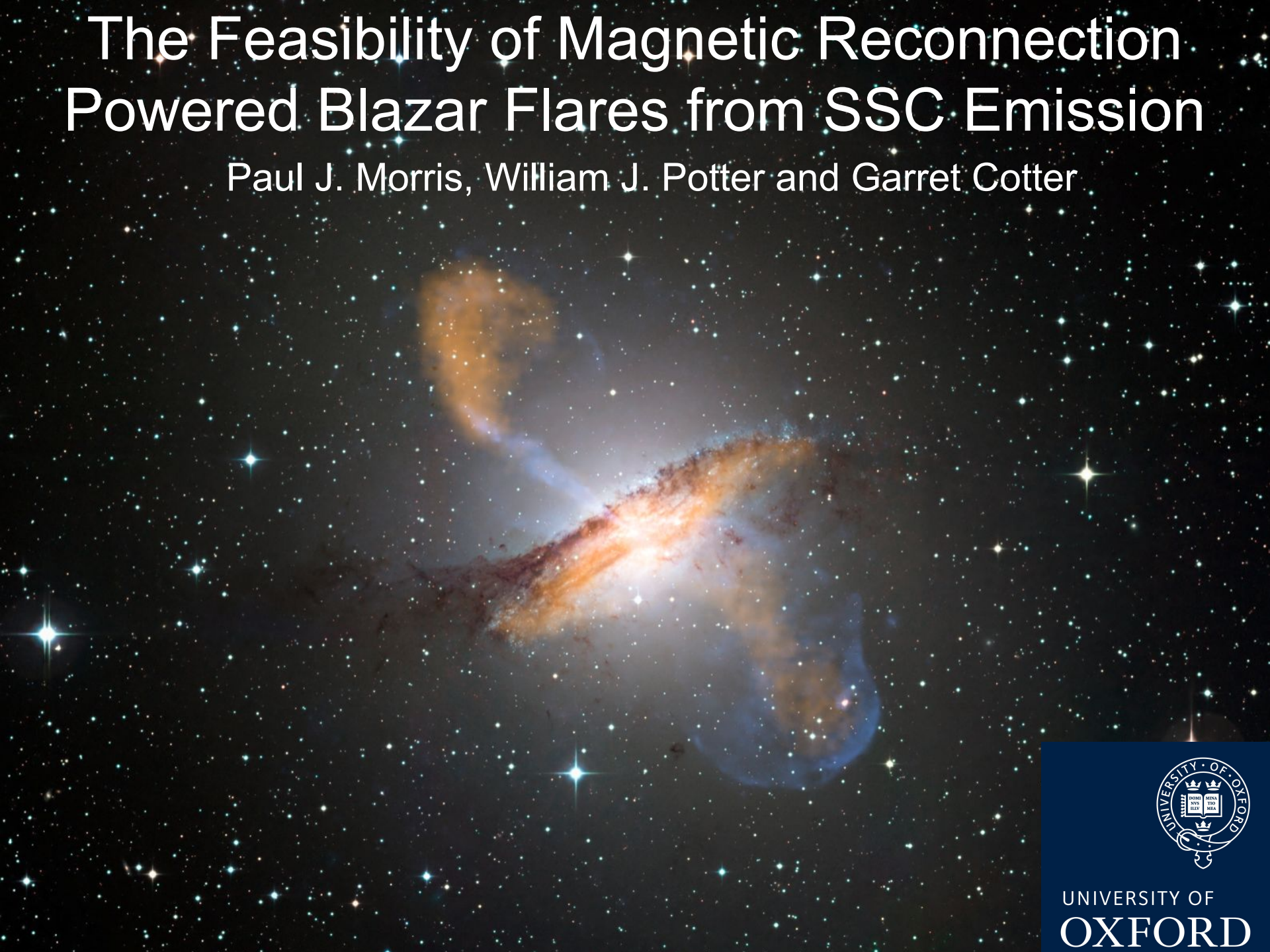
The Feasibility of Magnetic Reconnection Powered Blazar Flares from SSC Emission

Paul J. Morris, William J. Potter and Garret Cotter



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Outline

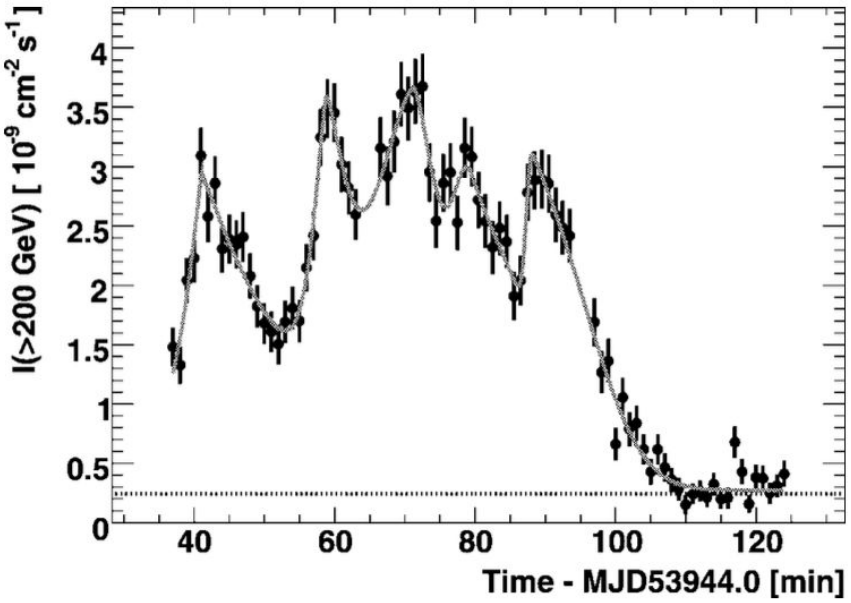
- **The Problem –** Why is flaring in blazars an interesting but challenging problem?
- **The Idea** – What is magnetic reconnection and why is a popular mechanism for powering blazar flares?
- **The model –** I will outline the properties of a macroscopic reconnection model with some parameterisation based on reconnection
- **The results –** The model is used to produce time evolving SEDs and TeV light curves. I will outline the general properties of these before discussing the fit to the 2016 TeV flare light curve and SED of BL Lacertae
- **The Conclusion –** Can reconnection power very rapid blazar flares?

