# Study of the Brightest Fermi Flares of PKS 1222+216: Role of Jet Dynamics

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**Abstract :** PKS 1222+216 (4C +21.35) is the third flat spectrum radio quasar detected at very high energies (VHEs, E> 100 GeV) during its two bright Fermi-LAT flares in April and June 2010. We performed a systematic study of the two LAT flares in four different LAT energy bands: 0.1-3, 0.1-0.3, 0.3-1 and 1-3 GeV at the shortest possible time bin of 6 hours allowed by the photon statistics. Both the flares show a clear asymmetric profile with similar rise time in all the LAT energy bands but a rapid decline within a day during the April flare and a gradual decline lasting ~4 days during the June. The energy resolved light curves during the April flare show a ~2 day long steady emission in 0.1-3 GeV band, an erratic variation in 0.3-1 GeV emission and an apparent daily feature in 1-3 GeV emission until the rapid rise. The June flare, on the other hand, shows a monotonic rise at all LAT energies followed by a gradual decline, powered mainly by the multi-peak 0.1-0.3 GeV emission. Interestingly, both the flares have similar peak fluxes in the corresponding LAT energy bands except in the 1-3 GeV band during the April flare which showed twice the corresponding flux during the June flare. The April flare showed spectral hardening until the flare peak followed by softening during the decay, indicating the activity to be initiated by a shock. On the contrary, hardness ratios during the June flare exhibit complex trends. Our study of the June LAT flare on daily timescale associated with a VHE variability of ~10 minutes and a photon spectral index of 2.7 ± 0.3 suggests that deceleration associated with recollimation can successfully reproduce the gamma-ray light curves in three LAT energy bands (0.1-0.3, 0.3-1, 1-3 GeV) along with the simultaneous high energy (X-rays and γ-rays) broadband spectral energy distributions (SEDs). However, the observed features in the high time resolution study of LAT data suggest contribution from other emission region and/or inhomogeneities besides the standard region responsible for June flaring.

PKS 1222+216 (4C 21.35): PKS 1222+216 (z = 0.432) is a flat spectrum radio quasar (FSRQ), a class of blazar characterized by presence of prominent broad-emission lines in their Optical-UV spectra. It belong to the high luminosity class of blazars with bolometric luminosity dominated by emission at γ-ray energies. The γ-ray dominance of FSRQs in leptonic scenario is primarily attributed to the high ambient photon density consisting of photons from accretion disk and broad line region (BLR) at sub-parsec scales, and IR photons from a torus at parsec-scales.

Figure 1 shows the daily 0.1 - 300 γ-ray light curve from Fermi-LAT during PKS 1222+216 high activity period in 2010. Two bright flares of similar amplitudes (labeled as April & June in Fig. 1) with emission extending up to VHEs were detected. The June VHE flare detected by the MAGIC observatory showed a rapid variability of ~ 10 minutes and an EBL corrected photon spectral index of 2.7 ± 0.3.

## June 2010 LAT-VHE Flare: Inferences from Observations

Constraints from VHE: A very hard VHE spectra (photon index of 2.7±0.3 between 70-400 GeV, Aleksic et al., 2011) with ~ 10 minutes variability and the smooth connection between the concurrent LAT and MAGIC data suggest emission from a compact region and inverse Compton (IC) scattering in Thomson regime. Thus the VHE variability and condition for Thomson scattering combined with the observed highest energy γ-ray photon leads to

$$R' \lesssim \frac{\delta}{(1+z)} c\, t_{var} \simeq 3\times 10^{14} \left(\frac{\delta}{22}\right)\left(\frac{t_{var}}{10\, min}\right) \text{ cm}$$

$$\epsilon_{seed} \lesssim \frac{(m_e c^2)^2}{\epsilon_{obs}(1+z)} \approx 0.45 \left(\frac{\epsilon_{obs}}{400\,\text{GeV}}\right)^{-1} \text{ eV}$$

The constraints suggest a very compact emission region (relative to jet width) beyond broad line region at i.e. pc scales from the central engine (IR region). Such a compact size requires a strong convergence of the relativistic flow and can be formed in blazars jets via compression of jet matter by a recollimation shock. One of the proposed example of this mechanism is HST-1 knot of the nearest active galactic nuclei M87.

