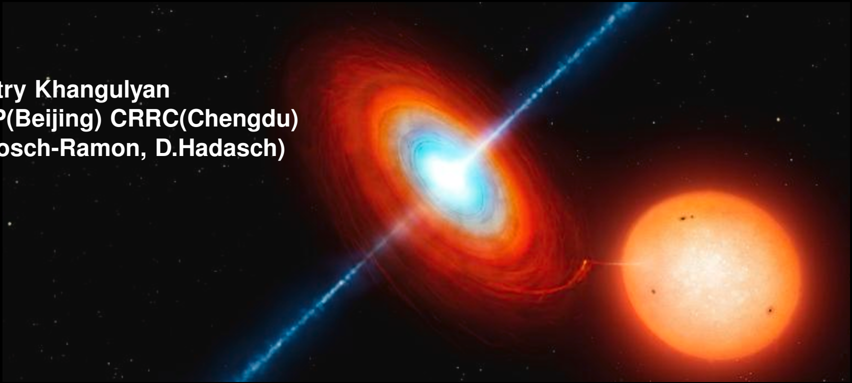
中國科學院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Barcelona
May 6th-8th, 2025

The Power of Jets in Microquasars and thier Multwavelength Emission



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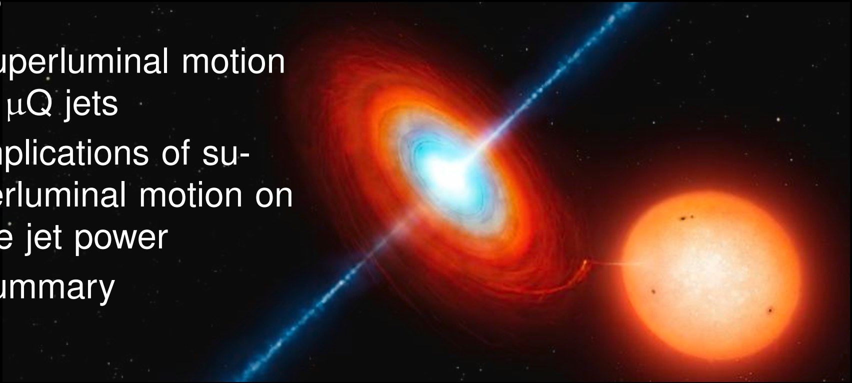
(V.Bosch-Ramon, D.Hadasch)

Variable Galactic Gamma-Ray Sources VII

OUTLINE

- Why do we care about power?
- How do we mesure it?
- Superluminal motion in μQ jets
- Implications of superluminal motion on the jet power
- Summary

Power of Jets in μQs and thier MWL Emission



Variable Galactic Gamma-Ray Sources VII
D. Khangulyan (Barcelona May 8$^{\mathrm{th}}$, 2025)

What are μQ?

What are the key features?

A μQ is a compact stellar system consisting of a stellar-mass black hole (or neutron star) accreting matter from a companion star. The accretion disk emits bright X-ray emission implying a high accration rate; two powerful, relativistic jets moving at nearly the speed of light are ejected.

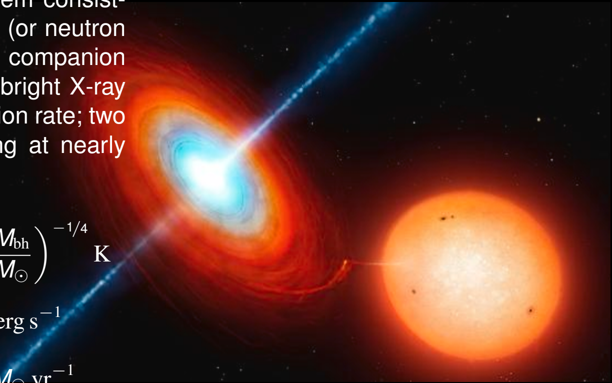
$$T_{\rm disk} = 6.3 \times 10^7 \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{1/4} \left(\frac{M_{\rm bh}}{M_\odot}\right)^{-1/4} {\rm K}$$

$$L_{\rm Edd} = 1.3 \times 10^{38} \left(\frac{M_{\rm bh}}{M_\odot}\right) {\rm erg\ s^{-1}}$$