The Problem

- **The Problem –** TeV flaring in the blazar sub-class of AGN has been observed on rapid timescales as fast as minutes.
- Conventional shock models struggle with the relatively compact emitting regions implies from light crossing time arguments. The size of the emitting region cannot exceed (Abevsekara et al. 2018),

$$R \leq \frac{ct_{\mathrm{var}}\delta}{(1+z)}.$$

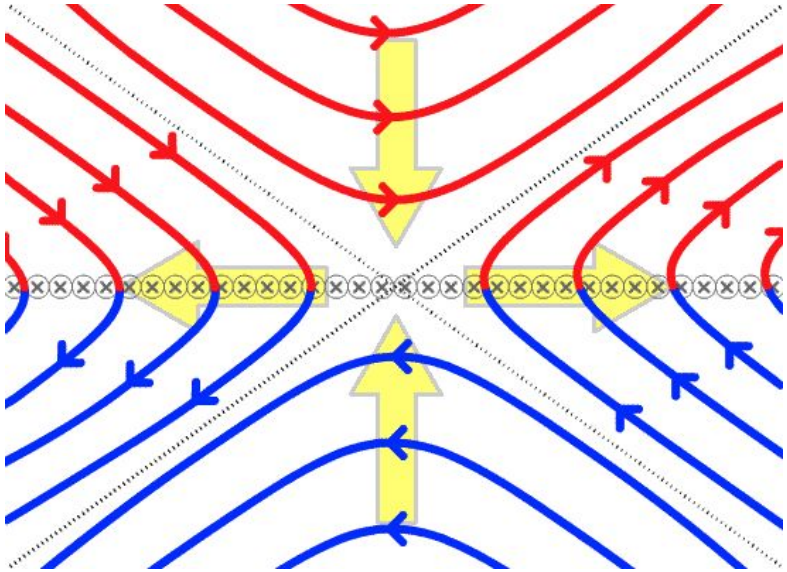
- Particle-in-Cell simulations have shown magnetic region can produce compact emitting plasmoids, which may be able to account for TeV blazar flaring
- However, PIC simulations do not currently scale up to the large sizes likely needed to model astrophysical sources.



Aharonian et al. (HESS Collaboration, 2007)

Magnetic Reconnection

- Magnetic field lines of opposite polarity converge, causing a current sheet to form in between them.
- A $\boldsymbol{j} \times \boldsymbol{B}$ acts on the field lines, forcing them towards the current sheet and annihilate with the opposing field lines.
- They then rearrange, or reconnect, changing the direction of $\boldsymbol{j} \times \boldsymbol{B}$ to expel material laterally
- This creates a pressure gradient, allowing more plasma to flow into the reconnection region



Magnetic Reconnection: PIC simulations

- The key to why reconnection may be able to power blazar flares is that the current sheet fragments into a series of magnetic islands.
- These happen as a consequence of the drift kink and tearing mode instabilities (Sironi & Spitkovsky 2014).
- These plasmoids collide and merge – particles can be accelerated in this process
- There is some debate as to whether the dominant acceleration mechanism is shock like or due to the reconnecting electric field

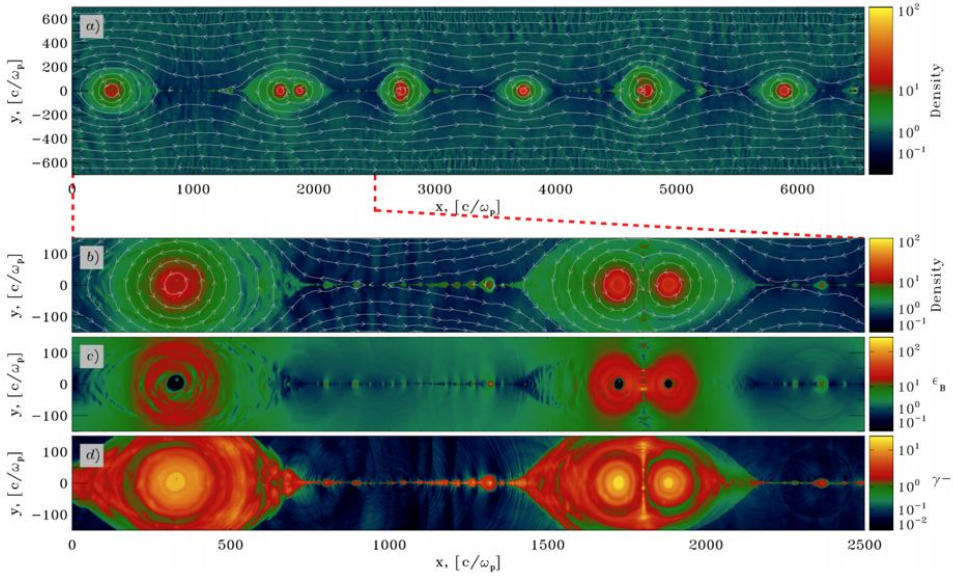
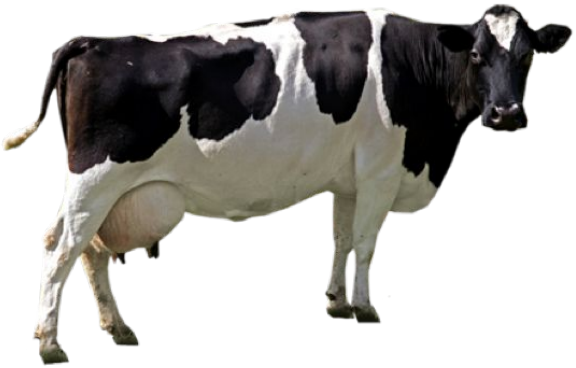


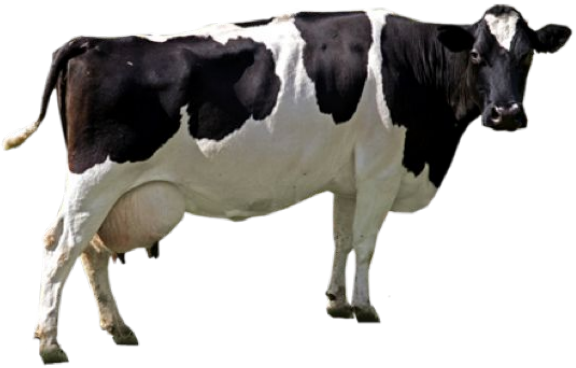
FIG. 1.— Structure of the reconnection layer at $\omega_p t = 3000$ (so, $\omega_c t \sim 10^4$), from a 2D simulation of $\sigma = 10$ reconnection. The box extends along x over $\sim 6550\, c/\omega_p$ (65536 cells), and along y over $\sim 6000\, c/\omega_p$ (~ 60000 cells), but along y it will expand even more at later times (we only show a subset of the domain along y). We present (a) particle density, in units of the density far from the sheet (with overplotted magnetic field lines), (b) magnetic energy fraction $\epsilon_B = B^2/8\pi mnc^2$ and (c) mean kinetic energy per particle.

