GRB 130831A: Rise and Fall of a Magnetar at z = 0.5

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Long duration Gamma-ray Bursts

- Cosmological sources, z from 0.0085 to 9.4

- Able to produce up to $10^{55}$ erg ($\sim 5 M_\odot c^2$) in prompt $\gamma$-ray and X-ray emission

- Power long-living “afterglows” visible in radio, optical, X-ray

- Associated with the death of massive stars

Basic questions on the physics of their sources are still open, for example:

- What is the central engine (black hole, magnetar, something exotic) and how does it work?

- What are the mechanism(s) that emit the high-energy radiation? How long can this emission last?
Prompt emission: produced by dissipation process(es) (shocks, magnetic reconnection, …) within the ultra-relativistic ejecta. As a consequence, it can vary and die very quickly.

Afterglows: synchrotron radiation by electrons of the circumburst medium, energized by the forward shock (FS) driven by the ejecta.

\[ F_\nu \approx t^{-\alpha} \nu^{-\beta} \]

FS emission fades with time but it lasts forever…
Typical FS afterglows vs “internal” afterglows

X-ray and opt afterglows decays follow a “canonical model”.

Plateaux then slightly steeper decays, explained as FS emission

However, a few X-ray afterglow plateaux give way to fast decay with $\alpha \sim 5 - 9$

can’t be interpreted as FS emission

It’s still internal dissipation

Testable and important prediction of the “internal emission” afterglow scenario:

Once high energy internal emission turns off, the X-ray flux will drop until the underlying, slowly decaying FS emission becomes dominant

The steep decay will end and give way to a slow decay, similar to that in the optical
Enter Swift GRB 130831A

- Detected by Swift and Konus;
- Bright and well sampled X-ray and optical afterglow;
- $z = 0.48$, spectroscopic detection of SN 2013fu (Cano et al. 2014)

- XRT detects a plateau followed by a very steep decay, with slope $\alpha \sim 7$, at $10^5$ s;
- Late Chandra DDT observations (PI: De Pasquale) show a new, slowly decaying component
- The optical LCs show an unbroken power-law decay; slope consistent with late X-ray
Early emission: signature of magnetar “central engine”?

Energy source: spin down process

**Basic Scenario:** B constant

Luminosity $L$ roughly constant up to $\tau$

$$L(t) = L_0 \frac{1}{(1 + t/\tau)^2} \approx \begin{cases} L_0, & t \ll \tau, \\ L_0(t/\tau)^{-2}, & t \gg \tau. \end{cases}$$

**More realistic scenario** B decays as P increases

$$B = 10^{16} R_6^{-1/2} P_{-3}^{-1} \, \text{G}$$

Luminosity decreases with time

Once the magnetar has spun down, it may collapse into a BH

$$T_{\text{collapse}} \approx 6 \times 10^4 \, \text{s}$$

...and drops dead

Late emission: Forward Shock

Built UVOIR and X-ray SED at 173 ks (2 days)

SED fitted by a simple power-law model:

\[ \beta_{OX} = 1.03 \pm 0.05 \]

The FS model predicts relations between decay and spectral slopes \( \alpha, \beta \) (Sari et al 98, Chevalier & Li 2000)

<table>
<thead>
<tr>
<th>( \nu )</th>
<th>ISM</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &lt; \nu_c )</td>
<td>( \alpha - \frac{3}{2} \beta = 0 )</td>
<td>( \alpha - \frac{3}{2} \beta - \frac{1}{2} = 0 )</td>
</tr>
<tr>
<td>( \beta = \frac{p-1}{2} )</td>
<td>( = 0.03 \pm 0.08 )</td>
<td>( -0.47 \pm 0.08 )</td>
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<tr>
<td>( &gt; \nu_c )</td>
<td>( \alpha - \frac{3}{2} \beta + \frac{1}{2} = 0 )</td>
<td>( \alpha - \frac{3}{2} \beta + 1/2 = 0 )</td>
</tr>
<tr>
<td>( \beta = \frac{p}{2} )</td>
<td>( = 0.53 \pm 0.08 )</td>
<td>( 0.53 \pm 0.08 )</td>
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</tbody>
</table>

FS prediction correct

ISM

\( \nu < \nu_c \)

\( p = 3.06 \pm 0.10 \)
Energy breakdown

Known parameters:

\[ E_{K,iso,52} = \left[ \frac{\nu F_{\nu}(\nu = 10^{18} \text{ Hz})}{6.5 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2}} \right]^{4/(p+3)} \times D_{28}^{8/(p+3)} (1 + z)^{-1} t_d^{3(p-1)/(p+3)} \times f_p^{-4/(p+3)} \epsilon_{B,-2}^{-(p+1)/(p+3)} \epsilon_{e,-1}^{4(1-p)/(p+3)} \times n^{-2/(p+3)} \nu_{18}^{2(p-3)/(p+3)}. \]