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{c^2} = 2.2 \times 10^{-9} M_\odot\ {\rm yr}^{-1}$$

$$T_\star = 10^{3-5}\ {\rm K}$$

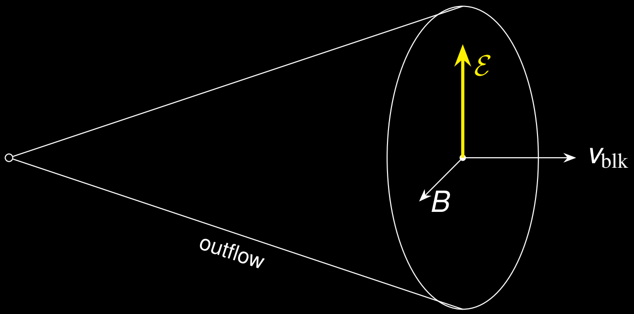
$$L_\star = 10^{33-39}\ {\rm erg\ s^{-1}}$$



Artistic view (credit NASA)

Hillas Criterion

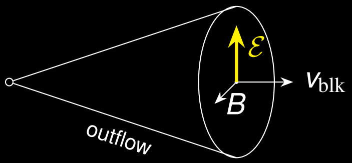
Potential drop determines the maximum energy



Hillas Criterion

Potential drop determines the maximum energy

- ☞ $E_{\rm max} \lesssim e\Delta\Phi_{\rm max} \approx e\Delta R\mathcal{E}$
- ☞ Electric field is $\mathcal{E} = \dfrac{v_{\rm blk}}{c} B$
- ☞ $E_{\rm max} < \dfrac{v_{\rm blk}}{c} eB\Delta R \underset{v_{\rm blk}=c}{\rightarrow} R_{\mathcal{G}} < \Delta R$
- ☞ $\Delta S \approx \dfrac{\pi \Delta R^2}{4} \rightarrow L_B = \dfrac{v_{\rm blk} B^2 \Delta R^2}{16}$
- ☞ Magnetization: $\sigma = \dfrac{L_B}{L}$



$$E_{\rm max} < 4\sqrt{\frac{v_{\rm blk}\sigma e^2 L}{c^2}} = 20\sigma_{0.1}^{1/2}\beta_{0.1}^{1/2}L_{39}^{1/2}\,{\rm PeV}$$

Hillas Criterion

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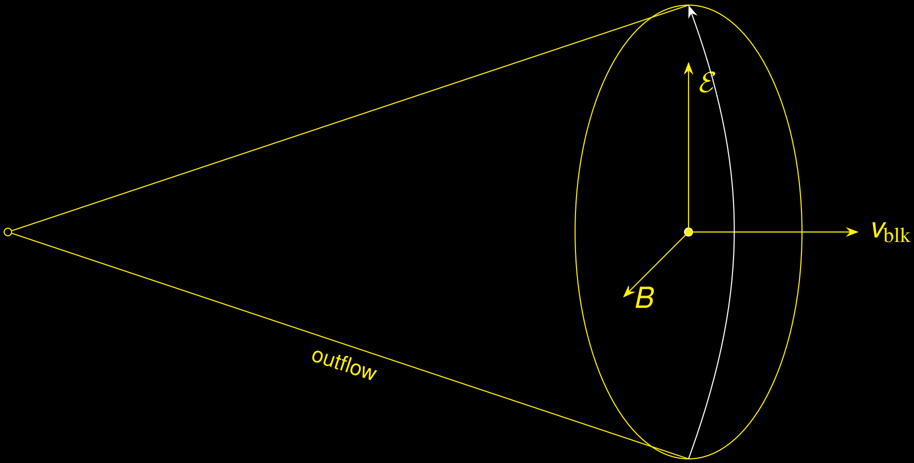
- ? How strongly can the parameters in this estimate vary?
- ☞ Bulk speed, β, may ranger from $\beta = 1$ for pulsar winds to $\beta \sim 10^{-2}$ for stellar wind
- ☞ Outflow magnetization, σ, is probably small between 10^{-2} and 10^{-6}

