into a black hole leaving its high magnetic field 'hair' and the associated magnetosphere outside the event horizon**

*** Curvature radio-emission due to bunched electrons (positrons) flowing out along the magnetic field lines:**

$$L_{curv} = \frac{2\gamma^4 N_{bunch}^2 e^2 c}{3R^2}$$

$$\approx 10^{42}\ (\frac{N_{bunch}}{1.5 \times 10^{27}})^2(\frac{\gamma}{10^2})^4(\frac{R}{10\ \mathbf{km}})^{-2}\ \mathbf{erg\ s}^{-1}$$

*** Characteristic frequency:**

$$\nu_{curv} = \frac{3\gamma^3 c}{4\pi R} \approx 7.2(\frac{\gamma}{10^2})^3(\frac{R}{10\ \mathbf{km}})^{-1}\ \mathbf{GHz}$$

• **Estimated FRB rate** ~ 0.25 **deg**$^{-2}$ **day**$^{-1}$ **(Thornton et al. 2013)**

All sky rate ~ 2100 **day**$^{-1}$ **for FRBs brighter than** ~ 2 **Jy (Champion et al. 2016)**

$\Rightarrow$ **FRB rate per volume** $\sim 10^4 - 10^5$ **Gpc**$^{-3}$**yr**$^{-1}$

While long GRB rate per volume $\sim 10^2 - 10^3$ **Gpc**$^{-3}$**yr**$^{-1}$

• **Zhang (2013), invoking Falcke-Rezzolla model, has proposed that some FRBs are physically**

associated with GRBs

• In this work, we explore a scenario in which all FRBs and majority of long GRBs are associated with collapse of the central iron core of initial size $\sim 10^8$ cm of massive, rotating Wolf-Rayet stars that leads to a supra-massive neutron star with large kick velocity, high B and rapid rotation, which eventually collapses to form a black hole after $10^3 - 10^4$ s

• Motivation:

*** Anomalous X-Ray pulsars (AXPs) as well as Soft Gamma Repeaters (SGRs) are widely believed to be part of unified class (Kaspi, 2003; Woods and Thompson, 2006; Turolla, Zane and Watts, 2015) $\Rightarrow$ Magnetars (Duncan and Thompson, 1992)**

*** X-Ray plateau followed by steep decay is naturally explained by magnetic braking of a rapidly spinning magnetar (Metzger et al., 2011; Granot et al. 2015)**

*** Can magnetars be the basis for all long GRBs? (For critical analyses, see Granot et al., 2015, Kumar and Zhang, 2015)**

*** SN Ib/c rates and FRB rates are comparable**

- **Basic Picture:**

*** Progenitor of long GRBs and FRBs are massive, rotating WR stars**

*** A rapidly rotating, unstable Fe core of mass**

$2-3\ M_\odot$ **collapses on a time scale of** ~ 1 **s to form a fast spinning supra-massive proto-neutron star (SPNS) with kick velocity ranging from 0 to** $\sim$ **1000 km/s**

*** Because of the rotation and core collapse a spherical region of size** $\sim 10^8$ **cm along with two narrow funnel shaped regions around the spin axis straddling the spherical region are essentially cleared out of baryonic stellar matter of the WR star**

*** If the kick velocity direction of the SPNS lies within the funnel shaped openings, there is no baryon loading problem** $\Rightarrow$ **gamma ray jet can break out of the He envelope giving rise to a long GRB**

If the opening angle θ_F **of the funnel shaped**

region of the WR star is also $\sim$ 0.1 corresponding to $\Delta\Omega_F \sim 0.01$ then the probability that the prompt gamma rays are not quenched is,

$$\approx 2\frac{\Delta\Omega_F}{4\pi} \approx 5 \times 10^{-3}$$

*** If the SPNS moves in any other direction it will encounter the stellar material, and due to baryon loading the γ-rays resulting from electron-positron pairs generated by the neutrino wind would get degraded to softer photons, and there will be no prompt gamma-emission**

*** The SPNS cools and contracts to form the supra-massive neutron star (NS) in $\sim 5 - 10$ s**

*** If $v_{kick} \sim 100$ km/s then the supra-massive NS crosses the spherical evacuated region of size $\sim$ 1000 km in $\sim$ 10 s, before the SPNS becomes**

transparent to the neutrinos

*** Magnetars with high kick velocities have been observed**

Example: For the magnetar Swift J 1834.9-0846, the kick velocity component perpendicular to the line of sight is ~ 580 km/s if it is at a distance 15 kpc (Granot et al. 2006; Granot et al., 2016)

*** The supra-massive magnetar collapses due to the spin down after about $10^3 - 10^4$ s and forms a black hole giving rise to a transient radio-burst**

- **Magnetar spin down:**

Dipole Radiation implies (Granot et al. 2015),

$$P_{em}(t) = \frac{E}{t_{sd}(1 + t/t_{sd})^2}$$

where,

$$E = \frac{1}{2} I\omega_0^2, \qquad t_{sd} = \frac{3c^3 I}{(B_p \omega R^3 \sin\chi)^2}$$

If $M = 2.5\ M_\odot$**,**

$$E = 10^{53}(P/1\ ms)^{-2}(M/2.5\ M_\odot)^{3/2}\ \textbf{erg}$$

where one has used (Lattimer and Schutz, 2005),

$R = 15(M/2.5\,M_\odot)^{1/4}$ **km** $\quad I = 2{\times}10^{45}(M/2.5\,M_\odot)^{3/2}$

and

$$t_{sd} = \frac{3.6 \times 10^2}{\sin^2\chi}(B_p/10^{15}\ G)^{-2}(P/1\ ms)^2\ \ s$$

• But Falcke-Rezzolla model, as it stands, cannot explain repeating FRBs. Can we salvage the model for repeating FRBs?