Constraints from LAT: Observed luminosity of L ~ $10^{48}$ erg $s^{-1}$ dominated by GeV-VHE γ-ray constrain the cooling time of particles emitting at GeV energies to

$$t_{cool,1GeV} \approx \left(\frac{1+z}{\delta}\right)\left(\frac{3 m_e c}{4\sigma_T \gamma'_{1GeV} u'_{ir}}\right)$$
$$\approx 0.8 \left(\frac{T}{1200\,K}\right)^{-7/2}\left(\frac{\delta}{22}\right)^{-1/2}\left(\frac{\Gamma}{32}\right)^{-3/2} \text{ min}$$

This cooling time is too short compared to the decay time of the γ-ray flare (~ 4 days), implying that the flare is not solely due to radiative cooling of non-thermal electrons but possibly an outcome of jet dynamics.

An example of recollimation and formation of shock from the field of aerodynamics is shown in Figure 2 (Top panel). The bright knots, known as shock diamonds are result of pressure recollimation of the supersonic fluid coming out of the jet nozzle. Bottom panel shows a systematic representation of same phenomena in case of an steady state jet flow along with streamline and temperature profile.

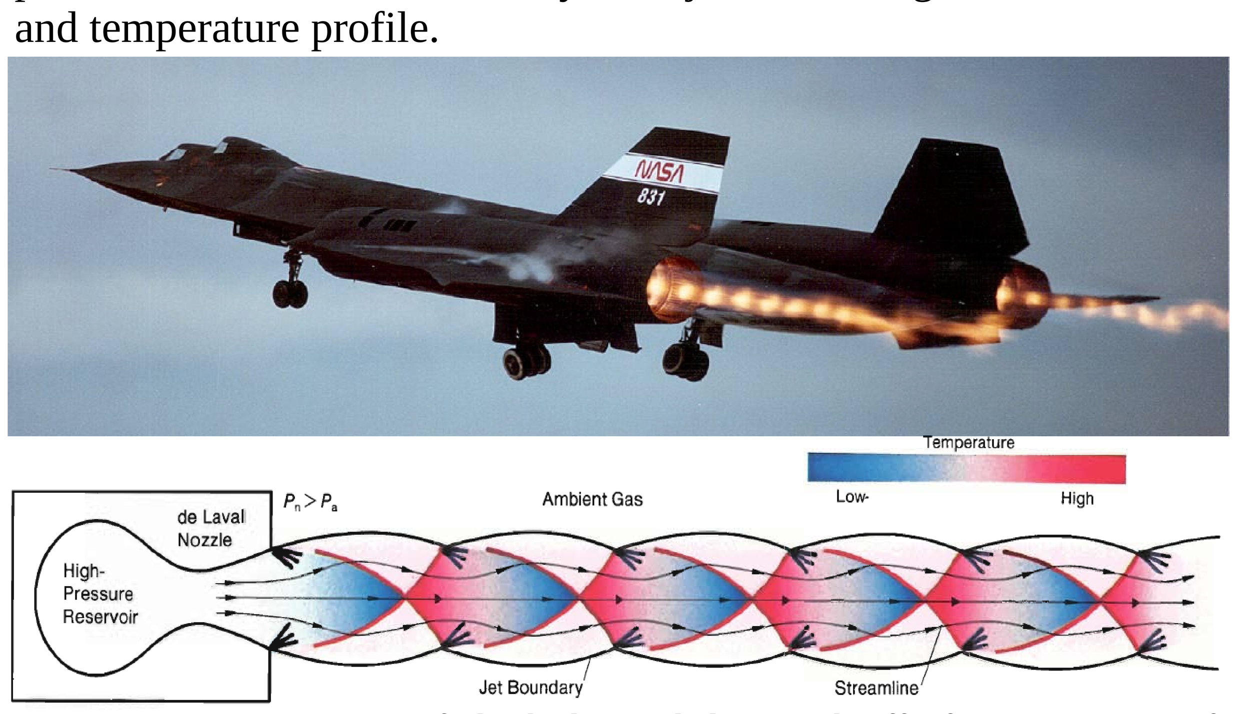


Figure 2 :Top- Formation of shock diamond during takeoff of an SR-71 aircraft (http://www.nasa.gov/centers/armstrong). Bright knots are the location of shock due to recollimation of flow under external-medium pressure. Bottom- Idealized steady-state structure of a slightly under-expanded supersonic jet. The red lines represent the incident and reflected shock. Black streamlines follow the oscillating flow path of the jet gas (Norman & Winkler, 1985).