Promising sources

- ☞ SN shocks (DSA): $\beta = 3 \cdot 10^{-2}, \sigma \sim 10^{-6}$ and $L \sim 10^{31-33}\frac{\rm erg}{\rm s}$
- ☞ Pulsar wind termination shocks (rel): $\beta = 1, \sigma \sim 10^{-2}$ and $L \sim 10^{37}\frac{\rm erg}{\rm s}$ (no protons!)
- ☞ μQs (DSA): $\beta \sim 0.1, \sigma \sim 10^{-2}$ and $L \sim 10^{39}\frac{\rm erg}{\rm s}$

Acceleration vs Losses Rates

In VHE/UHE regimes radiation losses are important



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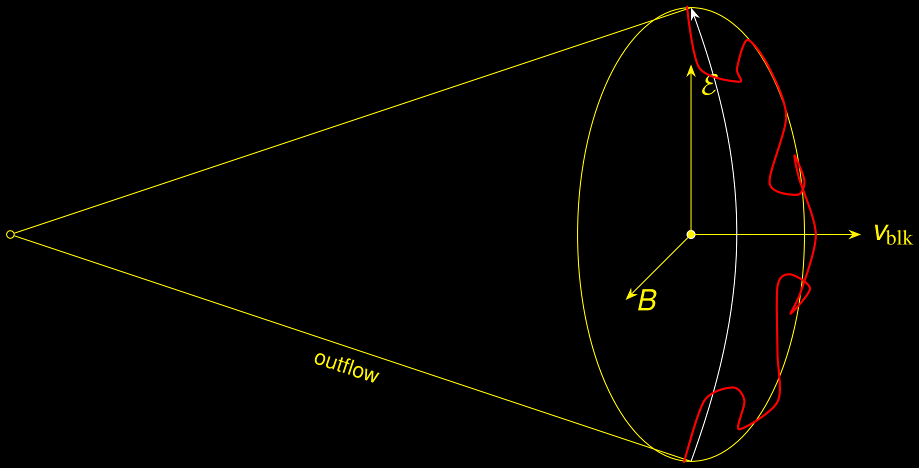


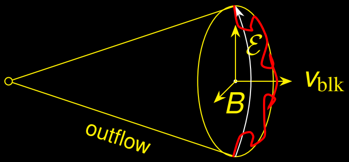
Acceleration vs Losses Rates

In VHE/UHE regimes radiation losses are important

☞ How quickly particles can gain energy?

$$\dot{E} = e\vec{\mathcal{E}}\vec{v} = \frac{ecB}{\eta}$$

where $\eta > c/v_{\rm blk}$ is the acceleration efficiency



☞ For DSA $\eta \sim 2\pi(c/v_{\rm blk})^2$

☞ Acceleration time:

$$t_{\rm acc} = \frac{E}{\dot{E}} = 10^2 \eta E_{\rm PeV} B_{\rm G}^{-1}\ {\rm s}$$

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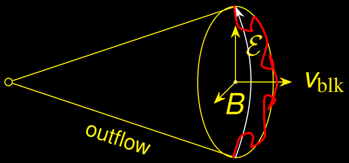

Typical cooling time

- ⋆ for $e^{\pm}$, $t_{\rm syn} \approx 0.4E_{\rm PeV}^{-1}B_{\rm G}^{-2}\,{\rm s}$
- ⋆ for p $t_{\rm pp} \approx 10^5 n_{10}\,{\rm s}$

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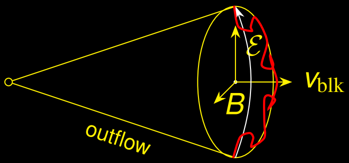

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$$E_{\rm max,e} \approx 30\left(\frac{B\eta}{5\,\mu{\rm G}}\right)^{-1}{\rm PeV}$$

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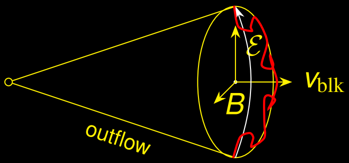