Sironi and Spitkovsky (2014)

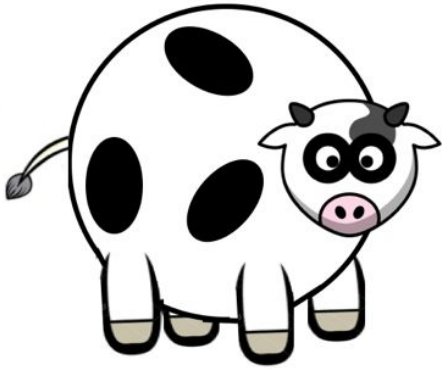
One zone models: A Useful Approximation



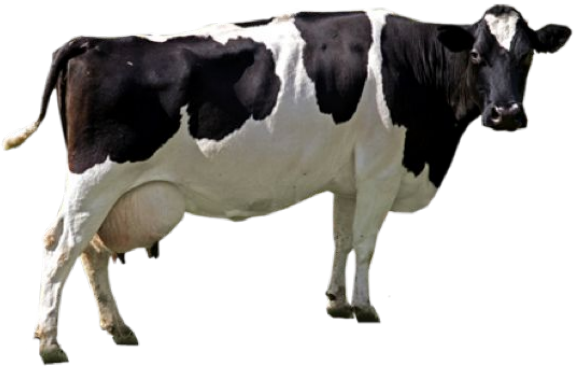
One zone models: A Useful Approximation



Simplifying Assumptions



One zone models: A Useful Approximation



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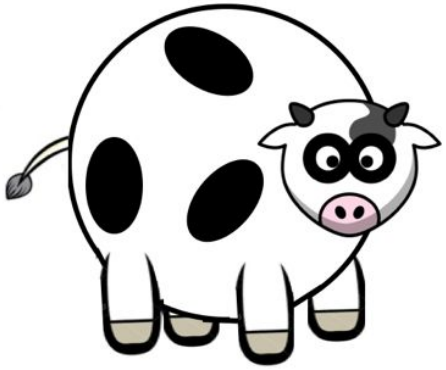

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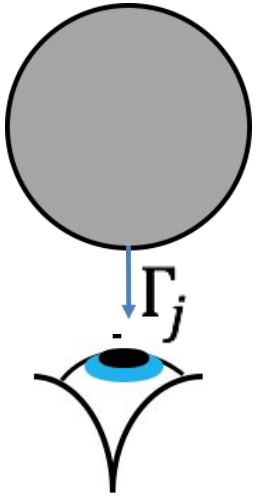


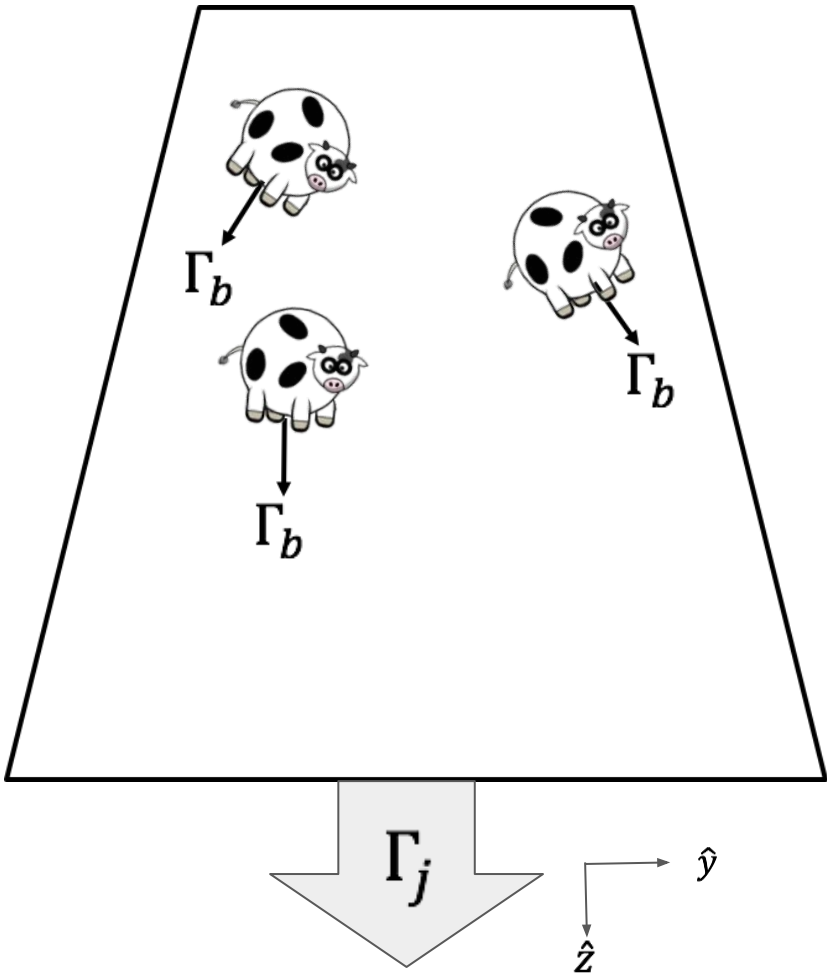
TeV Flares: The idea

- PIC simulations have shown that magnetic reconnection produces quasi-spherical blobs (e.g. Sironi, Giannos and Petropoulou (2016)).
- These blobs can move relativistically within the jet (see also Giannos et al. 2009)
- Thus they can have greater Doppler factors than the jet itself
- The emitting plasmoid moves relativistically within the jet, effectively adding an extra component to the velocity on the line of sight such that (see Sironi et al. 2016),