Knowing \( p = 3.06 \) and FS flux \( F = 7 \times 10^{-14} \text{ cgs} \)

Assuming typical \( \epsilon_e = 0.3, \epsilon_B = 0.002; n=0.001 \)

We find: \( E_{K,iso} = 11.8 \times 10^{52} \text{ erg} \)

Knowing prompt \( \gamma \)-ray fluence and \( z \) of GRB 130831A, we infer \( E_{\gamma,iso} = 1.1 \times 10^{52} \text{ erg} \)

Luminosity of X-ray “internal emission” up to 100 ks: \( E_{X,iso} = 2.8 \times 10^{50} \text{ erg} \)

The (non-relativistic) kinetic energy of the associated SN 2013fu: \( E_{SN} = 1.9 \times 10^{52} \text{ erg} \)

Total energy produced \( E_{tot} = E_{K,iso} + E_{\gamma,iso} + E_{X,iso} + E_{SN} = 1.5 \times 10^{53} \text{ erg} \)
Magnetar engine energetics

Magnetar energy reservoir is rotational energy:

\[ E_{\text{rot}} = \frac{1}{2} I \omega^2 = 3 \times 10^{52} \left( \frac{M}{1.4M_\odot} \right) \left( \frac{R}{12\text{km}} \right)^2 P_{\text{ms}}^{-2} \text{ erg} \]

Thus, an \( E_{\text{tot}} = 1.5 \times 10^{53} \text{ erg} \) rules out a magnetar?

Not necessarily. We have assumed isotropic emission. GRBs are collimated sources!
Jet expansion: break in the FS light curve

Knowing $t_{\text{jet}}$, $E_K$, redshift $z$, assuming reasonable $n$, we get $\theta_{\text{jet}}$:

$$\theta_{\text{jet}} = 0.12 \left( \frac{t_{\text{jet},d}}{1+z} \right)^{3/8} \left( \frac{E_{K,53}}{n} \right)^{-1/8} \text{ rad}$$

Beaming-corrected energy:

$$E_{\text{corr}} = E_{\text{iso}} \times \theta_{\text{jet}}^2 / 2$$

$f_b \leq 1$
No jet break: lower limit on $\theta_{\text{jet}}$ and energetics

$\theta_{\text{jet}} \geq 0.12$ rad $\rightarrow f_b \geq 0.008 \rightarrow E_{\text{tot}} \geq 2e+52$ erg (less than the magnetar limit)

If we had $f_b = 0.1 \rightarrow E_{\text{tot}} = 3e+52$ erg (the magnetar limit)
Summary of energy breakdowns

<table>
<thead>
<tr>
<th>Beaming factor $f_b$</th>
<th>$E_{\text{tot,52}}$</th>
<th>$E_{\gamma, \text{corr}}$</th>
<th>$E_{X, \text{corr}}$</th>
<th>$E_{K, \text{corr}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008 (lower limit)</td>
<td>2.0</td>
<td>0.4%</td>
<td>0.01%</td>
<td>4.5%</td>
</tr>
<tr>
<td>0.1 (magnetar limit)</td>
<td>3.0</td>
<td>3.3%</td>
<td>0.1%</td>
<td>37%</td>
</tr>
<tr>
<td>1 (isotropic outflow)</td>
<td>15</td>
<td>0.4%</td>
<td>0.2%</td>
<td>80%</td>
</tr>
</tbody>
</table>

$$E_{\text{tot}} = E_{\gamma} + E_{X} + E_{K} + E_{\text{SN}}$$

Comments

- The energy emitted in X-ray of “internal origin” is always small: 0.2% or less;
- Much more energy is produced in prompt $\gamma$-ray emission: 20-40 times as much;
- At least 4.5% of energy explosion goes into kinetic energy of relativistic ejecta (but no more than $\sim$37% if the central engine is a magnetar).
Conclusions

- We’ve studied the Swift GRB 130831A: its X-ray light-curve shows a very steep break unexplained by the standard Forward Shock model. Such behaviour can be interpreted instead as the end of spin-down emission by a newly born magnetar.

- The late X-ray afterglow, detected by DDT Chandra observations, and the well sampled optical LCs show a more slowly decaying component, interpreted as emergence of an underlying Forward Shock emission.