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$$L = 5\times 10^{38}\sigma_{-2}^{-1}\left(\frac{B}{5\,\mu{\rm G}}\right)^2\left(\frac{\Delta R}{10\,{\rm pc}}\right)^2\frac{\rm erg}{\rm s}$$

←

$$E_{\rm max,e} \approx 30\left(\frac{B\eta}{5\,\mu{\rm G}}\right)^{-1}{\rm PeV}$$

Acceleration vs Losses Rates

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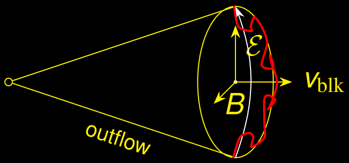

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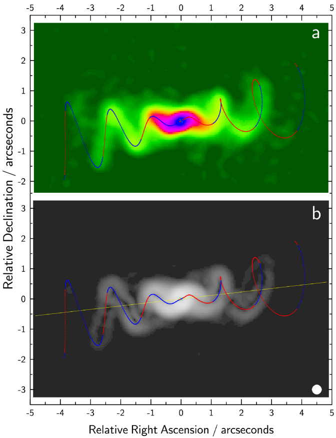
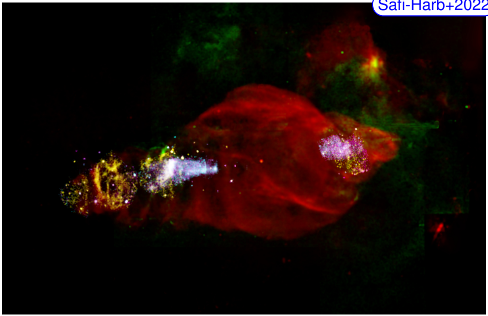
$$t_{\rm acc} = 10^3 E_{\rm PeV} \left(\frac{\eta}{10^3}\right)\left(\frac{B}{5\,\mu{\rm G}}\right)^{-1} {\rm yr} \leftarrow E_{\rm max,e} \approx 30 \left(\frac{B\eta}{5\,\mu{\rm G}}\right)^{-1} {\rm PeV}$$

SS433: the most powerful jet?

Blundell&Bowler2004

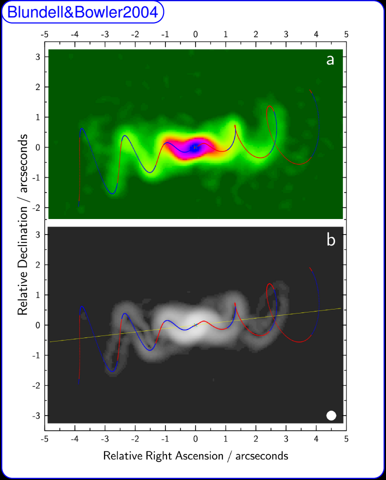


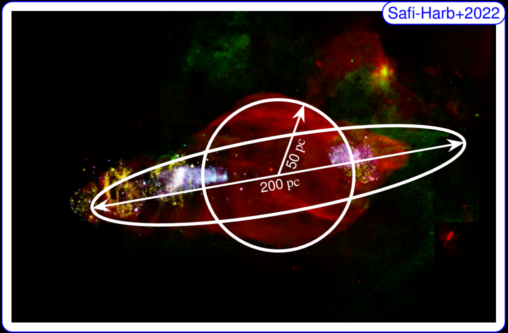
Safi-Harb+2022



- One can determin the speed and kinetic energy of the jet in SS 433 from line emission ($\sim 10^{39}$ $\mathrm{erg\,s^{-1}}$)
- The scales of the W50 and jets are $\sim$ 50 and $\sim$ 100 pc
- Does this help us to understand the evolution of the jet power?

SS433: the most powerful jet?





