"Inner engine" of the Gamma-Ray Bursts (GRBs)

The Fourth Zeldovich virtual meeting

R. Moradi

in collaboration with
R. Ruffini, J. A. Rueda, N. Sahakyan Y. Wang, Liang Li, L. Becerra, C. L. Bianco, S. S. Xue

ICRANet and Sapienza University of Rome

September 7, 2020
Outline

1. **GRB190114C**
   - Observation and prediction

2. **GeV radiation**
   - Satellites

3. **The properties of “inner engine”**
   - Black hole in a uniform magnetic field: Killing vectors as Maxwell field
   - Electromagnetic field

4. **Synchrotron emission from the Wald solution and the first elementary impulsive event**
   - Timescale of the first impulsive event after the UPE phase

5. **Self-consistent inference of the BH mass and spin, as well as of the magnetic field**

6. **The decrease of the BH mass and spin due to the extracted rotational energy**

7. **Synchrotron radiation power and the need of a low density ionized plasma**

8. **Ultra-relativistic Prompt Emission phase (UPE)**

9. **Transparency at the UPE phase**

10. **Transparency of GeV photons in the UPE phase**

11. **X-ray afterglow powered by the $\nu$NS**
GRB190114C

Observation and prediction

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Ultra-relativistic Prompt Emission phase (UPE)

Transparency at the UPE phase

Transparency of GeV photons in the UPE phase

X-ray afterglow powered by the $\nu$NS
At 20:57:02.63 UT on 14 January 2019, Fermi-GBM was triggered by GRB 190114C. Following the 0.37 second at 20:57:03 UT on 14 January 2019, the Neil Gehrels Swift Burst Alert Telescope (BAT) was triggered as well by GRB 190114C.

The Fermi-LAT had a boresight angle of 68 deg at the trigger time, the GRB remained in the field of view of Fermi-LAT for 150 seconds.

Nordic Optical Telescope (NOT) announced by GCN23695 the redshift of 0.424.

At time 15:29:54 GMT on January 15, 2019 we identified by GCN23715 this GRB as a BdHN I, and predicted that an optical SN should appear in the same location of the GRB within $18.8 \pm 3.7$ days, which indeed was confirmed by Melandri et al.

This successful prediction and the following detection of TeV radiation by MAGIC have made GRB 190114C as a prototype which all the BdHN phases have been observed.
BdHN I include three different components:

1. a CO core undergoing a SN explosion in presence of a binary NS companion;
2. an additional NS originating from the SN explosion indicated as a $\nu$NS (the newborn NS at the center of the SN), accreting the SN ejecta and giving origin to the afterglow;
3. the formation of the BH by the hypercritical accretion of the SN ejecta onto the NS reaching its critical mass. The newborn BH originates the GeV emission. Coincidence of these effect, the birth of BH and the onset of the GeV emission has been narrow down by our to $10^{-6}$ s.
GRB190114C

Observation and prediction

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The earliest evidence for high energy radiation over 100 MeV from GRBs where the detection by the Energetic Gamma-Ray Experiment Telescope (EGRET)

EGRET operates in the energy range 20 MeV-30 GeV, onboard of the Compton Gamma-Ray Observatory (CGRO, 1991-2000)

The detection was triggered by the Burst And Transient Source Experiment (BATSE), operating in energy range of 20-2000 keV.

EGRET has detected five GRBs, from our understanding today, all 5 GRBs where long GRBs: GRB 910503, GRB 910601, GRB 930131, GRB 940217, and GRB 940301.

Unfortunately no redshift were known at the time.
AGILE and FERMI

- A new era started with the launch of AGILE in 2007 with onboard Gamma Ray Imaging Detector (GRID).
- AGILE GRID operates in the 30 MeV-50 GeV energy range.
- June 2008 of the Fermi satellite, having onboard the Large Area Telescope (LAT) operating from early August 2008 in 20 MeV to 300 GeV.
**GeV radiation**

Satellites

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![Graph 1](Image)

- **Episode 1**
- **Episode 2**
- **Episode 3**

![Graph 2](Image)

- **Probability: < 50%**
- **Probability: 50% - 80%**
- **Probability: > 80%**
190114C: (2.7s-5.5s). $\alpha = -0.71, E_x = 717.56\text{keV}, kT = 111.64\text{keV}$

```
10^3

10^2

10^1

10^0

10^{-1}

10^{-2}

keV x [keV$^{-1}$s$^{-1}$cm$^{-2}$]

10^3

10^2

10^1

10^0

10^{-1}

10^{-2}

keV

Cut_Powerlaw
Blackbody
Model Total
Data
```
**GeV radiation**

**Satellites**

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<th>S</th>
<th>E</th>
<th>L</th>
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**“Inner engine” of the Gamma-Ray Bursts (GRBs)**

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GeV radiation

Satellites

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“Inner engine” of the Gamma-Ray Bursts (GRBs)

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The rest-frame 0.1–100 GeV luminosity light-curve of GRB 190114C obtained from *Fermi*-LAT, respectively. The green line shows the best fit for power-law behavior of the luminosity with slope of $1.2 \pm 0.04$ and amplitude of $7.75 \times 10^{52}$ erg s$^{-1}$.
a) Wilson, J. R. 1975, in Annals of the New York Academy of Sciences

The properties of “inner engine”

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Killing vectors and Maxwell field

\[ \mathcal{L}_\zeta g_{\mu\nu} = \zeta_{\mu;\nu} + \zeta_{\nu;\mu} \]

- **Papapetrou**: Killing vector in vacuum space-time generates a solution of Maxwell’s equations in that space-time.