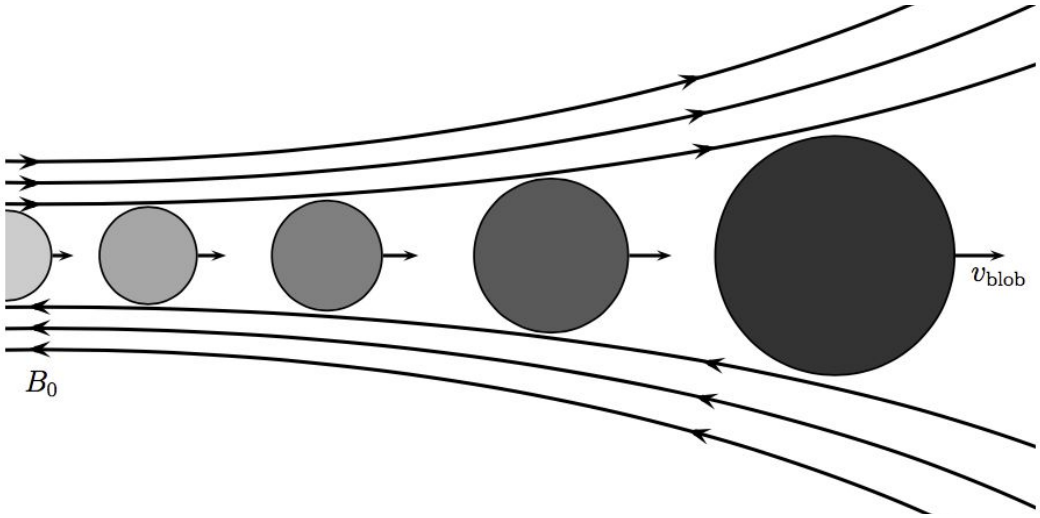
$$\beta_z = \frac{\beta_j + \beta_{blob} \cos\theta'}{1 + \beta_j \beta_{blob} \cos\theta'} \qquad \beta_y = \frac{\beta_{blob} \sin\theta'}{\Gamma_j (1 + \beta_j \beta_{blob} \cos\theta')}$$

- With $\beta_p = (\beta_y^2 + \beta_z^2)^2$, gives an observed plasmoid Lorentz factor of,

$$\Gamma_p = \Gamma_j \Gamma_b \left(1 + \beta_j \beta_b \cos\theta'\right) = \left(1 - \beta_p^2\right)^{\frac{1}{2}}.$$



The Model



- We assume a leptonic jet consisting entirely of electrons and positrons (hereafter electrons).
- The model assumes that one plasmoid in the reconnection layer dominates the emission. It grows and accelerates throughout its time in the reconnection later.
- Energy is converted from magnetic energy to particle energy, such that the total energy density, $U_{TOT} = U_B + U_e = (\sigma + 1)U_e$, is conserved.
- The magnetisation, $\sigma = U_B/U_e$, along with the initial magnetic field, B, are free parameters

The Model - merging timescale

- We assume that the characteristic acceleration timescale is given by the merge timescale of the plasmoids, given by,

$$\tau_{\rm acc} = \tau_{\rm merge} = f\frac{R(t)}{v_{\rm blob}(t)}$$

- The parameter *f* is a free parameter, which quantifies the spacing between adjacent plasmoids.

- We adopt the velocity profile of Sironi et al. (2016), with

$$\Gamma_{\rm b}\beta_{\rm b} = \sqrt{\sigma_0}\tanh\left(\frac{0.12x}{\sqrt{\sigma_0}R}\right),$$

- where *R* is the plasmoid radius and *x* is the distance travelled in the reconnection layer.
- We assume that the plasmoid volume doubles every $\tau_{\rm merge}$, thus the rate of radial increase is given by,

$$\frac{\rm dR}{\rm dt} = \left(2^{\frac{1}{3}} - 1\right)\frac{v_{\rm blob}}{f} \approx 0.26\frac{v_{\rm blob}}{f}.$$

The free parameter *f* quantifies the spacing between adjacent plasmoids

The Model - Particle Acceleration

$$\frac{\mathrm{d}N(E)}{\mathrm{d}t} = D\nabla^2 N + \frac{\partial}{\partial E}\left[b(E)N(E)\right] - \frac{N(E)}{\tau_{esc}} + Q(E),$$

Diffusion Term
Assume Bohm diffusion

Energy Change Term
Take $b(E) = \frac{-\alpha E}{\tau_{acc}}$

Escape Term

Injection Term
Take $Q(E) = 0$

$$\frac{\mathrm{d}N(E)}{\mathrm{d}t} = -\frac{N(E)}{\tau_g}\left(\frac{r_g}{R}\right)^2 - \frac{\alpha N(E)}{\tau_{acc}} - \frac{\alpha E}{\tau_{acc}}\frac{\mathrm{d}N(E)}{\mathrm{d}E} - \frac{N(E)}{\tau_{esc}},$$

Where are the gyroradius and gyro-period are,

$$r_g = \frac{\gamma m_e |v|}{e|B|}\sin\theta, \qquad \tau_g = \frac{2\pi r_g}{c},$$

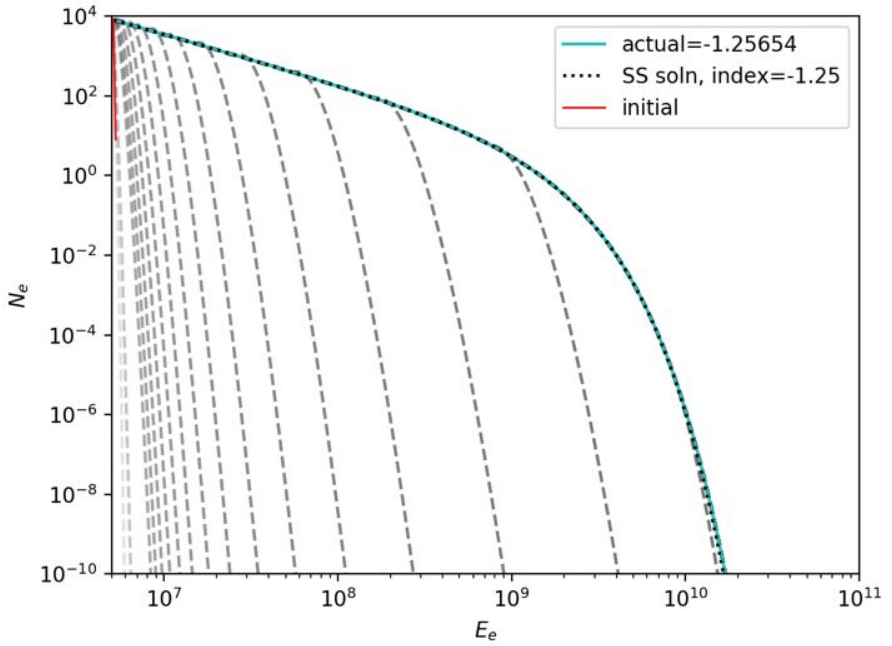
Particle Acceleration - A Steady State Solution

$$\frac{\mathrm{d}N(E)}{\mathrm{d}t} = -\frac{N(E)}{\tau_g}\left(\frac{r_g}{R}\right)^2 - \frac{\alpha N(E)}{\tau_{acc}} - \frac{\alpha E}{\tau_{acc}}\frac{\mathrm{d}N(E)}{\mathrm{d}E} - \frac{N(E)}{\tau_{esc}},$$