Sedov-type estimates:

- ☞ Shell: $R_{\rm sh} \sim \sqrt[5]{\frac{E_{\rm snr} t^2}{\rho}}$
- ☞ Jet: $R_{\rm j} \sim \sqrt[5]{\frac{L_{\rm j} t^3}{\rho \Delta\Omega}}$

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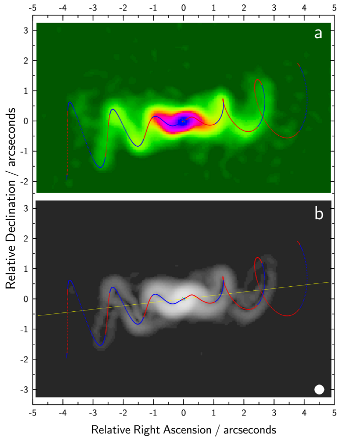

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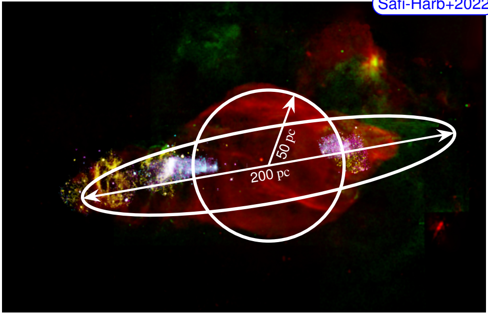
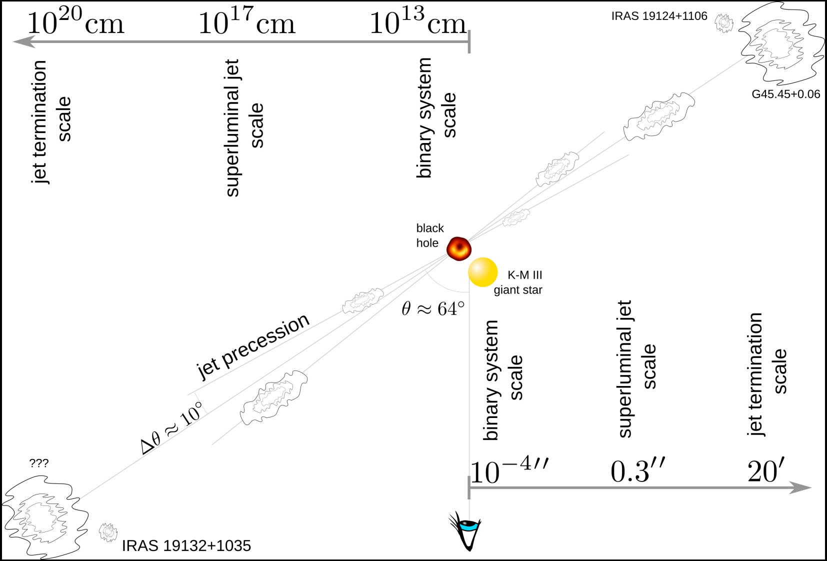


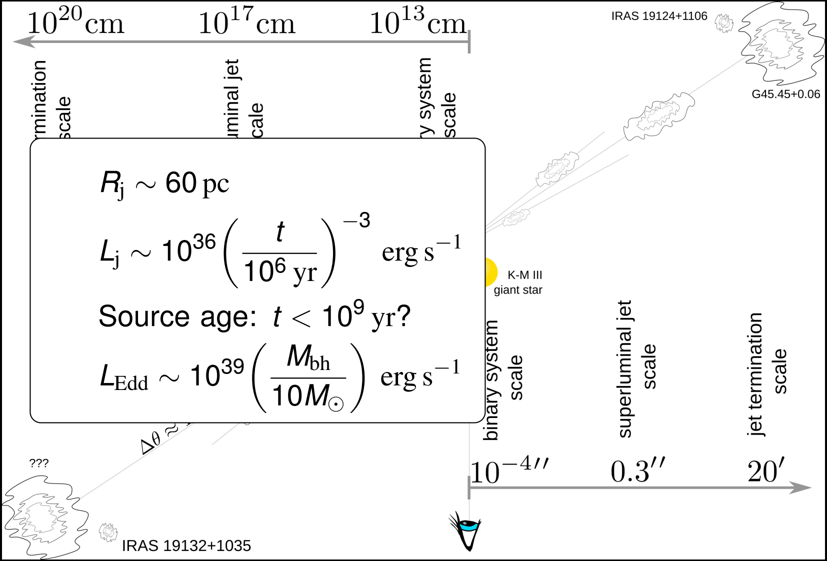
- ☞ $L_\mathrm{j} \sim \left(\frac{R_\mathrm{j}}{R_\mathrm{snr}}\right)^5 \frac{E_\mathrm{snr}\Delta\Omega}{t}$
- ☞ $E_\mathrm{snr} \sim 10^{51}\,\mathrm{erg}$, for $\rho = m_p\,\mathrm{cm}^{-3}$ we obtain $t \sim 3\times 10^5\,\mathrm{yr}$?
- ☞ Thus, for $\Delta\Omega \approx 5\times 10^{-2}$ we obtain