- The solution of electromagnetic test-field which occurs when a stationary, axisymmetric black hole is placed in an originally uniform magnetic field of strength \( B_0 \) aligned along the symmetry axis of rotation of the black hole is

\[ F = \frac{1}{2} B_0 (d\psi + \frac{2J}{M} d\eta) \]

J: angular momentum, M: mass of the black hole, \( \psi \): axial Killing vector, \( \eta \): timelike Killing vector.
The Kerr space-time metric (geometric units will be considered), which is stationary and axisymmetric, in standard Boyer-Lindquist (BL) coordinates reads

\[
\begin{align*}
\text{ds}^2 &= - \left( 1 - \frac{2Mr}{\Sigma} \right) dt^2 - \frac{4aMr \sin^2 \theta}{\Sigma} dtd\phi + \frac{\Sigma}{\Delta} dr^2 \\
&+ \Sigma d\theta^2 + \left[ r^2 + a^2 + \frac{2Mra^2 \sin^2 \theta}{\Sigma} \right] \sin^2 \theta d\phi^2,
\end{align*}
\]

(1)

where \( \Sigma = r^2 + a^2 \cos^2 \theta \) and \( \Delta = r^2 - 2Mr + a^2 \). The (outer) event horizon is located at \( r_+ = M + \sqrt{M^2 - a^2} \). 

The properties of “inner engine”

Black hole in a uniform magnetic field: Killing vectors as Maxwell field
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The electromagnetic field of the central engine in orthonormal tetrad is:

\[
E^r = \frac{aB_0}{\Sigma} \left( r \sin^2 \theta - \frac{M(\cos^2 \theta + 1)}{\Sigma} \left( r^2 - a^2 \cos^2 \theta \right) \right),
\]

\[
E^\theta = \frac{aB_0}{\Sigma} \sin \theta \cos \theta \sqrt{\Delta},
\]

\[
B^r = -\frac{B_0 \cos \theta \left( -\frac{2a^2 M r (\cos^2 \theta + 1)}{\Sigma} + a^2 + r^2 \right)}{\Sigma},
\]

\[
B^\theta = \frac{B_0 r}{\Sigma} \sin \theta \sqrt{\Delta}.
\]
we here for simplicity evaluate the field in the polar direction $\theta = 0$:

\[
E_\phi = -B_0 \frac{2J (r^2 - a^2)}{(r^2 + a^2)^2} \quad (6)
\]

\[
E_\theta = 0 \quad (7)
\]

\[
B_\phi = B_0 \left( -\frac{4Ja}{(r^2+a^2)} + a^2 + r^2 \right) \frac{1}{(r^2 + a^2)} \quad (8)
\]

\[
B_\theta = 0. \quad (9)
\]

similar to Kerr-Newman Geometry when $Q_{\text{eff}} = 2B_0J$. 

$\theta = 0$: 

\[
E_\phi = -B_0 \frac{2J (r^2 - a^2)}{(r^2 + a^2)^2}
\]

\[
E_\theta = 0
\]

\[
B_\phi = B_0 \left( -\frac{4Ja}{(r^2+a^2)} + a^2 + r^2 \right) \frac{1}{(r^2 + a^2)}
\]

\[
B_\theta = 0.
\]
Figure 4.5 The electromagnetic field lines of the Wald solution. The blue lines show the magnetic field lines and the violet show the electric field lines. **a:** Magnetic field is “parallel” to the spin of the Kerr BH, so parallel to the rotation axis. On the polar axis up to $\theta \sim \pi/3$ electric field lines are inwardly directed, therefore electrons are accelerated away from the BH. For $\theta > \pi/3$ electric field lines are outwardly directed and consequently protons are accelerated away from the BH. **b:** Magnetic field is “antiparallel” to the Kerr BH rotation axis. On the polar axis up to $\theta \sim \pi/3$ electric field lines are outwardly directed, therefore protons will be accelerated away from the BH. For $\theta > \pi/3$ electric field lines are inwardly directed and consequently electrons will be accelerated away from the BH.
The total electromagnetic energy contained in the whole space-time using this is obtained by

$$\mathcal{E} = \frac{(2B_0J)^2}{4r_+} + \frac{1}{4} \frac{(2B_0J)^2}{ar_+^2} (r_+^2 + a^2) \arctan \frac{a}{r_+},$$  \hspace{1cm} (10)

In the range $\alpha \lesssim 0.7$ reduces to

$$\mathcal{E} \approx \frac{(2B_0J)^2}{2r_+} = 1.25 \times 10^{43} \frac{\beta^2 \alpha^2 \mu^3}{1 + \sqrt{1 - \alpha^2}} \text{ erg},$$  \hspace{1cm} (11)

where we have introduced the notation $\beta = B_0/B_c$ and $\mu = M/M_\odot$.

The total electrostatic injection (potential) energy available to accelerate particles of charge $e$ (along the rotation axis) is

$$\epsilon = e \frac{B_0 J}{M} \approx 1.96 \times 10^{21} \beta \alpha \mu \text{ eV}.$$  \hspace{1cm} (12)
We assume that the magnetic field and the spin of the BH are parallel: along the symmetry axis direction electrons in the surrounding ionized medium are repelled, while protons are pulled into the BH.
Synchrotron emission from the Wald solution and the first elementary impulsive event

The relativistic expression for the Lorentz force is

$$\frac{dp^\mu}{d\tau} = \frac{e}{c} F^{\mu\nu} u_\nu, \quad p^\mu = m u^\mu, \quad u^\mu = \frac{dx^\mu}{d\tau},$$

(13)

- $\tau$ is the proper time
- $p^\mu$ is the four-momentum
- $u^\mu$ is the four-velocity
- $x^\mu$ are the coordinates
- $F^{\mu\nu}$ is the electromagnetic field tensor
- $m$ is the particle mass, $e$ is the elementary charge and $c$ is the speed of light.
In the laboratory frame using vector notation:

\[ mc \frac{d (\gamma \mathbf{v})}{dt} = e (\mathbf{E} + \mathbf{v} \times \mathbf{B}). \]  