Steady State Solution

$$\dot{N(E)} = 0$$

$$\frac{\mathrm{d}N}{\mathrm{d}E} = AE^{-\left(1+\frac{\tau_{\mathrm{merge}}}{\alpha\tau_{\mathrm{esc}}}\right)} \exp\left(-\frac{\tau_{\mathrm{merge}}}{\alpha\tau_{\mathrm{g}}}\frac{r_{\mathrm{g}}^2}{R^2}\right),$$



- The plasmoid is initialised as having $R = 10^{10}$ m with an electron population approximated as a δ-fn with γ =10
- In the limit of no losses, which are discussed later, the differential equation has an analytical solution, which has been used to test the code
- The parameter α quantifies the average energy gain per merge time and is another free parameter. We assume $\tau_{esc} = \infty$ as we do not expect particles to escape the reconnection region.

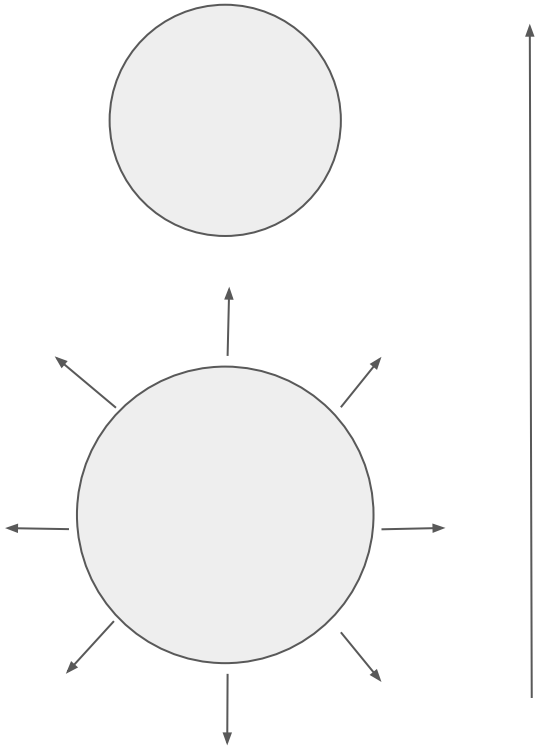
The Model - Radiative Losses

- It is assumed that emission is dominated from a single plasmoid and that the constituent electrons emit via synchrotron and synchrotron self-Compton (SSC). The emitted power from each of these mechanisms is,

$$P_{\rm sync} = \frac{4\sigma_{\rm T}}{3m_{\rm e}^2c^3}\beta^2E^2U_{\rm B},$$

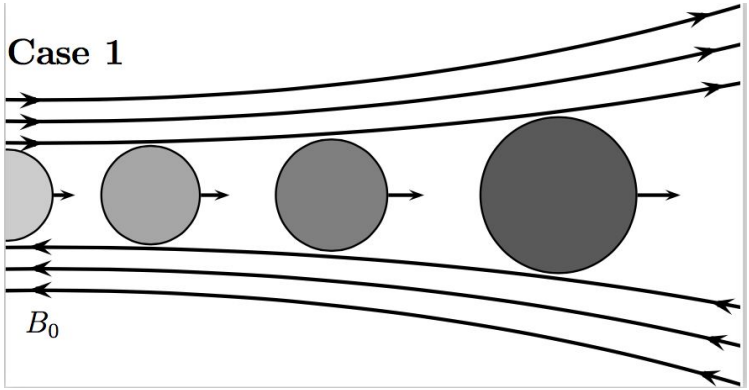
$$P_{\rm IC} = \frac{4\sigma_{\rm T}}{3m_{\rm e}^2c^3}\beta^2E^2U_{\rm rad},$$

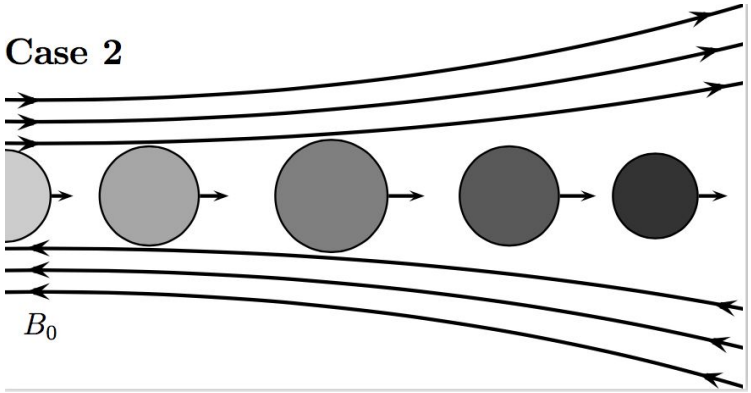
- The Klein-Nishina cross-section is explicitly computed (Blumenthal & Gould, 1970) as are effects from TeV absorption (Gould & Schreder 1967), which can convert photon pairs into an electron and positron.