$L_\mathrm{j} \sim 2\times 10^{38}\ \mathrm{erg\,s}^{-1}$

Power of the Jet in GRS1915-105



Power of the Jet in GRS1915-105



$$R_{\rm j} \sim 60\,{\rm pc}$$

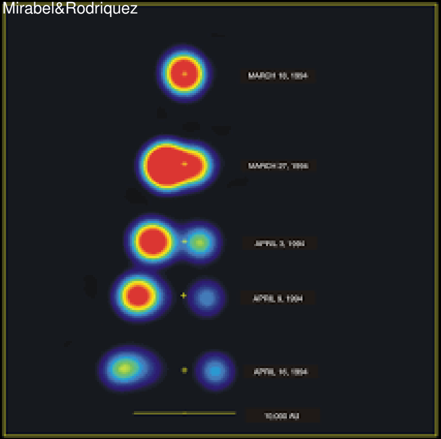
$$L_{\rm j} \sim 10^{36} \left(\frac{t}{10^6\,{\rm yr}} \right)^{-3} {\rm erg\,s^{-1}}$$

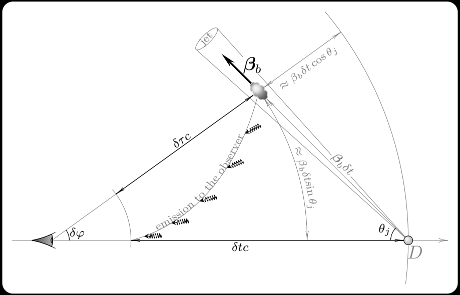
Source age: $t < 10^9\,{\rm yr}$?

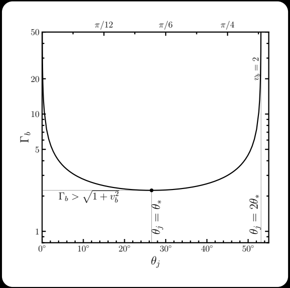
$$L_{\rm Edd} \sim 10^{39} \left(\frac{M_{\rm bh}}{10 M_\odot} \right) {\rm erg\,s^{-1}}$$

Super Luminal Motion in μQ Jets

Mirabel&Rodriquez



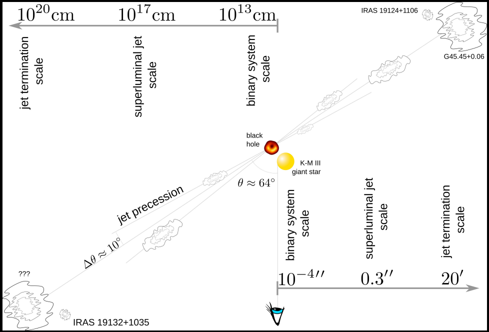




GRS1915-105 is one of the sources where one established superluminal motion in the jet. While the luminosity of the radio blobs is small, the cooling time of electrons is very long, thus the energy contained in the electrons might be very significant.