(14)

Assuming the one-dimensional motion along the radial directions, the dynamics of the electrons in the electromagnetic field, for \( \gamma \gg 1 \), is determined by the equation

\[ m_e c^2 \frac{d\gamma}{dt} = e \frac{1}{2} \alpha B_0 c^2 - \frac{2}{3} e^4 \frac{B_0^2 \sin^2 \langle \theta \rangle}{m_e^2 c^3} \gamma^2 c^2, \]  

(15)

- \( \gamma \) is the electron Lorentz factor
- \( \langle \theta \rangle \) is the injection angle between the direction of electron motion and the magnetic field
- \( m_e \) is the electron mass.
- solved with an initial Lorentz factor of \( \gamma = 1 \) at \( t = 0 \).
Assuming all parameters are constant, the approximate solution in the limit $\gamma \gg 1$ has the following asymptotic value:

$$\gamma = \begin{cases} 
\frac{1}{2} \frac{B_0}{B_c} \alpha \frac{t}{\hbar/m_e c^2}, & t \ll t_c, \\
\gamma_{\text{max}} = \frac{1}{2} \left( \frac{3e^2}{\hbar c} \alpha \frac{B_c}{B_0 \sin^2 \langle \theta \rangle} \right)^{1/2}, & t \gg t_c,
\end{cases}$$

(16)

where the critical time is

$$t_c = \frac{\hbar}{m_e c^2 \sin \langle \theta \rangle} \left[ \frac{e^2}{\hbar c} \left( \frac{B_0}{B_c} \right)^3 \alpha \right]^{-1/2}.$$  

(17)

The maximum peak photon energy of the synchrotron spectrum is obtained by using the maximum Lorentz factor of the radiating electrons which is given by the equilibrium between energy gain and energy. Consequently, the following maximum energy of the electron-synchrotron photons is found:

$$\epsilon_{\text{max}, \gamma} = \frac{3e\hbar}{2m_e c} B_0 \sin \langle \theta \rangle \gamma_{\text{max}}^2 = \frac{9}{8} \frac{m_e c^2}{e^2/\hbar c \sin \langle \theta \rangle} \frac{\alpha}{\alpha \sin \langle \theta \rangle} \approx \frac{80}{\sin \langle \theta \rangle} \alpha \text{MeV}.$$  

(18)

The maximum energy is independent of the magnetic field strength, which for different angles leads to different energy bands for the photons.
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Ultra-relativistic Prompt Emission phase (UPE)

Transparency at the UPE phase

Transparency of GeV photons in the UPE phase

X-ray afterglow powered by the νNS
The timescale of the first impulsive event after the UPE phase is given by

$$\tau_1 = \frac{\mathcal{E}_{t_{\text{rf}}=3.99\ \text{s}}}{L_{\text{GeV}}(t_{\text{rf}}=3.99\ \text{s})} = 8.54 \times 10^{-10} \frac{\beta^2 \alpha^2 \mu^3}{1 + \sqrt{1 - \alpha^2}} \text{ s}$$

(19)

where $L_{\text{GeV}}(t_{\text{rf}} = 3.99\ \text{s})$ and $\mathcal{E}_1 \equiv \mathcal{E}_{t_{\text{rf}}=3.99\ \text{s}}$ are the GeV luminosity and the energy of the first elementary event after the UPE phase evaluated at $t_{\text{rf}} = 3.99\ \text{s}$. 
Self-consistent inference of the BH mass and spin, as well as of the magnetic field.

Three unknown parameters

1. mass of BH $\mu = \frac{M}{M_\odot}$
2. spin parameter $\alpha = \frac{a}{M}$
3. Magnetic field $\beta = \frac{B_0}{B_c}$

The first equation to determine these three parameters has been determine by the requiring that the rotational energy of the BH guarantees the observed GeV energetics.

$$E_{\text{GeV}} = E_{\text{extr}} = (1.8 \pm 1.3) \times 10^{53} \text{ erg.} \quad (20)$$
We used the mass-energy formula of the Kerr BH,

\[
M^2 = \frac{J^2}{4M_{irr}^2} + M_{irr}^2, \quad (21.1)
\]

\[
S = 16\pi M_{irr}^2, \quad (21.2)
\]

\[
\delta S = 32\pi M_{irr}\delta M_{irr} \geq 0, \quad (21.3)
\]

\[
E_{ext} = M - M_{irr} \quad (21.4)
\]

where \(J, M, M_{irr}\) and \(S\) are the angular momentum, mass, irreducible mass and horizon surface area of the Kerr BH, from which we obtain consequently the extractable energy (in \(c = G = 1\) units).

Analogy: \(E^2 = M^2 = p^2 + M_0^2\)

Hawking, S. W. 1971, Physical Review Letters, 26, 1344
The second equation comes by requiring that the GeV synchrotron-produced photons, be transparent to the $e^+e^-$ pair creation process in the external magnetic field. The inverse of the attenuation coefficient

$$\bar{R} \sim 0.23 \frac{e^2}{\hbar c} \left( \frac{\hbar}{m_e c^2} \right)^{-1} \beta \sin \langle \theta \rangle \exp \left( -\frac{4/3}{2m_e c^2 \beta \sin \langle \theta \rangle} \right).$$  \hspace{1cm} (22)