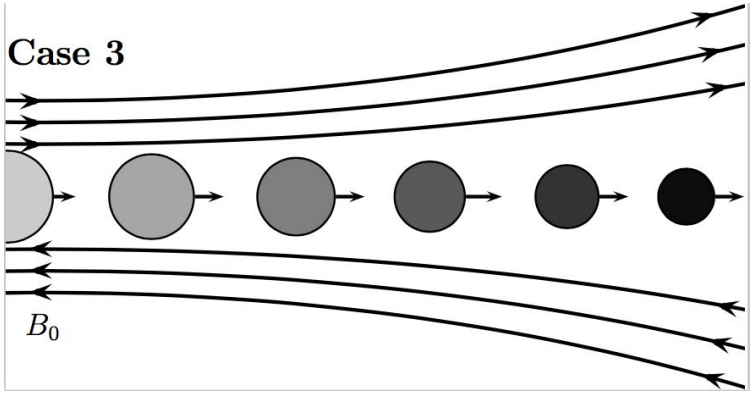


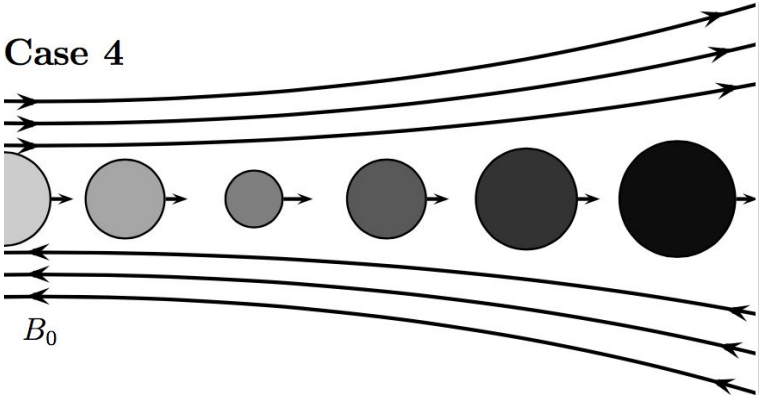
The emitting plasmoid is assumed to be in pressure equilibrium with its surroundings. Thus, it shrinks slightly when radiating.

The Model - Possible Scenarios







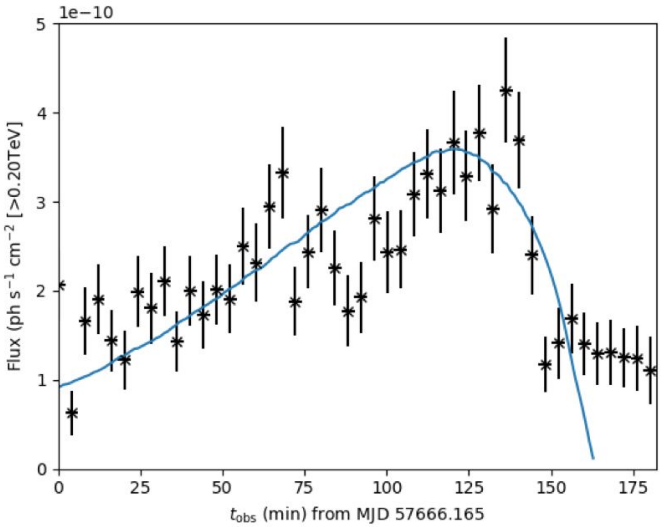


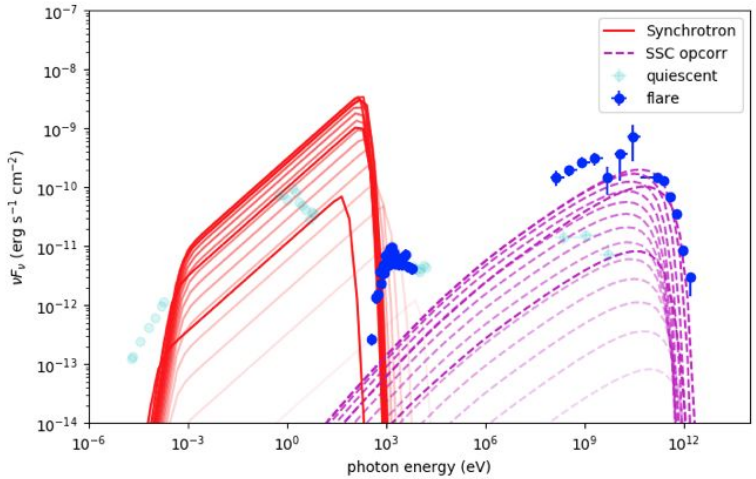
The assumption that the emitting plasmoid remains in pressure equilibrium leads to four possible scenarios. For the plasmoid to grow large enough to be detectable, we require case 1, where the radiative losses are not extreme enough to inhibit the growth.

Fitting to the 2016 TeV Flare of BL Lacertae

- We fit to the 2016 TeV flare of BL Lacertae (Abeysekara et al. 2018) and are able to replicate the slow rise and rapid decay with the model. The fit has a reduced chi squared value of 3.64.
- The SED well fits the TeV points, but appears to be synchrotron dominated. This was a general property of SEDs produced by the code.
- The flaring light curve and SED data are from Abeysekara et al. 2018. Quiescent SED data is shown for comparison (Abdo et al. 2011)

B_0 (T)	5×10^{-5}
σ_0	9×10^4
α	2.0
f	1.6
Γ_j	28
θ_{rf} (DEG)	87
θ_{obs} (DEG)	1.2





Morris et al. 2018 (in prep)

Synchrotron Dominated Flares

- The ratio of SSC to synchrotron peaks is given by U_{rad}/U_B
- The code converts $U_B \rightarrow U_e \rightarrow U_{rad}$. Initially, $U_B >> U_e$, thus the flare cannot be Compton dominated in this phase.
- Though $U_e > U_B$ is possible, as U_B decreases, so does the magnetic field, which vastly reduces the seed photons needed for SSC emission as $P_{sync} \propto B^2$
- Therefore, flares are never Compton-dominated

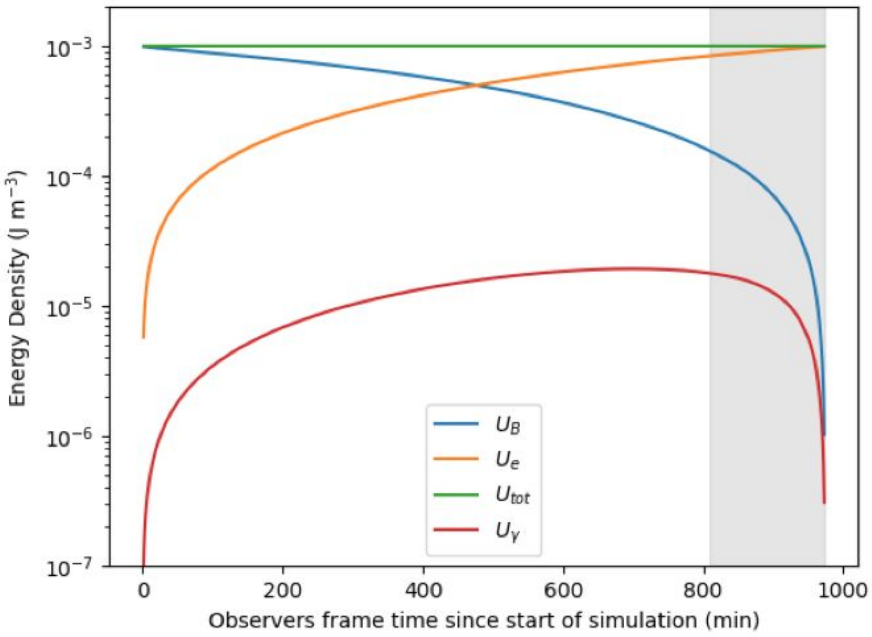
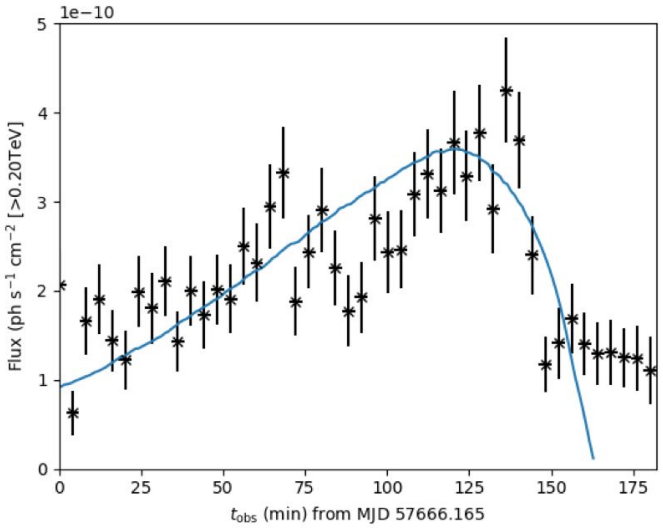


