GRB emission from inside the fireshell

Carlo Luciano Bianco, Aimuratov, Yerlan; Enderli, Maxime; Karlica, Mile; Kovacevic, Milos; Moradi, Rahim; Muccino, Marco; Pisani, Giovanni B.; Rueda, Jorge A.; Ruffini, Remo; Wang, Yu

Italian – Korean Meeting
ICRANet Headquarters – Pescara – Italy – 22/07/2015
Space-time diagram for Long GRBs $> 10^{52}$ erg (see R. Ruffini’s talk)
Moving sources: 
Arrival time and emission time 

$R$ 

$t$
Moving sources:
Arrival time and emission time
Moving sources: Arrival time and emission time

\[ t \approx R \]

\[ \gamma \approx 4 \]
Moving sources:
Arrival time and emission time

\[ t_0 + \Delta t \]

\[ \gamma \approx 4 \]
Moving sources:
Arrival time and emission time

\[ t = t_0 + \Delta t \]

\[ \gamma \approx 4 \]
Moving sources: Arrival time and emission time

\[ R_t \]

\[ \Delta t_a \approx 4 (t_0 + \Delta t) \]

\[ \gamma \approx 4 \]

\[ \frac{r(\Delta t)}{c} = \frac{u}{c} \Delta t \]
Moving sources:
Arrival time and emission time

\[ \Delta t_a = \Delta t - \frac{r(\Delta t)}{c} = \Delta t \left(1 - \frac{\nu}{c}\right) \]

\[ \gamma \approx 4 \]

\[ t \]

\[ t_0 \]

\[ t + \Delta t \]

\[ R \]

\[ r \]

\[ \Delta t_a \]

\[ \Delta t \]

\[ \frac{r(\Delta t)}{c} \]

\[ \frac{\nu}{c} \]

\[ \Delta t \]

\[ (1 - \frac{\nu}{c}) \]
Moving sources:

Arrival time and emission time

The arrival time on the Earth of a signal depends on the motion of the source!

\[ \Delta t_a = \Delta t - \frac{r(\Delta t)}{c} = \Delta t \left(1 - \frac{v}{c}\right) \]

\[ \gamma \approx 4 \]

\[ t_0 + \Delta t \]

\[ t \]

\[ t + \Delta t \]

\[ \Delta t \]

\[ r \]

\[ R \]
Moving sources:

Arrival time and emission time

The arrival time on the Earth of a signal depends on the motion of the source!

It's possible to observe superluminal velocities!

\[ \Delta t_a = \Delta t - \frac{r(\Delta t)}{c} = \Delta t \left(1 - \frac{v}{c}\right) \]

where \( \gamma \approx 4 \)
Lorentz contraction or Doppler effect?

Doppler contraction: \[ T = T_0 \gamma \left(1 - \frac{v}{c}\right) \]

where:
- \( \gamma \) is the Lorentz gamma factor of the moving source,
- \( T_0 \) is the period of the radiation measured in the co-moving frame,
- \( T \) is the period of the radiation measured by an observer at rest.
Lorentz contraction or Doppler effect?

Doppler contraction: \[ T = T_0 \gamma \left(1 - \frac{\nu}{c}\right) \]

where:

– \( \gamma \) is the Lorentz gamma factor of the moving source,
– \( T_0 \) is the period of the radiation measured in the co-moving frame,
– \( T \) is the period of the radiation measured by an observer at rest.

Arrival time: \[ \Delta t_a = \Delta \tau \gamma \left(1 - \frac{\nu}{c}\right) = \Delta t \left(1 - \frac{\nu}{c}\right) \]
Lorentz contraction
or Doppler effect?

Doppler contraction: 
\[ T = T_0 \gamma \left( 1 - \frac{v}{c} \right) \]

where:
– \( \gamma \) is the Lorentz gamma factor of the moving source,
– \( T_0 \) is the period of the radiation measured in the co-moving frame,
– \( T \) is the period of the radiation measured by an observer at rest.

Arrival time: 
\[ \Delta t_a = \Delta \tau \gamma \left( 1 - \frac{v}{c} \right) = \Delta t \left( 1 - \frac{v}{c} \right) \]

Is then only a Doppler contraction and does not involve any Lorentz transformation.
Moving sources: Constant speed vs. variable speed

\[ \Delta t_a = \Delta t - \frac{r (\Delta t)}{c} = \Delta t \left( 1 - \frac{v}{c} \right) \approx \frac{\Delta t}{2\gamma^2} = \frac{\Delta t}{32} \]

Moving sources: Constant speed vs. variable speed

\[ \Delta t_a = \Delta t - \frac{r(\Delta t)}{c} = \Delta t \left(1 - \frac{v}{c}\right) \approx \frac{\Delta t}{2\gamma^2} = \frac{\Delta t}{32} \]

\[ \Delta t_a = \Delta t - \frac{r(\Delta t)}{c} = \Delta t - \frac{1}{c} \int_{t_0}^{t_0+\Delta t} v(t) \, dt \]