Imposing the following transparency condition for 0.1 GeV photons, $\bar{R}^{-1} \geq 10^{16}$ cm, we obtain:

$$\beta \leq 3.67 \times 10^{-4} \alpha^{-1},$$  \hspace{1cm} (23)
By requesting that the timescale of the synchrotron radiation timescale obtained at the time $t_{\text{rf}} = 3.99$ s. t

$$\tau_1 = t_c$$  \hspace{1cm} (24)
The following set of three equations must be solved simultaneously:

\[ E_{\text{GeV}} = E_{\text{extr}}(\mu, \alpha) \quad (25) \]
\[ \beta = 3.67 \times 10^{-4} \alpha^{-1} \quad (26) \]
\[ t_c(\langle \theta \rangle, \alpha, \beta) = \tau_{\text{ob}, 1}(\mu, \alpha, \beta, L_{\text{GeV}}) \quad (27) \]
Solving simultaneously

\[
\mu = \left(1 - \sqrt{\frac{1 + \sqrt{1 - \alpha^2}}{2}} \right)^{-1} \frac{E_{\text{GeV}}}{M_\odot c^2}.
\] (28)

\[
\beta = \beta(\epsilon_\gamma, E_{\text{GeV}}, L_{\text{GeV}}, \alpha)
\]

\[
= \frac{1}{\alpha} \left( \frac{64}{9} \sqrt{3} \frac{e^2}{\hbar c} \frac{\epsilon_\gamma}{B_c^2 r_+(\mu, \alpha)} \frac{L_{\text{GeV}}}{e B_c c^2} \right)^{2/7},
\] (29)

\[
\beta \leq 3.67 \times 10^{-4} \alpha^{-1},
\] (30)

with \(E_{\text{GeV}} = 1.8 \times 10^{53} \text{ erg}, L_{\text{GeV}} = 1.46 \times 10^{52} \text{ erg s}^{-1}\) and photon energy \(\epsilon_\gamma = 0.1 \text{ GeV}\).
For the given energy and luminosity,

- $\beta = 8.9 \times 10^{-4}$, i.e. $B_0 \approx 3.9 \times 10^{10}$ G.
- $\alpha = 0.414$
- $M = 4.447 \ M_\odot$
- $M_{\text{irr}} = 4.346 \ M_\odot$

Synchrotron photons in the 0.1 GeV–1 TeV energy band, do not produce pairs if the magnetic field is below $B_0 < 3.9 \times 10^{10}$ G. Therefore, this region is transparent for such photons.
Self-consistent inference of the BH mass and spin, as well as of the magnetic field.

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"Inner engine" of the Gamma-Ray Bursts (GRBs)
Known luminosity expressed in the rest-frame of the sources, and known the initial values of the spin and of the mass of the BH:

\[ L = - \frac{dE_{\text{extr}}}{dt} = - \frac{dM}{dt}, \]  

(31)

\( M_{\text{irr}} \) is constant, and using our relation for luminosity.

\[ M = M_0 + 5At^{-0.2} - 5At_0^{-0.2}, \]  

(32)

where \( M_0 \) is the initial BH mass at, \( t_0 = 3.99 \) s and \( A = (7.75 \pm 0.44) \times 10^{52} \).

From the mass-energy formula of the BH we have

\[ J = 2M_{\text{irr}} \sqrt{M^2 - M_{\text{irr}}^2}, \]  

(33)

therefore

\[ a = \frac{J}{M} = 2M_{\text{irr}} \sqrt{1 - \frac{M_{\text{irr}}^2}{(M_0 + 5At^{-0.2} - 5At_0^{-0.2})^2}}. \]  

(34)

- Both \( \alpha \) and \( M \) decrease with time which shows the decrease of rotational energy of the BH due to the energy loss in GeV radiation.
The decrease of the BH mass and spin due to the extracted rotational energy

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The decrease of the BH mass and spin due to the extracted rotational energy