- Modeling this late FS emission, we infer the kinetic energy of relativistic ejecta $E_K$; and gathering the energetics of the $\gamma$-ray prompt emission $E_\gamma$, the X-ray emission of “internal origin” $E_X$, and the kinetic energy of SN 2013fu, we work out the breakdown of the total energy of the explosion. This is the energy breakdown for a GRB with internal emission, associated SN, and likely magnetar central engine.

- We find that, regardless of the beaming, $\leq 0.2\%$ of all energy goes into $E_X$, while 20-40 times as much goes into $E_\gamma$; at least 4% of all energy goes into relativistic kinetic energy (less than 37% if the central engine is a magnetar).
What kind of “central engine” we have got?

A new magnetar is born
Spin-down process temporarily overcome the typical, FS-powered afterglow

Fall-back disk around a newly formed black hole
Depending on the star envelope and disk viscosity, different LCs might be produced, including steep drops

Kumar et al. 2008, Wu et al. 2013
A fall-back black hole?

**Low viscosity disk**

**Pro:** it can explain a $10^4 - 10^5$ s plateau.

**Con:** it predicts a post-plateau decay slope of $\alpha \sim 1.3$, whereas we have $\alpha \sim 7$.

**High viscosity disk;** $L \sim \dot{M}$

**Pro:** it might explain the post-plateau $\alpha \sim 7$.

**Con:** Fall back and Accretion for $\sim 10^5$ s required. To explain the plateau $\alpha \sim 0.8$ and steep drop, one needs non-standard density profile and low angular momentum of the progenitor envelope.

**Merger of a compact object with a WR star** (Barkov & Komissarov 2010)

**Pro:** luminosity and accretion time scale may be in the right range.

**Con:** same as above.
What are the newly born magnetar parameters?

\[
L_0 = 1.0 \times 10^{49} \text{ erg s}^{-1} (B_{p,15}^2 P_{0,-3}^{-4} R_6^6)
\]
\[
\tau = 2.05 \times 10^3 \text{ s} (I_{45} B_{p,15}^{-2} P_{0,-3}^2 R_6^{-6})
\]

\(P_0 \sim 1\text{-}10\text{ms}, B_p \sim 10^{15\text{-}16} \text{ G} \) can explain most bursts with internal plateau.

For GRB130831A:

\(B \sim 3.5 \times 10^{14} \text{ G}, P_0 = 2 \text{ ms}:\)

\(L_0 = 10^{47} \text{ erg/s}, 1 \text{ order of magnitude larger than observed but can’t see all the emission!}\)

\(\tau = 70000 \text{ s}; (1+z) = 10^5 \text{ s}, \text{ as observed}\)
SN 2013fu associated to GRB 130831A

\[ M_v = -19.2 \pm 0.2 \]

\[ 0.85 \times \text{SN1998bw} \]

\[ M_{Ni} = 0.30 \pm 0.07 \, M_{\odot} \]

\[ M_{ej} = 4.7 +0.8_{-0.6} \, M_{\odot} \]

\[ E_K = 1.9 +0.9_{-0.6} \times 10^{51} \, \text{erg} \]

Cano et al. 2014
Is the slow decay after the steep drop real?

Fit with one power-law: $\chi^2 / \text{d.o.f.} = 17.8 / 5$

Fit with 2 power-law’s: $\chi^2 / \text{d.o.f.} = 2.4 / 3$

$F (1.5 \text{ Ms}) \approx 5 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$: no detection at all, even with Chandra!

Instead, Chandra ToO at 1.5 Ms yielded 8 counts, i.e. $\approx 5.4 \sigma$ detection
How robust is our estimate of $E_K$?

Kinetic energy $E_K$ does depend on assumptions on $\varepsilon_e$, $\varepsilon_B$ and $n$. However:

cooling frequency $\nu_c$ above X-ray band implies that $\varepsilon_B$ and $n$ cannot be much larger than the assumed $2 \times 10^{-3}$ and $10^{-3}$:

$$\nu_c \sim \varepsilon_B^{-3/2} n^{-1} t^{-1/2} >> \nu_X \text{ at } t = 2 \text{ days;}$$

On the other hand, $n < 10^{-3}$ is not expected for long GRBs which occur in dense star forming regions, and $\varepsilon_B < 0.001$ may produce IC, which is not observed;

$\varepsilon_e$ cannot be much lower than 0.3: $\nu_m \sim \varepsilon_e^2 t^{-3/2}$ and, for $\varepsilon_e < \sim 0.25$, the synchrotron peak would be close to the radio band and violate EVLA radio upper limits.

Our estimate on $E_K$ is therefore robust at least as order of magnitude