\( \gamma \equiv 4 \)

1 \leq \gamma \leq 300 (in GRBs)

Couderc, Ann. Astr., 2, 271, (1939)
\[ \Delta t_a = \Delta t - \frac{1}{c} \left[ \int_{t_0}^{t_0+\Delta t} v(t) \, dt + r(t_0) \right] \cos \vartheta + \frac{r(t_0)}{c} \]

Optically thin Fireshell EoMs

\[
\begin{align*}
    dE_{\text{int}} &= (\gamma - 1) \, dM_{\text{ism}} c^2 \\
    d\gamma &= -\frac{\gamma^2 - 1}{M} \, dM_{\text{ism}} \\
    dM &= \frac{1 - \varepsilon}{c^2} \, dE_{\text{int}} + dM_{\text{ism}} \\
    dM_{\text{ism}} &= 4\pi m_p n_{\text{ism}} r^2 \, dr
\end{align*}
\]
Optically thin Fireshell EoMs

\[
\begin{align*}
    dE_{\text{int}} &= (\gamma - 1) dM_{\text{ism}} c^2 \\
    d\gamma &= -\frac{\gamma^2 - 1}{M} dM_{\text{ism}} \\
    dM &= \frac{1-\epsilon}{c^2} dE_{\text{int}} + dM_{\text{ism}} \\
    dM_{\text{ism}} &= 4\pi m_p n_{\text{ism}} r^2 dr
\end{align*}
\]

Fully radiative condition: $\epsilon = 1$

Fully adiabatic condition: $\epsilon = 0$

Optically thin Fireshell EoMs

\[ dE_{\text{int}} = (\gamma - 1) dM_{\text{ism}} c^2 \]
\[ d\gamma = -\frac{\gamma^2 - 1}{M} dM_{\text{ism}} \]
\[ dM = \frac{1-\varepsilon}{c^2} dE_{\text{int}} + dM_{\text{ism}} \]
\[ dM_{\text{ism}} = 4\pi m_p n_{\text{ism}} r^2 dr \]

Fully radiative condition: \( \varepsilon = 1 \)

\[ \gamma_0 \gg \gamma \gg 1 \]
Blandford – McKee

\[ \gamma \propto r^{-3} \]
\[ t = \frac{r}{c} \left( 1 + \frac{1}{14\gamma^2} \right) \]

Fully adiabatic condition: \( \varepsilon = 0 \)

\[ \gamma_0^2 \gg \gamma^2 \gg 1 \]
Blandford – McKee

\[ \gamma \propto r^{-3/2} \]
\[ t = \frac{r}{c} \left[ 1 + \frac{1}{8\gamma^2 (r)} \right] \]

Optically thin Fireshell EoMs

\[
\begin{align*}
\text{Fully radiative condition: } & \varepsilon = 1 \\
\text{Fully adiabatic condition: } & \varepsilon = 0 \\
\end{align*}
\]

\[
\begin{align*}
dE_{\text{int}} &= (\gamma - 1) dM_{\text{ism}} c^2 \\
d\gamma &= -\frac{\gamma^2 - 1}{M} dM_{\text{ism}} \\
dM &= \frac{1-\varepsilon}{c^2} dE_{\text{int}} + dM_{\text{ism}} \\
dM_{\text{ism}} &= 4\pi m_p n_{\text{ism}} r^2 dr
\end{align*}
\]

\[\gamma_0 \gg \gamma \gg 1\]

Blandford – McKee

\[\gamma \propto r^{-3}\]

\[t = \frac{r}{c} \left(1 + \frac{1}{14\gamma^2}\right)\]

\[\gamma_0^2 \gg \gamma^2 \gg 1\]

Blandford – McKee

\[\gamma \propto r^{-3/2}\]

\[t = \frac{r}{c} \left[1 + \frac{1}{8\gamma^2 (r)}\right]\]

Comparison between exact and approximate fireshell equations of motion (radiative and adiabatic)

Exact solution

Effective power-law index: $\gamma \propto r^{-a}$

- $a = 3.0 \ (\gamma_0 \gg \gamma \gg 1)$
- $a = 1.5 \ (\gamma_0^2 \gg \gamma^2 \gg 1)$

The EQuiTemporal Surfaces (EQTSs)

\[ t^d_a = (1 + z) \left[ t(r) - \frac{r}{c} \cos \theta + \frac{r^*}{c} \right] \]
The EQuiTTemporal Surfaces (EQTSs)

\[ t^d_a = (1 + z) \left[ t(r) - \frac{r}{c} \cos \theta + \frac{r^*}{c} \right] \]

\[ t(r) = \frac{r}{v} \]

\[ r^* = 0 \]