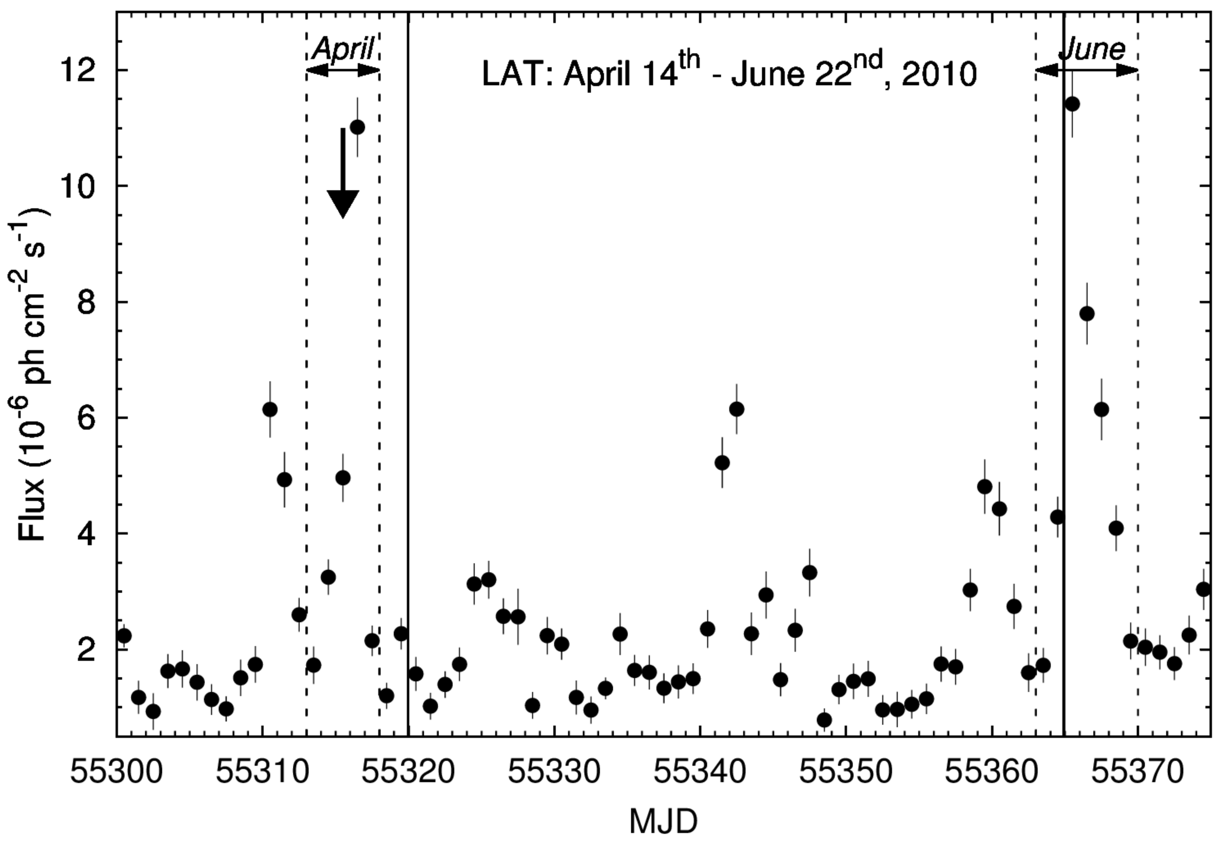


Figure 1: Daily 0.1 – 300 GeV Fermi-LAT light curve during the high γ-ray activity of the source in 2010. The vertical solid lines and arrow are the epochs of VHE detection by the MAGIC observatory and the Fermi-LAT respectively.