• We explore two scenarios to salvage the above model for sources like FRB 121102

Scenario I:

Sporadic accretion onto a fast spinning Kerr BH resulting from the collapse of a supra-massive magnetar

- **Blandford-Znajek mechanism:**

- **Potential difference developed due to a rotating horizon of a Kerr BH embedded in an external magnetic field B,**

$$V_{el} \sim \frac{1}{c}(\Omega_H/2\pi)(B.\pi R_{BH}^2)$$

where Ω_H is the angular speed of the horizon,

$$\Omega_H = \frac{J}{M R_s R_{BH}}$$

$$R_s = \frac{2GM}{c^2}$$

$$R_{BH} = \frac{R_s}{2} + \sqrt{(\frac{R_s}{2})^2 - (\frac{J}{Mc})^2}$$

- **Mining of the rotational energy of the BH**

via B-Z process leads to radiated power,

$$L_{B-Z} \approx \textbf{current} \times V_{el} \sim\sim \frac{V_{el}^2}{\mathcal{R}} \sim \frac{c\ V_{el}^2}{4}$$

• **For extremal BHs,**

$$J = cMR_s/2 \Rightarrow R_{BH} = R_s/2 \Rightarrow \Omega_H = \frac{c}{R_s} \Rightarrow V_{el} \sim R_s B/8$$

$$\Rightarrow L_{B-Z} \approx \frac{cB^2 R_s^2}{256}$$

$$= 5.58 \times 10^{42} (B/3.2 \times 10^{11}\ G)^2\ (M/2.3\ M_\odot)^2\ \textbf{erg s}^{-1}$$

• **Sporadic relativistic electron wind towards FRB 121102 by the persistent radio-source < 40 pc far can cause radio-bursts arising out of B-Z mechanism**

Caveats:

*** Requires large B $\sim 10^{11}$ G to be still present near the event horizon of the Kerr BH. Question is whether when a magnetar with polar B field $\sim 10^{14} - 10^{15}$ G collapses to form a BH,**

a vestigial plasma with field $\sim 10^{11}$ is retained near the event horizon (In the context of GRB modeling, Contopoulos et al 2017 claim that $B \sim 10^4$ G can hover near the horizon)

*** Accretion of plasma cannot generate such high B field since the Eddington limit for B is,**

$$B_{Edd} = \sqrt{\frac{8\pi c^4 m_p}{\sigma_T G M}} \cong 2 \times 10^8 \ (M/2.3 \ M_\odot)^{-1/2} \ G$$

Scenario II:

The core of the Magnetar that collapses has angular momentum too large to form a Black hole

•

$$R_{BH} = \frac{R_s}{2} + \sqrt{(\frac{R_s}{2})^2 - (\frac{J}{Mc})^2}$$

• **Initial angular momentum of the supra-massive magnetar,**

$$J_0 \sim M_0 R_0^2 \Omega_0$$

with,

$$\Omega_0 < \Omega_{Break-up} = \sqrt{\frac{GM_0}{R_0^3}}$$

As it spins down due to magnetic dipole radiation, it starts collapsing on time scales $1/\sqrt{G\rho_{nuc}}$ satisfying,

$$M_0 R^2(t)\Omega(t) \sim \beta J_0$$

where $\beta < 1$.

•The equatorial region forms a disc-like structure while the core of mass M_c and angular momentum J_c collapses

$$M_c = M_0 - M_{disc}$$

$$J_c = \beta J_0 - J_{disc}$$

• Assuming the disc to be thin so that angular momentum per unit mass is $\sqrt{GM_c r}$, one gets:

$$J_c \approx \beta J_0 [1 - \frac{8}{5}(1 - M_c/M_0)(M_c/M_0)^{1/2}]$$

• **No black hole formation if**

$$J_c > \frac{GM_c^2}{c} \Rightarrow J_0 > \frac{GM_c^2}{c\beta[1 - \frac{8}{5}(1 - M_c/M_0)(M_c/M_0)^{1/2}]}$$

• **For** $\beta \sim 0.8$, $M_0 = 2.3\ M_\odot$ **and** $M_c \sim 1.4\ M_\odot$**:**

$$\Omega_0 > 9 \times 10^3\ rad\ s^{-1}$$

for no black hole formation, while for $M_0 = 2.3\ M_\odot$,

$$\Omega_{Break-up} = 1.75 \times 10^4\ rad\ s^{-1}$$

• **What happens to the collapsed core? It becomes a strange star when the density becomes greater than** $5 \times 10^{14} gm\ cm^{-3}$ **(Witten 1984; Alcock et al. 1986)**

• **Signatures: Emission of thermal photons and neutrinos in a burst**

• **The strange star will have an outward electric field** $\approx 5 \times 10^{17}\ -\ 10^{18}$ **V/cm that manages to**

hold on to a layer of electrons few fm thick (Alcock et al. 1986)

- **Mannarelli et al. 2014 have shown that torsional oscillation of the thin electron cloud relative to the positively charged strange star can cause emission of GHz radiowaves with luminosity $\sim 10^{45}$ erg/s.**

- **Torsional oscillations can be excited by relativistic wind from the persistent radio-source near FRB 121102**

CONCLUSION

• **Collapse of spun down supra-NS is a natural framework to describe both GRBs and FRBs if pre-natal kicks are included**

• **Repeating bursts from FRB 121102 may also be explained either by (a) invoking intermittent Blandford-Znajek processes around the collapsed black hole or by (a) torsional oscillations of electrons close to the surface of a bare strange star**

THANK YOU