The EQuiTemporal Surfaces (EQTs)

\[ t^d_a = (1 + z) \left[ t(r) - \frac{r}{c} \cos \vartheta + \frac{r^*}{c} \right] \]

\[ t(r) = \frac{r}{v} \]

\[ r^* = 0 \]

\[ r(\vartheta) = \frac{v \frac{t^d_a}{1 + z}}{1 - \frac{v}{c} \cos \vartheta} \]

Ellipsoid with eccentricity \( v/c \)

The EQuiTEmental Surfaces (EQTTSs)

Using the fireshell dynamics

Ellipsoid with eccentricity $v/c$

\[ t^d_a = (1 + z) \left[ t(r) - \frac{r}{c} \cos \theta + \frac{r^*}{c} \right] \]

\[ t(r) = \frac{r}{v} \]

\[ r^* = 0 \]

\[ r(\theta) = \frac{v \frac{t^d_a}{1 + z}}{\frac{v}{1 - \frac{v}{c} \cos \theta}} \]

The EQuiTEnporal Surfaces (EQTTSs)
Importance of exact EQTS
Importance of exact EQTS
Computing the exact EQTS shape is not only important from a kinematical point of view, but is also fundamental to study the properties of the observed radiation.
Luminosity over selected EQTSs
EQTS

apparent size

\[
\begin{align*}
    r_\perp &= \frac{r}{\gamma (r)} \\
    t_a &= t (r) - \frac{r}{c} \sqrt{1 - \frac{1}{\gamma (r)^2}} + \frac{r^*}{c}
\end{align*}
\]

With the exact solutions for \( t(r) \) and \( \gamma(r) \), both in the fully radiative and in the adiabatic regimes.
EQTS

apparent size

\[
\begin{align*}
\left\{ \begin{array}{l}
\frac{r}{\gamma(r)} \\
-t_a = t(r) - \frac{r}{c} \sqrt{1 - \frac{1}{\gamma(r)^2}} + \frac{r^*}{c}
\end{array} \right.
\]

With the exact solutions for \( t(r) \) and \( \gamma(r) \), both in the fully radiative and in the adiabatic regimes.

Sari (1998), adiabatic:

\[
r_\perp = 3.91 \times 10^{16} \left( \frac{E_{52}}{n_1} \right)^{1/8} \left( \frac{T_{days}}{1+z} \right)^{5/8} \text{ cm}
\]

Waxman, et al. (1998), adiabatic:

\[
r_\perp = 3.66 \times 10^{16} \left( \frac{E_{52}}{n_1} \right)^{1/8} \left( \frac{T_{days}}{1+z} \right)^{5/8} \text{ cm}
\]
EQTS apparent size

\[
\begin{align*}
    r_\perp &= \frac{r}{\gamma(r)} \\
    t_a &= t(r) - \frac{r}{c} \sqrt{1 - \frac{1}{\gamma(r)^2} + \frac{r^*}{c}}
\end{align*}
\]

With the exact solutions for \( t(r) \) and \( \gamma(r) \), both in the fully radiative and in the adiabatic regimes.

Sari (1998), adiabatic:
\[
r_\perp = 3.91 \times 10^{16} \left( \frac{E_{52}}{n_1} \right)^{1/8} \left( \frac{T_{\text{days}}}{1+z} \right)^{5/8} \text{ cm}
\]

Waxman, et al. (1998), adiabatic:
\[
r_\perp = 3.66 \times 10^{16} \left( \frac{E_{52}}{n_1} \right)^{1/8} \left( \frac{T_{\text{days}}}{1+z} \right)^{5/8} \text{ cm}
\]
Space-time diagram for Long GRBs $> 10^{52}$ erg (see R. Ruffini’s talk)
Emission from the other side of the fireshell
Emission from the other side of the fireshell
Emission from the other side of the fireshell
Emission from the other side of the fireshell
Emission from the other side of the fireshell

$$(v/c)\Delta t = (t + \Delta t) - t_0$$
Emission from the other side of the fireshell

\[
\Delta t_a = \Delta t (1+\nu/c) \sim 2 \Delta t
\]
Conclusions
Conclusions

- Great care has to be given to the Doppler contraction of the arrival time of the radiation emitted from the external surface of the fireshell moving toward the observer. Such a contraction can easily lead to apparent superluminal effects.
Conclusions

- Great care has to be given to the Doppler contraction of the arrival time of the radiation emitted from the external surface of the fireshell moving toward the observer. Such a contraction can easily lead to apparent superluminal effects.

- On the contrary, the radiation coming from the other side of the fireshell, the one receding from the observer, is not affected by such a contraction and the correction to the arrival time is less than a factor 2.
Conclusions

• Great care has to be given to the Doppler contraction of the arrival time of the radiation emitted from the external surface of the fireshell moving toward the observer. Such a contraction can easily lead to apparent superluminal effects.

• On the contrary, the radiation coming from the other side of the fireshell, the one receding from the observer, is not affected by such a contraction and the correction to the arrival time is less than a factor 2.

• Consequently, we are seeing at the same time and apparent position radiation emitted from very different places and times.