<table>
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<th>GRB</th>
<th>$z$</th>
<th>$E_{p,i}$ (MeV)</th>
<th>$E_{\gamma,iso}$ ($10^{52}$ erg)</th>
<th>Fermi GCN</th>
<th>$E_{\text{LAT}}$ ($10^{52}$ erg)</th>
<th>$\theta$ (deg)</th>
<th>TS</th>
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<td>2.27 ± 0.13</td>
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<td>090323A</td>
<td>3.57</td>
<td>2.9 ± 0.7</td>
<td>438 ± 53</td>
<td>9021</td>
<td>$\gtrsim 48.85 \pm 0.59$</td>
<td>57.2</td>
<td>150</td>
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<tr>
<td>090328A</td>
<td>0.736</td>
<td>1.13 ± 0.08</td>
<td>14.2 ± 1.4</td>
<td>9044</td>
<td>$\gtrsim 3.04 \pm 0.01$</td>
<td>64.6</td>
<td>107</td>
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<tr>
<td>090902B</td>
<td>1.822</td>
<td>2.19 ± 0.03</td>
<td>292.0 ± 29.2</td>
<td>9867</td>
<td>$\gtrsim 110 \pm 5$</td>
<td>50.8</td>
<td>1832</td>
</tr>
<tr>
<td>090926A</td>
<td>2.106</td>
<td>0.98 ± 0.01</td>
<td>228 ± 23</td>
<td>9934</td>
<td>$\gtrsim 151 \pm 7$</td>
<td>48.1</td>
<td>1983</td>
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<tr>
<td>091003A</td>
<td>0.897</td>
<td>0.92 ± 0.04</td>
<td>10.7 ± 1.8</td>
<td>9985</td>
<td>$\gtrsim 1.29 \pm 0.03$</td>
<td>12.3</td>
<td>108</td>
</tr>
<tr>
<td>091127</td>
<td>0.49</td>
<td>0.05 ± 0.01</td>
<td>0.81 ± 0.18</td>
<td>10204</td>
<td>$\gtrsim 0.05 \pm 0.03$</td>
<td>25.8</td>
<td>34</td>
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<tr>
<td>091208B</td>
<td>1.063</td>
<td>0.25 ± 0.04</td>
<td>2.10 ± 0.11</td>
<td>10266</td>
<td>$\gtrsim 0.41 \pm 0$</td>
<td>55.6</td>
<td>20</td>
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<tr>
<td>100414A</td>
<td>1.368</td>
<td>1.61 ± 0.07</td>
<td>55.0 ± 0.5</td>
<td>10594</td>
<td>$\gtrsim 8.79 \pm 0.31$</td>
<td>69</td>
<td>81</td>
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<tr>
<td>100728A</td>
<td>1.567</td>
<td>1.00 ± 0.45</td>
<td>72.5 ± 2.9</td>
<td>11006</td>
<td>$\gtrsim 1.15 \pm 0.20$</td>
<td>59.9</td>
<td>32</td>
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<td>110731A</td>
<td>2.83</td>
<td>1.21 ± 0.04</td>
<td>49.5 ± 4.9</td>
<td>12221</td>
<td>$\gtrsim 31.4 \pm 7.4$</td>
<td>3.4</td>
<td>460</td>
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<td>120624B</td>
<td>2.197</td>
<td>1.39 ± 0.35</td>
<td>347 ± 16</td>
<td>13377</td>
<td>$\gtrsim 28 \pm 2$</td>
<td>70.8</td>
<td>312</td>
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<td>130427A</td>
<td>0.334</td>
<td>1.11 ± 0.01</td>
<td>92 ± 13</td>
<td>14473</td>
<td>$\gtrsim 5.69 \pm 0.05$</td>
<td>47.3</td>
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<td>130518A</td>
<td>2.488</td>
<td>1.43 ± 0.38</td>
<td>193 ± 1</td>
<td>14675</td>
<td>$\gtrsim 3.5 \pm 0.6$</td>
<td>41.5</td>
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<td>131108A</td>
<td>2.40</td>
<td>1.27 ± 0.05</td>
<td>51.20 ± 3.83</td>
<td>15464</td>
<td>$\gtrsim 50.43 \pm 5.86$</td>
<td>23.78</td>
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<tr>
<td>131231A</td>
<td>0.642</td>
<td>0.27 ± 0.01</td>
<td>21.50 ± 0.02</td>
<td>15640</td>
<td>$\gtrsim 2.18 \pm 0.02$</td>
<td>38</td>
<td>110</td>
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<td>141028A</td>
<td>2.33</td>
<td>0.77 ± 0.05</td>
<td>76.2 ± 0.6</td>
<td>16969</td>
<td>$\gtrsim 7.36 \pm 0.46$</td>
<td>27.5</td>
<td>104.5</td>
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<td>150314A</td>
<td>1.758</td>
<td>0.86 ± 0.01</td>
<td>70.10 ± 3.25</td>
<td>17576</td>
<td>$\gtrsim 1.93 \pm 0.89$</td>
<td>47.13</td>
<td>27.1</td>
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<td>150403A</td>
<td>2.06</td>
<td>0.95 ± 0.04</td>
<td>87.30 ± 7.74</td>
<td>17667</td>
<td>$\gtrsim 7.55 \pm 5.19$</td>
<td>55.2</td>
<td>37</td>
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<tr>
<td>150514A</td>
<td>0.807</td>
<td>0.13 ± 0.01</td>
<td>1.14 ± 0.03</td>
<td>17816</td>
<td>$\gtrsim 0.42 \pm 0.05$</td>
<td>38.5</td>
<td>33.9</td>
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<tr>
<td>160509A</td>
<td>1.17</td>
<td>0.80 ± 0.02</td>
<td>84.5 ± 2.3</td>
<td>19403</td>
<td>$\gtrsim 35.92 \pm 0.26$</td>
<td>32</td>
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<td>160625B</td>
<td>1.406</td>
<td>1.3 ± 0.1</td>
<td>337 ± 1</td>
<td>19581, 19604</td>
<td>$\gtrsim 29.90 \pm 3.51$</td>
<td>41.46</td>
<td>961.33</td>
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<td>170214A</td>
<td>2.53</td>
<td>0.89 ± 0.04</td>
<td>392 ± 3</td>
<td>20675, 20686</td>
<td>$\gtrsim 79.51 \pm 6.34$</td>
<td>33.2</td>
<td>1571</td>
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<td>170405A</td>
<td>3.51</td>
<td>1.20 ± 0.42</td>
<td>241.01 ± 52.02</td>
<td>20990, 20986</td>
<td>$\gtrsim 23.91 \pm 1.62$</td>
<td>52.0</td>
<td>56</td>
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<td>180720B</td>
<td>0.654</td>
<td>1.06 ± 0.24</td>
<td>68.2 ± 2.2</td>
<td>22996, 23042</td>
<td>$\gtrsim 3.04 \pm 0.6$</td>
<td>49.1</td>
<td>975</td>
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The decrease of the BH mass and spin due to the extracted rotational energy
The decrease of the BH mass and spin due to the extracted rotational energy.

Inner engine of the Gamma-Ray Bursts (GRBs).