## Recollimation Scenario: Model Assumptions (June 2010 Flare)

- Spherical emission region of radius R' moving down the jet with an evolving bulk Lorentz factor Γ(t) given by

$$\Gamma(t) = \Gamma_0 + \Gamma_1 e^{-(t-t_0)/\tau}$$

t & t' are related by Doppler factor δ(t)

- Continuous injection of non-thermal particles with a broken power-law energy distribution.

$$Q(\gamma',t')d\gamma' = \begin{cases} K(t')\gamma'^{-p}d\gamma', & \gamma'_{min} < \gamma' < \gamma'_b \\ K(t')\gamma_b'^{(q-p)}\gamma'^{-q}d\gamma', & \gamma'_b < \gamma' < \gamma'_{max} \end{cases}$$

- Radiative energy loss via synchrotron and IC scattering of both synchrotron and IR photons from the dusty torus (T~1200 K)
- Particle evolution described by (solved numerically)

$$\frac{\partial n'(\gamma',t')}{\partial t'} = \frac{\partial}{\partial \gamma'}[P(\gamma',t')n'(\gamma',t')] - \frac{n'(\gamma',t')}{t_{esc}} + Q(\gamma',t')$$
$$P(\gamma',t') = \frac{4c\sigma_T}{3 m_e c^2}\gamma'^2(u'_B + u'_{syn} + u'_{ir})$$

- Observed flux given by

$$F_{obs}(\nu_{obs},t_{obs}) = \frac{\delta^3(t)(1+z)}{d_L^2} V'\epsilon'\left(\frac{(1+z)}{\delta(t)}\nu_{obs}, \frac{\delta(t)}{(1+z)}t_{obs}\right)$$

$d_L$: Luminosity distance; ε': Total emissivity; V': Emission region volume

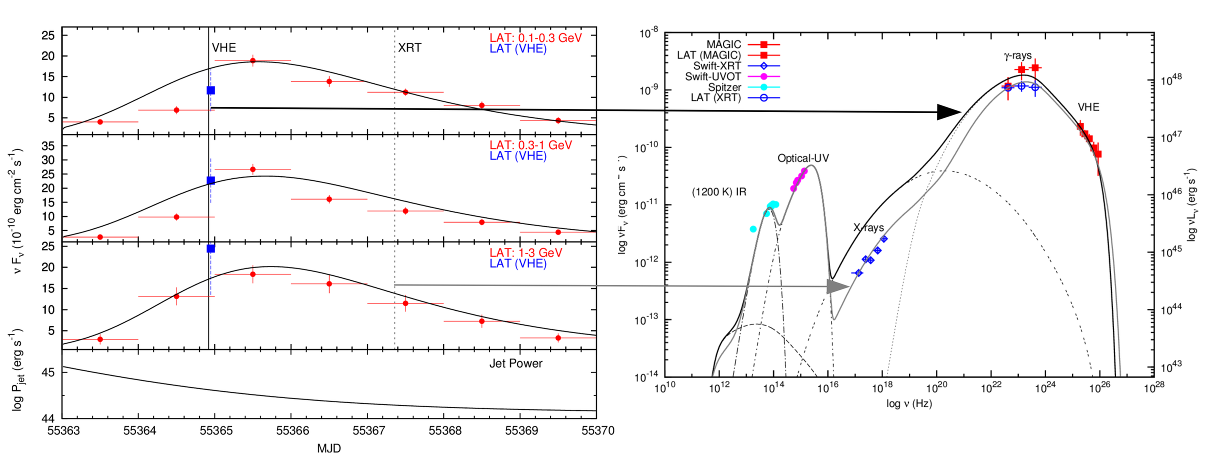

Figure 3: Model reproduced γ-ray light curves and the simultaneous high energy SEDs during the June 2010 flare (see Table 1 for model parameters).

## Table 1: Model Parameters in the Recollimation Scenario

| Parameters | Symbol | Numerical values |
|---|---|---|
| Particle spectral index (before break) | p | 1.15 |
| Particle spectral index (after break) | q | 3.0 |
| Magnetic field (*Gauss*) | *B* | 0.1 |
| Range of bulk Lorentz factor | Γ | 60-18 |
| Particle spectrum break energy ( unit of $m_e c^2$) | $\gamma'_b$ | $4.2\times 10^3$ |

Emission region size, $R' : 3\times 10^{14}\ cm$
Angle between bulk velocity and line of sight, $\theta : 2.5^\circ$
Torus temperature , $T_* : 1200$ K
Minimum particle energy (injected), $\gamma'_{min} : 30$ ( unit of $m_e c^2$)
Maximum particle energy, $\gamma'_{max} : 7\times 10^4$

