ORPHAN GAMMA-RAY FLARES FROM
RELATIVISTIC BLOBS COMPTONIZING RADIATION OF LUMINOUS STARS IN JETS OF AGNs

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Stellar clusters around SMBHs in AGNs

The example of nearby radio galaxy: Centaurs A

- Galactic Bulge: stars in the jet $\sim 8 \times 10^8$ (Wykes et al. 2014), if $10^{-3}$ of them Red Giants $\approx 10^6$ Red Giants within the jet.

- Nuclear stellar cluster: $(6 - 12) \times 10^7 \, M_\odot$ in young stars (Wykes et al. 2014), $\sim 100$ massive (O and WR type) stars within the jet.

- Globular clusters:
  $\sim 1550$ GC around Cen A (Gültekin et al. 2009),
  $\sim 13000$ GC around M87 (McLaughlin et al. 1994),

  ↓

  a few to several GCs within a jet
Collision scenario: a star (stellar cluster) within the jet
Collisions of compact objects with the jet plasma in AGNs

High energy radiation models

- Collision of jet plasma with massive star wind (scenario I)
  e.g. Bednarek & Protheroe (1997), Araudo et al. (2013), Bosch-Ramon (2015), de la Cita et al. (2016), ...

- Collision of jet plasma directly with stellar surface - disruption of star (scenario II)
  e.g. Barkov et al. (2010), Bosch-Ramon et al. (2012), ...

- Collisions of jet plasma with clouds of matter (and also globular clusters, supernova remnants, ... ?)
  e.g. Dar & Laor (1997), Beall & Bednarek (1999), Torres & Reimer (2011), Bednarek & Banasiński (2015, GC), ...

- Interaction of relativistic blob of particles in the jet with stellar radiation (scenario III)
  (Banasiński, Bednarek, Sitarek 2016)
Collision of jet plasma with massive star wind
**Shock localization - different scenarios**

- **Distance of the shock from stellar surface** (Bednarek & Protheroe 1997):

\[
R_{\text{sh}}^* \approx 6 \times 10^{12} (M_{-5}v_3)^{1/2} \theta_{-1} l_{-1} / L_{46}^{1/2} \text{ cm},
\]

where \(\dot{M} = 10^{-5} M_5 M_\odot\) and \(v = 10^3 v_3 \text{ km s}^{-1}\) are the mass loss rate and the velocity of the stellar wind, and \(L_b = 10^{46} L_{46} \text{ erg s}^{-1}\) is the power of the blob in the observer’s frame, \(\theta = 0.1 \theta_{-1} \text{ rad}\) is the jet opening angle, and \(l = 0.1 l_{-1} \text{ pc}\) is the distance of the star from the base of the jet.

- **If** \(R_{\text{sh}} >> R_*\): Shock around star accelerates particles (I)
  (strong stellar winds)

- **If** \(R_{\text{sh}} < R_*\): Jet collides with the stellar surface (II)
  (powerful jets, close to the jet base)

- **If** \(R_{\text{sh}} << R_*\): Jet particles interact with stellar radiation (III)
  (moderate winds, everywhere in the jet)
A star colliding with the blob in jet of AGN (Banasiński et al. 2016):

- Relativistic electrons in the blob, moving with the Lorentz factor $\gamma_b$, suffer strong energy losses on comptonization of radiation coming from a single star.
- Electrons are injected isotropically into the blob with a power law spectrum to TeV energies.
- Electrons scatter stellar radiation to $\gamma$-rays.
- $\gamma$-ray photons initiate IC $e^\pm$ pair cascade.
- $\gamma$-ray spectrum from IC $e^\pm$ pair cascade is calculated.
Optical depths for gamma-rays and electrons in stellar radiation

Figure 1: Optical depth for the inverse Compton scattering of the stellar radiation (O type star: $T = 3 \times 10^4$ K, $R = 10^{12}$ cm) by electrons in the blob (on the left) and for absorption of produced $\gamma$-rays in this stellar radiation (on the right) as the function of the energy (measured in the reference frame of the blob with $\gamma_b = 10$ for the electrons and in the reference frame of the star for the $\gamma$-rays). The impact distance, $d$, is equal to $1.1 R_\star$ (red, solid lines), $10 R_\star$ (green dotted) and $100 R_\star$ (black dashed).
Gamma-ray spectra from star-blob encounter (specific impacts)