Graph showing the decrease of the BH mass and spin over time for different GRBs.
Synchrotron radiation power and the need of a low density ionized plasma

R. Moradi in collaboration with R. Ruffini, J. A. Rueda, N. Sahakyan, Y. Wang, Liang Li, L. Becerra, C. L. Bianco, S. S. Xue (ICRANet and Sapienza University of Rome)

Inner engine” of the Gamma-Ray Bursts (GRBs)
For the available electromagnetic energy budget the system can accelerate a total number of electrons with the above energy:

\[ N_e = \frac{\mathcal{E}_1}{\epsilon_e} \approx 9.7 \times 10^{39}. \]  

(36)

In principle as the timescale increases the total available electron will decrease. The timescale of the process is in general set by the density of particles around the BH, which is provided by the structure of the cavity and SN ejecta.
Such elementary process the BH experiences a very small fractional change of angular momentum

\[ \frac{|\Delta J|}{J} \approx \left( \frac{\dot{J}}{J} \right) \tau_{ob} \approx 10^{-16}, \]
\[ \frac{|\Delta M|}{M} \approx \left( \frac{\dot{M}}{M} \right) \tau_{ob} \approx 10^{-16}. \]  

(37)

The electromagnetic energy of the first impulsive event given above is a small fraction of total extractable rotational energy of the Kerr BH

\[ \frac{E_1}{E_{\text{ext}}} \approx 10^{-16}. \]  

(38)
This clearly indicates that the rotational energy extraction from the Kerr BH:

- Occurs in “discrete quantized steps”.
- The steps are temporally separated by $10^{-14} - 10^{-10}$ s.
- The luminosity of the GeV emission in GRB 190114C is not describable by a continuous function as traditionally assumed: it occurs in a “discrete sequence of elementary quantized events”.
- Synchrotron radiation is not emitted isotropically but it is angle dependent; the smaller the angle the higher the synchrotron photon energy.
sequence of iterative impulsive events

System after radiation the first impulse starts over with a new value of the electric field set by the new values of the BH angular momentum and mass,

- \( J = J_0 - \Delta J \) and \( M = M_0 - \Delta M \), keeping the magnetic field value constant \( B_0 \)

Timescale \( \tau(t) \) of the repetition time of the impulsive events can be obtained by

1. GeV luminosity of the GRB
2. energy of impulse, \( E \), obtained from the “inner engine”

\[
L_{\text{GeV}} = \frac{E}{\tau(t)},
\]

where \( E \) is electrostatic energy. Therefore we obtain for the timescale

\[
\tau(t) = \frac{1}{2} \frac{(2B_0J)^2}{r_+L_{\text{GeV}}},
\]

- \( r_+ \) is the the horizon radius determined from the new values of \( J \) and \( M \)

\( \tau_{\text{ob}} \) is a increasing power-law function of time, i.e.

\[
\tau_{\text{ob}} \propto \frac{\alpha^2}{L_{\text{GeV}}} \propto t.
\]
The efficiency of the system diminishes with time as shown by the increasing value of $\tau_{ob}$.

- this can be understood by the evolution of the density of particles near the BH decreases owing to the expansion of the SN remnant, making the iterative process become less efficient.
- in the immediate vicinity of the BH a cavity is created of approximate radius $10^{11}$ cm and with very low density on the order of $10^{-14}$ g cm$^{-3}$.
- This implies an approximate number of $\sim 10^{47}$ electrons inside the cavity. Then, the electrons of the cavity can power the iterative process only for a short time of 1–100 s.
- We notice that at the beginning of the gamma-ray emission the required number of electrons per unit time for the explanation of the prompt and the GeV emission can be as large as $10^{46}$–$10^{54}$ s$^{-1}$.
- This confirms that this iterative process has to be sustained by the electrons of the remnant, at $r \gtrsim 10^{11}$ cm, which are brought from there into the region of low density and then into the BH.
At \( t_{\text{rf}} = 3.99 \text{ s} \) when the synchrotron timescale obtained is \( t_c = 1.7 \times 10^{-14} \text{ s} \), the total energy available for each electron is \( \epsilon_e = 5.6 \times 10^8 \text{ eV} \), which leads to the total number of electrons, \( N_e = \mathcal{E}_1/\epsilon_e \approx 9.7 \times 10^{39} \).

When at \( t_{\text{rf}} = 10^8 \text{ s} \), the synchrotron timescale is \( t_c = 4 \times 10^{-5} \text{ s} \), the total energy available for each electron is \( \epsilon_{e,\text{max}} = 1.65 \times 10^{18} \text{ eV} \) and the total number of electrons is \( N_e = \mathcal{E}/\epsilon_{e,\text{f}} \approx 1.6 \times 10^{31} \).
Synchrotron radiation power and the need of a low density ionized plasma

R. Moradi in collaboration with R. Ruffini, J. A. Rueda, N. Sahakyan Y. Wang, Liang Li, L. Becerra, C. L. Bianco, S. S. Xue (ICRANet and Sapienza University of Rome)

“Inner engine” of the Gamma-Ray Bursts (GRBs)

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We have that at $t_{rf} = 3.99 \text{ s}$ the values of mass and spin parameters of the BH and the magnetic field are $M = 4.446M_{\odot}$ and $\alpha = 0.414$ and $B_0 = 3.9 \times 10^{10} \text{ G}$, respectively.

We can now working backward and determine the BH mass and spin at $t_{rf} = 1.9 \text{ s}$, when the BH is formed.

Using the MeV luminosity in UPE phase, we can integrate the mass formula and obtain at the beginning of the UPE, namely at $t_{rf} = 1.9 \text{ s}$, the values of mass and spin of BH.

We obtain $M = 4.518M_{\odot}$ and $\alpha = 0.525$, respectively.

This demands that all the luminosity of UPE phase originates of the rotational energy of the BH (vacuum polarization!)
Ultra-relativistic Prompt Emission phase (UPE)

R. Moradi in collaboration with R. Ruffini, J. A. Rueda, N. Sahakyan, Y. Wang, Liang Li, L. Becerra, C. L. Bianco, S. S. Xue (ICRANet and Sapienza University of Rome)

"Inner engine" of the Gamma-Ray Bursts (GRBs)

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Figure 4.12 Luminosity of the UPE observed by Fermi-GBM. The luminosity is best fitted by a power-law of amplitude $2.53 \pm 1.1 \times 10^{53}$ erg s$^{-1}$ and power-law index $-1.32 \pm 0.34$. 
The UPE phase is characterized by an electric field $|E| > E_c$

Having determined the boundary value of the magnetic field at $t_{rf} = 3.99$ s to be $B_0 = 3.9 \times 10^{10}$ G, we must now require that at $t_{rf} = 3.99$ s the electric to be critical, and overcritical inside the UPE phase.