Power of Jets in GRS1915-105

- ☞ If IRAS 19132+1035 is the jet termination cavity and it can serve as the jet power calorimeter than $L_\mathrm{j} \sim 10^{33}\ \mathrm{erg\,s^{-1}}$ (Tetarenko+2018)
- ☞ The radio blobs require $L_\mathrm{j} > 10^{38}\ \mathrm{erg\,s^{-1}}$ is electron positron (Atoyan&Aharonian 1999)
- ☞ The radio blobs require $L_\mathrm{j} > 10^{40}\ \mathrm{erg\,s^{-1}}$ is electron proton (Atoyan&Aharonian 1999)



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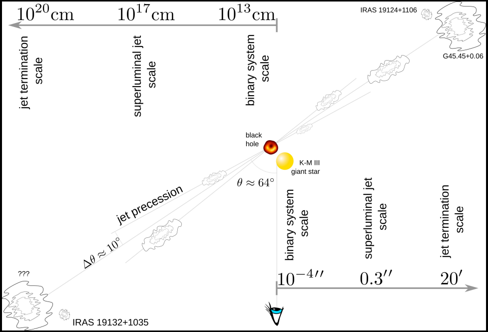


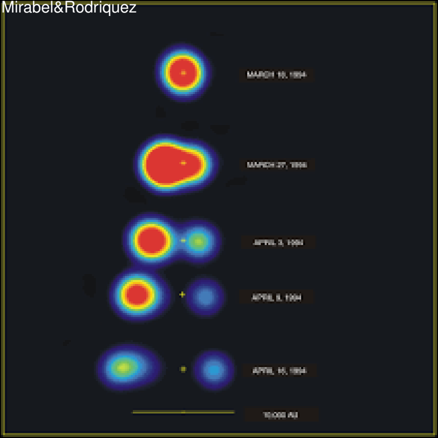
Why did we look at this again?

- Discrepancy between the blob speed and their brightness
- Refine the energy estimate assuming external origin of protons

Blob speed and Doppler boosting

- Apparent speed depends on the jet viewing angle and proper speed
- If there is a symmetric ejection then one can measure the speed of approaching and receding → determine the jet properties
- Doppler boosting is determined by the jet speed, viewing angle, and spectral index → independent check on the parameters obtained from the superluminal motion
- Parameters inferred from the superluminal motion give a wrong prediction for the brightness ratio...

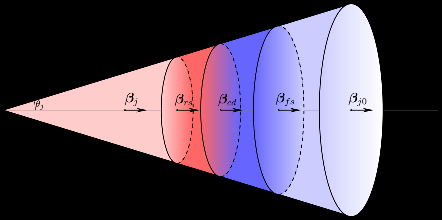
Mirabel&Rodriquez



$$\frac{F_{\rm a}}{F_{\rm r}} = \left(\frac{1 + v_{\rm bl} \cos\theta_{\rm j}}{1 - v_{\rm bl} \cos\theta_{\rm j}} \right)^{3+\alpha}$$

What is the Doppler boosting factor?

- Doppler boosting is determined by relativistic transformation of the emission from the plasma frame to the observer frame
- Hydrodynamic structure of the flow plays the crucial role in determining the boosting factor
- If blobs are produced by internal shocks in the jet, one need to account both for the plasma speed and for the shock speed
- Effectively one needs to account for three speeds: upstream, downstream, shock (defined by the RH conditions)



$$\frac{F_{\rm a}}{F_{\rm r}} = \left(\frac{1+v_{\rm ds}\cos\theta_{\rm j}}{1-v_{\rm ds}\cos\theta_{\rm j}}\right)^{2+\alpha}\left(\frac{1+v_{\rm sh}\cos\theta_{\rm j}}{1-v_{\rm sh}\cos\theta_{\rm j}}\right)$$

using three observational parameters (two speeds and brightness ratio) we can obtain the jet orientation, and down stream/shock speeds

Jet composition and its power

- ☞ Radio emitting source requires relativistic electrons and magnetic field. If we know the size of the source we can determine the minimum energy required for the emission
- ☞ If we know the proper motion, we can convert this estimate into the minimal jet power
- ☞ One should account also for electro neutrality (there must be positron and/or protons)
- ☞ Rest energy of proton might be very significant compared to the energy of radio emitting electrons, thus proton kinetic energy may dominate the jet power
- ☞ If protons are external to the jet then their rest energy does not contribute to the jet power