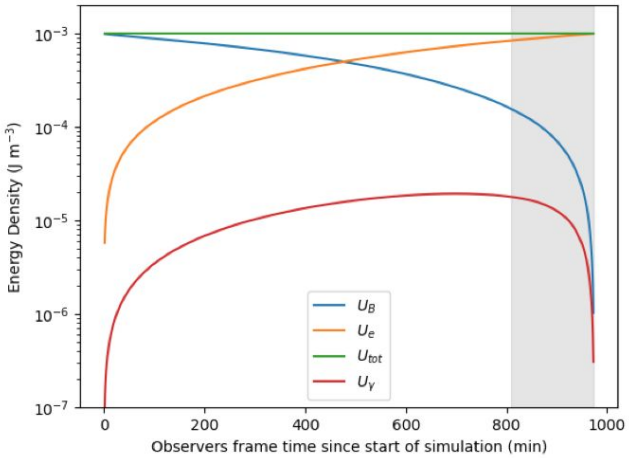
Figure showing the strength of the energy densities for the best fit to the 2016 BL Lacertae TeV flare. The time corresponding to the flare in the light curve is shown in grey.

Explaining the shape of the flare

Rise Time

- The maximum electron energy is governed by a balance between particle acceleration and radiative losses
- During the emission phase, the value of *B* is decreasing, allowing the maximum electron energy to increase and more are able to emit in the TeV range
- This causes the flare to rise





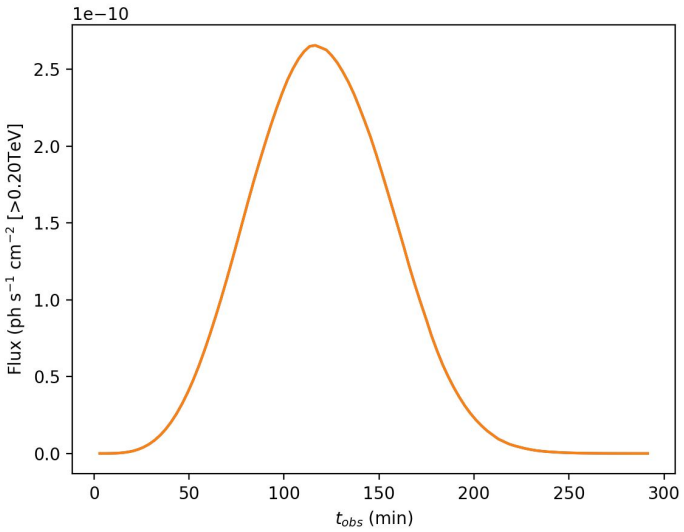
Decay Time

- Eventually, the *B*-field falls enough that significantly fewer synchrotron seed photons are produced.
- This happens when the emitting plasmoid is approaching complete particle dominance
- The lack of seed photons quickly attenuates the flare, giving a characteristic rapid decay time.

Magnetically dominated flares

Rise Time

- During these flares, there is little change in the value of *B*
- Here, particle acceleration accelerates the constituent electrons so they emit in the TeV range.
- However, the merge timescale increases as the radius of the emitting plasmoid increases, thus making the acceleration less efficient
- This eventually slows the rise as radiative losses begin to dominate
- The peak is reached when radiative losses are balanced by particle acceleration

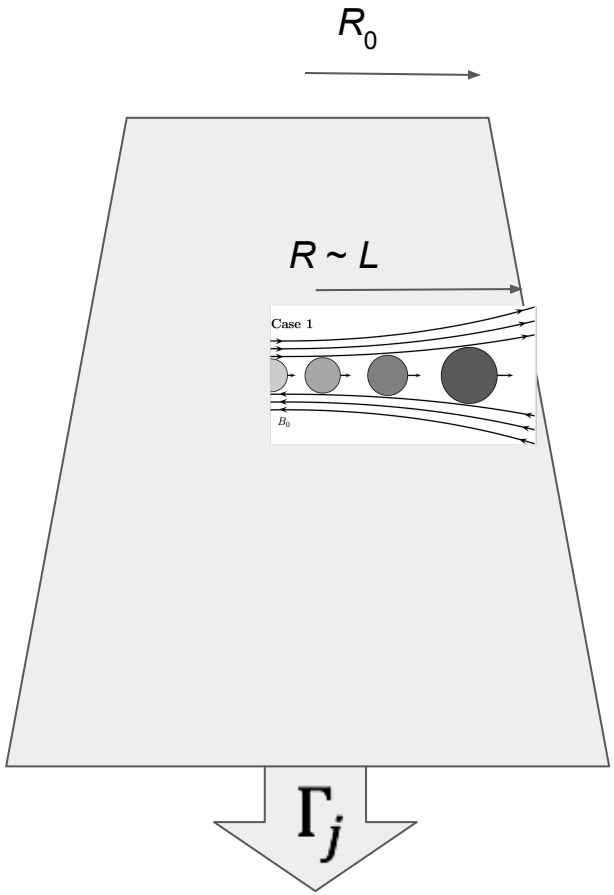


Decay Time

- The radius of the emitting plasmoid continues to increase with successive merging in the reconnection layer, further reducing the acceleration efficiency.
- This causes a steady reduction in the peak frequency of the flare as the emitting electrons decrease in energy
- Lower energy electrons have longer radiative lifetimes, giving a longer characteristic flare decline.