Since we have determined the overall behavior of the mass and spin of BH during the UPE since the moment of the formation of BH

We assume during the entire UPE phase the value of the magnetic field to be constant which sharply decreases to its boundary value $B_0 = 3.9 \times 10^{10}$ G at $t_{rf} > 3.99$ s.

We set the value of $B_0$ in the UPE phase, i.e. at times $t_{rf} < 3.99$ s, such that the electric field therein is overcritical.

The magnitude of magnetic field is determined in a way that in the “inner engin” electromagnetic field $E_{r+b} = E_c$ at the end of the UPE phase; at $t_{rf} = 3.99$ s.

For BH mass and spin parameter at the end of UPE it implies a magnetic field of $\beta = B_0/B_c = 5.1$, where $B_c = E_c$. 
Dyadoregion: Kerr Newman approximation with $Q_{\text{eff}} = 2B_0J$

\[
E_{(r_+,r_d)} = \frac{(2B_0J)^2}{4r_+} \left( 1 - \frac{r_+}{r_d} \right) + \frac{(2B_0J)^2}{4r_+} \left[ \left( 1 + \frac{a^2}{r_+^2} \right) \times \frac{\arctan(a/r_+)}{a/r_+} - \frac{r_+}{r_d} \left( 1 + \frac{a^2}{r_d^2} \right) \times \frac{\arctan(a/r_d)}{a/r_d} \right],
\]

where $r_d$ is the radius of dyadoregion

\[
\left( \frac{r_d}{M} \right)^2 = \frac{1}{2} \frac{\lambda}{\mu\epsilon} - \alpha^2 + \left[ \frac{1}{4} \frac{\lambda^2}{\mu^2\epsilon^2} - 2 \frac{\lambda}{\mu\epsilon} \alpha^2 \right]^{1/2}
\]

- $\epsilon = E_c M_\odot \approx 1.873 \times 10^{-6}$,
- $\lambda = (2B_0J)/M$
The characteristic time of each impulse, $t_{q}$

The observed time of the thermal component in each impulse which using slab approximation

$$t_{q}(t) = \frac{r_{d}(t) - r_{+}(t)}{c},$$  \hspace{1cm} (44)$$

- The luminosity can be obtained as

$$L = \frac{E_{(r_{+}(t),r_{d}(t))}}{r_{d}(t) - r_{+}(t)} c \approx 1.4 \times 10^{50} \cdot t^{-0.6} \text{erg s}^{-1},$$  \hspace{1cm} (45)$$

At the moment which BH is formed, namely $t_{rf} = 1.9$ s,

- $(2B_{0}J)/M \approx 4.6 \times 10^{-5}$
- $r_{ds} = 1.12 \cdot r_{+}$
- the total energy of dyadoregion is $E_{d} \approx 5.5 \times 10^{44}$ erg
- $t_{q}(1.9) = 5.85 \times 10^{-6}$ s,

this leads to a luminosity of

$$L = \frac{E_{(r_{+}(1.9),r_{d}(1.9))}}{r_{d}(1.9) - r_{+}(1.9)} c \approx 9.5 \times 10^{49} \text{ erg s}^{-1}.$$  \hspace{1cm} (46)$$
Ultra-relativistic Prompt Emission phase (UPE)

R. Moradi in collaboration with R. Ruffini, J. A. Rueda, N. Sahakyan Y. Wang, Liang Li, L. Becerra, C. L. Bianco, S. S. Xue (ICRANet and Sapienza University of Rome)

"Inner engine" of the Gamma-Ray Bursts (GRBs)
In presence of an overcritical electric field around the BH:

1. An optically thick fireshell of $e^+e^-$ plasma of total energy $E_{e^+e^-}^{\text{tot}} = E_{\gamma,\text{iso}}$ endowed with baryon load occurs.

2. The transparency of the $e^+e^-$ plasma. When the fireshell becomes transparent, a thermal radiation, what has been called the Proper-GRB (BB), is emitted.
\[
\frac{E_{BB}^{obs}}{E_{iso}} = \frac{a T_{obs}^4}{16 \Gamma^2} \sigma_T \frac{B}{m_N c} t_{BB}^{90} .
\]  

(47)

From the total energy conservation we have that:

\[
E_{iso} = E_{BB} + E_{Kinetic},
\]

(48)

therefore

\[
1 = \frac{E_{BB}}{E_{iso}} + \frac{E_{Kinetic}}{E_{iso}},
\]

(49)

where \( E_{Kinetic} \) is the kinetic energy of the baryonic fireshell:

\[
E_{Kinetic} = (\Gamma - 1) M_B c^2.
\]

(50)

\[
B = \frac{1}{\Gamma - 1} \left(1 - \frac{E_{BB}^{obs}}{E_{iso}} \right),
\]

(51)

or, equivalently:

\[
\Gamma = 1 + B^{-1} \left(1 - \frac{E_{BB}^{obs}}{E_{iso}} \right).
\]

(52)

The radius of transparency, \( R^{tr} \):

\[
R^{tr} = \left(\frac{\sigma_T}{8\pi} \frac{BE_{iso}}{m_N c^2}\right)^{1/2}.
\]

(53)

In general the values of \( B \) and \( \Gamma \) can be estimated by the values of \( E_{BB}^{obs}/E_{iso} \), \( T_{obs} \) and \( t_{BB}^{90} \).
This leads to the
\[ R^{tr} = 7.6 \times 10^9 \text{ cm}, \]  
(54)
with baryon load parameter of
\[ B = 5.9 \times 10^{-3}, \]  
(55)
and the Lorentz factor of
\[ \Gamma \sim 120. \]  
(56)