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$$L = \pi R^2 \left(T_{\mathrm{p}}{}^{0z} + T_{\mathrm{f}}^{0z} \right)$$

$$L_{\mathrm{p}} = \pi R^2 \Gamma_{\mathrm{j}}^2 v_{\mathrm{j}} (\varepsilon_r + \varepsilon_t + p_r + p_t)$$

if we subtract the rest energy we obtain

$$L_{\mathrm{p}} = \pi R^2 \Gamma_{\mathrm{j}}^2 v_{\mathrm{j}} \left(\varepsilon_r + \varepsilon_t + p_r + p_t - \frac{\rho_r + \rho_t}{\Gamma_{\mathrm{j}}} \right)$$

also we can assume that there are both positrons and protons in the jet; that there are also relativist protons (do not produce any detectable emission in the jet). Also we cannot dissipate the entire jet energy at the shock, which increase the constrain on the jet luminosity

What are the energy requirements in this case?

Summary

- ☞ Considering internal shock as sites for radio emission allows one to resolve the discrepancy between the jet speed and brightness ratio of the superluminal blobs in GRS1915-105
- ☞ This allows to determine consistently the jet orientation, upstream and downstream speeds
- ☞ Using the jet properties one can constrain the jet luminosity accounting for a number additional factors, in particular the energy dissipated at the shock
- ☞ In the rest energy of particle is subtracted from the jet luminosity, then the energetic of electron-positron and electron-proton jets are not that different as it was anticipated before
- ☞ Jet luminosity required to produced superluminal radio emitting blobs is about $10^{39}\,\mathrm{erg\,s^{-1}}$
- ☞ Magnetic field is quite strong in the parsec jet, $\sim$G

μQ on different Scales

Basic physical parameters:

- ☞ **Jet power:** $L \sim 10^{39}\,\mathrm{erg\,s^{-1}}$
- ☞ **Jet bulk speed:** $v_{\mathrm{blk}} \approx 0.3c$
- ☞ **Jet opening angle:** $\Delta\Omega \approx 0.3$
- ☞ **Jet magnetization:** $\sigma \approx 0.03$
- ☞ **Stellar luminosity:** $L_\star \sim 10^{38}\,\mathrm{erg\,s^{-1}}$
- ☞ **Stellar temperature:** $T_\star \approx 3 \times 10^4\,\mathrm{K}$
- ☞ **Wind mass-loss rate:** $\dot{M}_\star \sim 10^{-9} M_\odot\,\mathrm{yr^{-1}}$
- ☞ **Wind speed:** $v_\star \sim 10^3\,\mathrm{km\,s^{-1}}$

- ☞ $B = 0.3 R_{15}^{-1}\,\mathrm{G}$
- ☞ $w_B = 4 \times 10^{-3} R_{15}^{-2}\,\mathrm{erg\,cm^{-3}}$
- ☞ $w_\star = 3 \times 10^{-3} R_{15}^{-2}\,\mathrm{erg\,cm^{-3}}$
- ☞ $w_{\mathrm{bgr}} \sim 10^{-11}\,\mathrm{erg\,cm^{-3}}$

- ☞ $n_{wind} = 30 R_{15}^{-2}\,\mathrm{cm^{-3}}$
- ☞ $n_{ism} = 1\,\mathrm{cm^{-3}}$
- ☞ $n_{ph} = 2 \times 10^{10} R_{15}^{-2}\,\mathrm{cm^{-3}}$

Radiation vs Escape

Can particle generate emission?

Cooling time

- Synchrotron

$$t_{\rm syn} = 0.4 E_{\rm PeV}^{-1} B_{\rm G}^{-2}\,{\rm s}$$

- Thomson similar to synchrotron
- Klein-Nishan is gradually less efficient
- Hadronic pp

$$t_{\rm pp} = 10^5 n_{10}\,{\rm s}$$

- Hadronic pγ

$$t_{\rm p\gamma} = 10^7 n_{10}\,{\rm s}$$

Escape time

- Advection (in the jet)

$$t_{\rm adv} = 10^5 R_{15}\,{\rm s}$$

- Diffusion (in the termination region)

$$t_{\rm diff} = 10^9 R_{pc}^2 D_{30}^{-1}\,{\rm s}$$

Meaning

- Electrons are in fast cooling regime
- Escape dominates losses for protons in the jet
- For $R < 10\,{\rm pc}$ pγ dominates
- In the termination region pp becomes efficient