Constraining the location of the emission region along the jet from the fit of BL Lacertae

- The final size of the reconnection plasmoid is $R = 1.2 \times 10^{14}$ m, with the size of the reconnection layer being $L = 7 \times 10^{14}$ m.
- Assuming a adiabatic jet, $B \propto R^{-1}$. Assuming the jet is in equipartition between magnetic and particle pressure, equating the plasmoid energy density to the jet energy density gives $U_{jet} = U_{blob} = B_{jet}/\mu_0$ yielding $B_{jet} = 3.5 \times 10^{-5}$ T.
- Assuming a conical jet, and taking values from Potter & Cotter (2013) gives a jet radius at this point of $R_{jet} = 6 \times 10^{14}$ m.
- Therefore, it is expected that the reconnection layer occupies a substantial fraction of the jet width.



Summary and Conclusions

- The model is able to fit to the light curve of the 2016 TeV flare of BL Lacertae with a reduced chi squared of χ_ν^2 = 3.64. This is the first time a reconnection emission model has been able to do so.
- The model produces synchrotron-dominated flares, and cannot produce Compton dominated flares.
- The shape of the flaring profile depends on the merge timescale of the emitting reconnecting plasmoid and the magnetisation of the plasma.
- The final size of emitting plasmoids which are radiatively bright enough to be detected are comparable to those used in one-zone jet models.
- By assuming an adiabatic jet, we estimate that the size of the reconnection layer is comparable to the jet radius, assuming the emitting plasmoid to be in pressure equilibrium with the jet plasma.
- We conclude that reconnection cannot power TeV flares in blazar sources if the primary emission mechanism is SSC.

Backup - Doppler Boosting

- The emitting plasmoid moves relativistically within the jet, effectively adding an extra component to the velocity on the line of sight such that (see Sironi et al. 2016),

$$\beta_z = \frac{\beta_j + \beta_{blob}\cos\theta'}{1+\beta_j\beta_{blob}\cos\theta'} \qquad \beta_y = \frac{\beta_{blob}\sin\theta'}{\Gamma_j(1+\beta_j\beta_{blob}\cos\theta')}$$

- With $\beta_p = (\beta_y{}^2 + \beta_z{}^2)^2$, gives an observed plasmoid Lorentz factor of,

$$\Gamma_p = \Gamma_j\Gamma_b\left(1+\beta_j\beta_b\cos\theta'\right) = \left(1-\beta_p^2\right)^{\frac{1}{2}}.$$

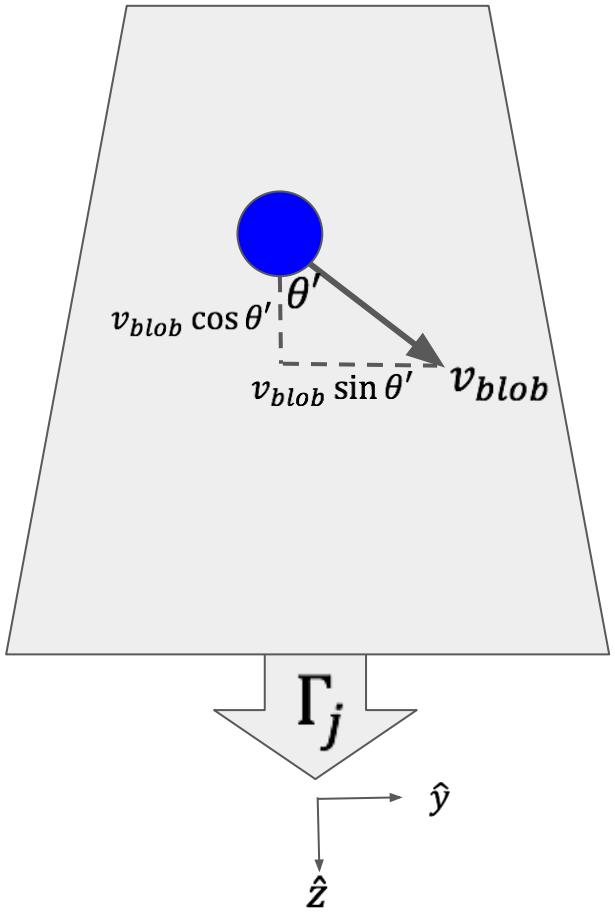
- The angle in the observer's frame is given by,

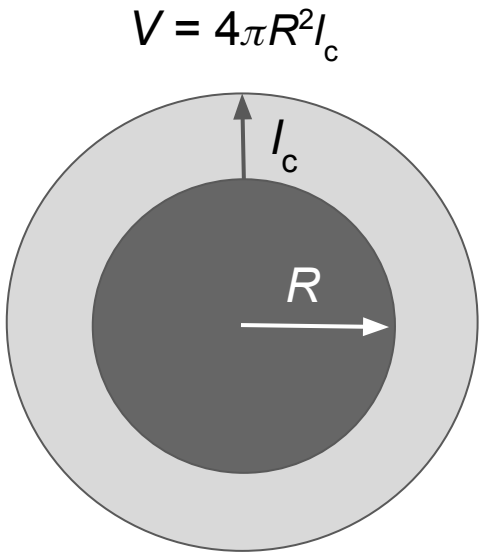
$$\tan\theta = \frac{\beta_b\sin\theta'}{\Gamma_j\left(\beta_j+\beta_b\cos\theta'\right)},$$

- With the Doppler factor defined as,

$$\delta_p = \frac{1}{\Gamma_p\left(1-\beta_p\cos\omega\right)},$$

where $\omega = \theta - \theta_{obs}$. The parameters θ_{obs}, θ' and Γ_j were left free.



Backup - Compton-dominance scales with radius

- The strength of the SSC radiation is proportional to the photon number density from the synchrotron emission process
- The strength of the synchrotron is proportional to the number of emitting electrons, N_e. This depends on the volume, such that $N_e \propto R^3$
- The SSC computation assumes the synchrotron emission is emitted into spherical shell of depth one light second, l_c (see Potter & Cotter 2012). This shell has volume $V = 4\pi R^2 l_c$
- Hence, the photon number density depends on R by $n_{sync} \propto N_e/V \propto R^3/R^2 \propto R$