## Bright LAT Flares of PKS 1222+216: Temporal Study

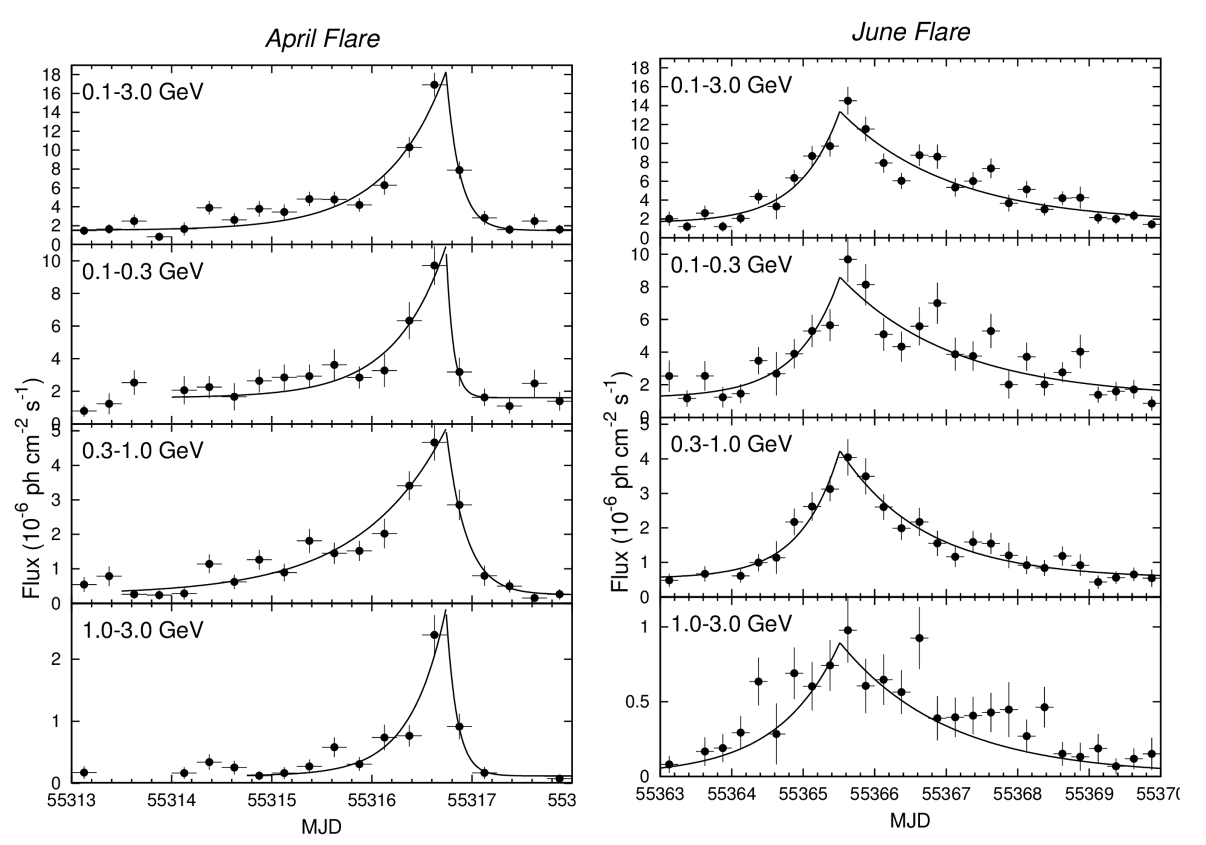


Figure 4: LAT light curves during the two bright flares in April and June 2010 at the best time resolution of 6 hours in four different energy bands: 0.1–3 , 0.1-0.3, 0.3–1, 1–3 GeV.