Figure 2: SED of the $\gamma$-ray spectrum for a power law differential spectrum of electrons with an spectral index of $\alpha$ between 0.1 GeV and $E'_{\max}$ for fixed impact distance of electrons. Top left panel: dependence on impact distance $d$, thick lines show the spectra from the full cascade, thin lines the spectra escaping from the first generation of photons. Top right panel: dependence on the Lorentz factor of the blob $\gamma_b$. Bottom left panel: dependence on the spectral index of electrons $\alpha$. Bottom right panel: dependence on the maximum energy of the electrons (measured in the blob’s frame): $E'_{\max}$. Unless specified otherwise $\gamma_b = 10$, $d = 10 R_\star$, $\alpha = 2$, $E'_{\max} = 1$ TeV. The spectra are normalised to 1 erg of injected electron energy in the blob’s frame of reference.
Gamma-ray spectra from star-blob encounter (the whole blob)

Figure 3: SED from a cylindrical blob filled homogeneously with electrons with a power law energy distribution between 0.1 and 1000 GeV and a spectral index of 2. The total energy in the electron spectrum is normalised to 1 erg per $\pi (10^{14} \text{ cm})^2$ cross section of the blob. The blob is moving with $\gamma_b = 10$. Left figure: $\gamma$-ray spectra for different radii of the blob: $3 \times 10^{13} \text{ cm}$ (red, solid), $10^{14} \text{ cm}$ (blue, dashed), $3 \times 10^{14} \text{ cm}$ (black, dotted). Right figure: spectra emitted within the solid angle observed at different range of observation angles $0^\circ - 3^\circ$ (red solid), $3^\circ - 6^\circ$ (blue dashed), $6^\circ - 9^\circ$ (black dotted), $9^\circ - 12^\circ$ (green dot-dashed). The radius of the blob is equal to $10^{14} \text{ cm}$. 
The extreme gamma-ray blazar PKS 1222+21

- FSRQ PKS 1222+21 at $z = 0.432$;
- Relativistic jet with superluminal motion ($\beta_{\text{app}} > 10$) (Hooimeyer et al. 1992);
- Detected by Fermi-LAT with the flat spectrum (-2) below a few GeV (Tanaka et al. 2011, Ackermann et al. 2014);
- Short flare, with rapid variability ($\sim 10$ min), between 70-400 GeV (index -3.75), observed by MAGIC (Aleksić et al. 2011);
- Isotropic GeV power: $L_{\gamma} \approx 7 \times 10^{47}$ erg s$^{-1}$;
- Black hole mass: $(6 - 8) \times 10^8$ M$_\odot$ (Farina et al. 2012);
- Low energy emission does not change significantly during $\gamma$-ray flare (Ackermann et al. 2014):

Orphan $\gamma$-ray flare?

As an example, we interpret PKS 1222+21 in terms of our model:
Figure 4: Interpretation of the $\gamma$-ray emission (SED) observed during the flare from the FSRQ PKS 1222+21 in June 2010 by Fermi-LAT (empty squares) and MAGIC (full circles). A blob has the radius $d = 3 \times 10^{14}$ cm and a Gaussian longitudinal spread with a standard deviation of $H_b = 1.3 \times 10^{13}$ cm (the reference frame of the observer), and moves with $\gamma_b = 100$ encountering the O type star ($T_\star = 3 \times 10^4$ K and $R_\star = 10^{12}$ cm). The electrons are injected with a power law spectrum (index $-2.5$ between 10 MeV and 10 GeV, total energy density of $\rho_E = 24$ erg cm$^{-3}$ (in the blob’s frame of reference). The $\gamma$-ray emission is averaged over the observation angle $0 - 1/\gamma_b$ rad. The absorption in the Extragalactic Background Light is taken into account according to Dominguez et al. (2011) model.
Interpretation of the extreme blazar PKS 1222+21: light curve

Figure 5: Interpretation of the $\gamma$-ray light curve during the flare above 100 GeV from PKS 1222+21 observed by MAGIC (Aleksić et al. 2011). The dashed vertical lines are the time range from which the SED is computed.
Discussion

• We test our model applicability to extreme FSRQ (PKS 1222+21):
  
• In order to fit the observations we require the following parameters:
  
  Cylindrical blob with radius $R_b = 3 \times 10^{14}$ cm,

  Longitudinal distribution of electrons with height $H_b = 1.3 \times 10^{13}$ cm,

  The blob moves with the Lorentz factor $\gamma_b = 100$,

  Relativistic electron energy density $\rho_b = 20$ erg cm$^{-3}$.

• The power of the blob in the observer’s frame:

  $$L_\gamma = \pi R_b^2 c \rho_b \gamma_b^2 \approx 1.7 \times 10^{45} \text{ erg s}^{-1};$$

• Eddington luminosity of the SMBH in PKS 1222+21 is:

  $$L_{\text{Edd}} = (8 - 10) \times 10^{46} \text{ erg s}^{-1};$$

• $\sim 2\% \ L_{\text{Edd}} \text{ in the blob seems not excluded in the inner jet.}$