We have numerically checked these values which shows the good agreement. The numerical values are:
\[ R^{tr} = 9.3 \times 10^9 \text{ cm}, \]  
(57)
the temperature of
\[ T = 150 \text{ keV}, \]  
(58)
and the Lorentz factor of
\[ \Gamma \sim 140. \]  
(59)
In the UPE in addition to MeV photons also GeV photons are present
Transparency of GeV photons in the UPE phase

The scattered/absorbed luminosity of GeV photons by the MeV photons can be estimated as:

\[ L_{\text{GeV,scat}} = L_{\text{GeV,unsc}} e^{-\tau_{\gamma\gamma}}, \]  

(60)

- \( L_{\text{GeV,unsc}} \) is the unscattered/unabsorbed GeV luminosity
- \( \tau_{\gamma\gamma} \) is the optical depth of the two-photon pair creation process.

The scattered and unscattered GeV luminosities are best fitted by

\[ L_{\text{GeV,scat}} = 1.1 \times 10^{51} t^{1.79} \text{ erg s}^{-1}, \]  

(61)

\[ L_{\text{GeV,unsc}} = 2.53 \times 10^{53} t^{-1.32} \text{ erg s}^{-1}. \]  

(62)

This leads to the optical depth of the two-photon pair creation process to be

\[ \tau_{\gamma\gamma} = \ln (2.3 \times 10^{2} t^{-3.12}), \]  

(63)
The optical depth of the two-photon pair creation can be calculated as:

$$\tau_{\gamma\gamma} \approx n_{\text{target}} \sigma_{\gamma\gamma} \approx \frac{E_{\text{target}}}{4\pi R^2 \epsilon_{\text{target}}} \sigma_{\gamma\gamma}, \quad (64)$$

For the cross-section we use the two-photon interaction as a function of the energies $\epsilon_1$ (incident) and $\epsilon_2$ (target):

$$\frac{\sigma_{\gamma\gamma}}{\sigma_T} = \frac{3}{16} (1 - \zeta^2) \left[ 2\zeta(\zeta^2 - 2) + (3 - \zeta^4) \ln \left( \frac{1 + \zeta}{1 - \zeta} \right) \right], \quad (65)$$

where $\sigma_T = (8\pi/3)e^4/(m_ec^2)^2 = 6.65 \times 10^{-25}$ cm$^2$ is the Thomson cross-section and $\zeta = \sqrt{1 - 2(m_ec^2)^2/(\epsilon_1 \epsilon_2)}$ is the velocity of the particle in the center of momentum frame and, for simplicity, an isotropic radiation field is adopted.
The target luminosity is the one of the unscattered MeV photons, $L_{\text{MeV,unsc}}$, namely the one produced by the Dyadoregion

$$L_{\text{MeV,unsc}} = 1.40 \times 10^{50} \, t^{-0.6} \, \text{erg s}^{-1},$$

where $t$ is the rest-frame in seconds.
The incident luminosity is the one of the initial, unscattered GeV photons, $L_{\text{GeV,unsc}}$.

- The two-photon interaction leads in the present case to a significant production of optically thick $e^+e^-$ plasma.
- Therefore, it is expected that the GeV photons thermalize and their input energy be emitted in form of MeV photons at the moment of transparency.
- It is then clear that the initial incident GeV photon luminosity, should cover what it is then observed as MeV luminosity.

Based on this, we adopt $L_{\text{GeV,unsc}}$ to be of the same order as the observed MeV luminosity which is well fitted by

$$L_{\text{GeV,unsc}} \approx L_{\text{UPE}} = 2.53 \times 10^{53} t^{-1.32} \text{ erg s}^{-1},$$

(67)

where $t$ is the rest-frame time measured in seconds.
We use here that the difference between the unscattered and scattered GeV luminosity is transferred and re-radiated at transparency by the target in form of MeV photons. We adopt in this example as target and incident photon energy, respectively, $\epsilon_{\text{target}} = 1.5$ MeV and 3.0 GeV, as well as baryon load of $\approx 10^{-2}$. This leads the emitter radius (i.e. the transparency radius) of $R \approx 10^{10}$ cm.
Transparency of GeV photons in the UPE phase

R. Moradi in collaboration with R. Ruffini, J. A. Rueda, N. Sahakyan Y. Wang, Liang Li, L. Becerra, C. L. Bianco, S. S. Xue (ICRANet and Sapienza University of Rome)

"Inner engine" of the Gamma-Ray Bursts (GRBs)

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Extracted energy of the $\nu$NS is paid by the change in its gravitational binding energy and rotational kinetic energy.

The total energy of the spheroid is given by:

$$E = T + W$$  \hspace{1cm} (68)

where $W$ is the gravitational binding energy

$$W = -\frac{3}{5} \frac{M^2}{a} \frac{\text{arcsin}(e)}{e}$$  \hspace{1cm} (69)

and $T$ is the rotational kinetic energy:

$$T = \frac{1}{2} I \Omega^2.$$  \hspace{1cm} (70)
Figure 3. A: Eccentricity as a function of time. B: $dE/dt$ calculated from Eq. (36). The blue-dashed line shows the rate of gravitational binding energy and the black-solid line shows the rate of rotational energy. The green-line shows the sum of two energy losses which equals to the observed power-law luminosity given by Eq. (2). C: The period of the νNS in GRB 190114C is $P = 0.9$ ms at 1 s, and $P = 33$ ms at 1000 yr. D: The black-solid line is the νNS braking index for GRB 190114C, considering both rotational and gravitational binding energy losses. The red-solid line is νNS braking index for GRB 190114C neglecting the role of binding energy, namely when only the rotational energy loss is considered.
Thank you!