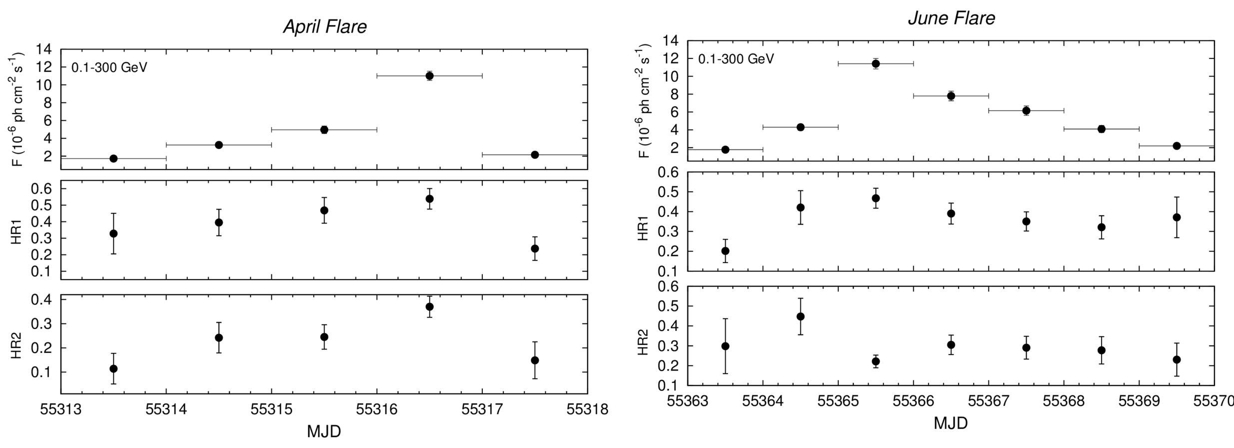


Figure 5: Flux variability (0.1-300 GeV) and hardness ratios (HR1:F(0.3-1 GeV)/F(0.1-0.3 GeV), HR2:F(1-3 GeV)/F(0.3-1 GeV)) on a day timescale during the April and June 2010 flare.

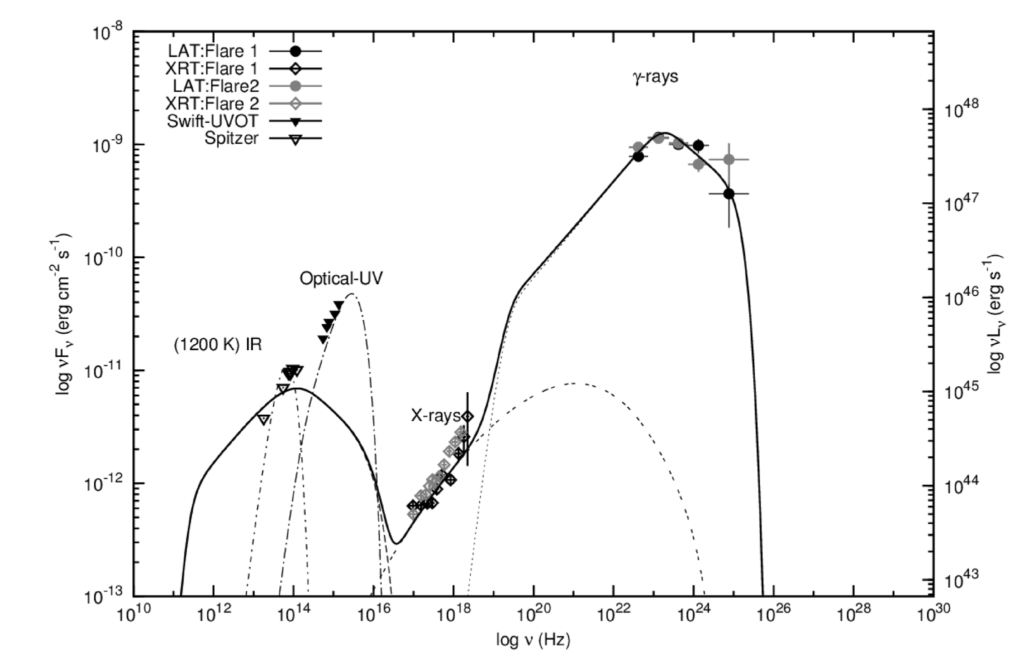


Figure 6: PKS 1222+216 SEDs during the April and the June bright LAT flares with one zone leptonic model reproduced fluxes.

## Summary

- Continuous injection under recollimation scenario successfully reproduces the daily LAT light curves along with simultaneous high energy SEDs (Fig. 3).
- The inferred value of bulk Lorentz factor (Γ~60-18) under recollimation scenario is consistent with the super-luminal motion observed in radio monitoring of blazars.
- Similar LAT SEDs (Fig. 6) but contrastingly different variability (Fig. 4) and hardness ratios (Fig. 5).
- April flare consistent with being originated at a shock (left panel, Figs. 4 & 5) .
- Energy dependent HRs and the multi-peak features during the June flare suggest contribution from multiple emission region and/or inhomogeneities within the jet (right panel, Figs. 4 & 5).

## References


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