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The Properties of Parsec-Scale Blazar Jets

Submitted to ApJ

Justin Finke
US Naval Research Laboratory, Washington, DC, USA

Basic Idea

Using the Blandford-Konigl jet model and five observables, one can determine a number of properties of blazar jets

Observables:

1. Redshift
2. core flux density
3. extended flux density
4. core shift
5. apparent opening angle

Nuisance parameters:

1. electron distribution parameters (γ_1, γ_2, p)
2. equipartition parameters (ξ_e, ξ_p)

Results (jet parameters):

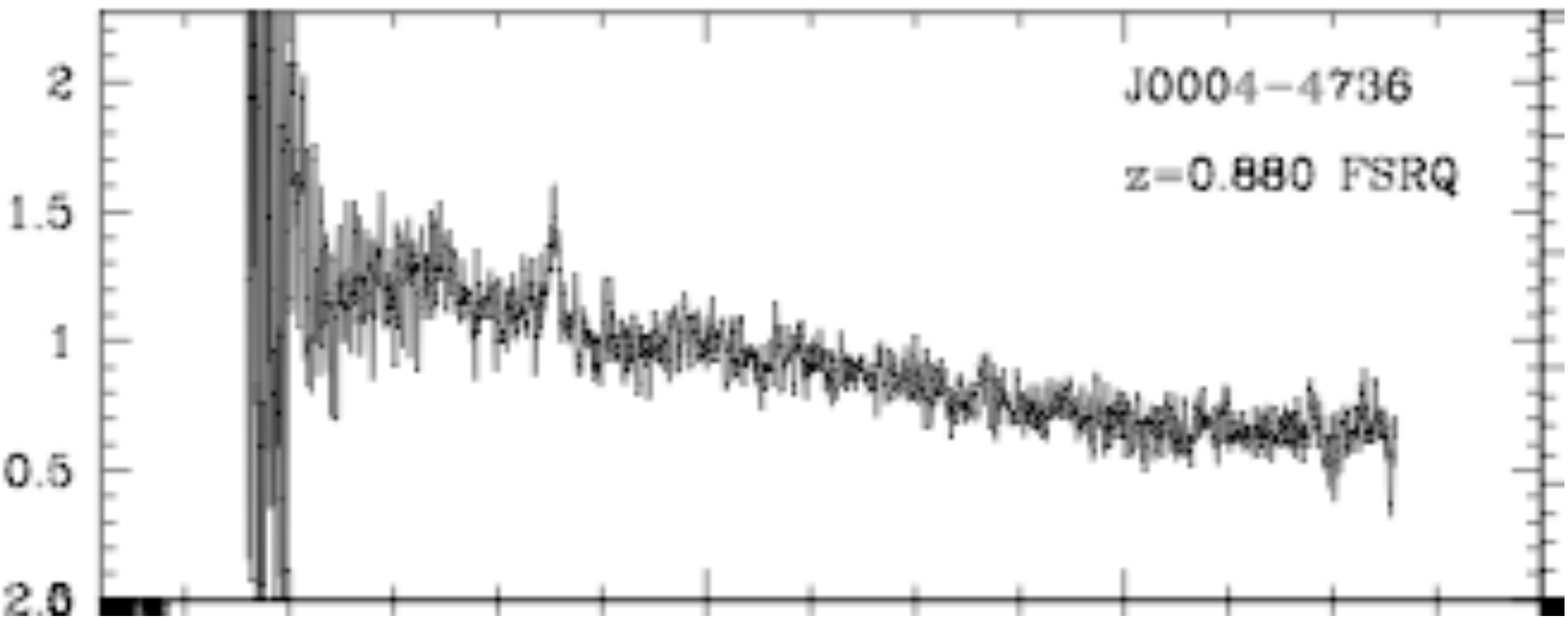
1. Lorentz factor (Γ)
2. angle to line of sight (θ)

Other parameters:

1. Doppler factor (δ)
2. jet opening angle (α)
3. Magnetic field B(1 pc)

Redshift

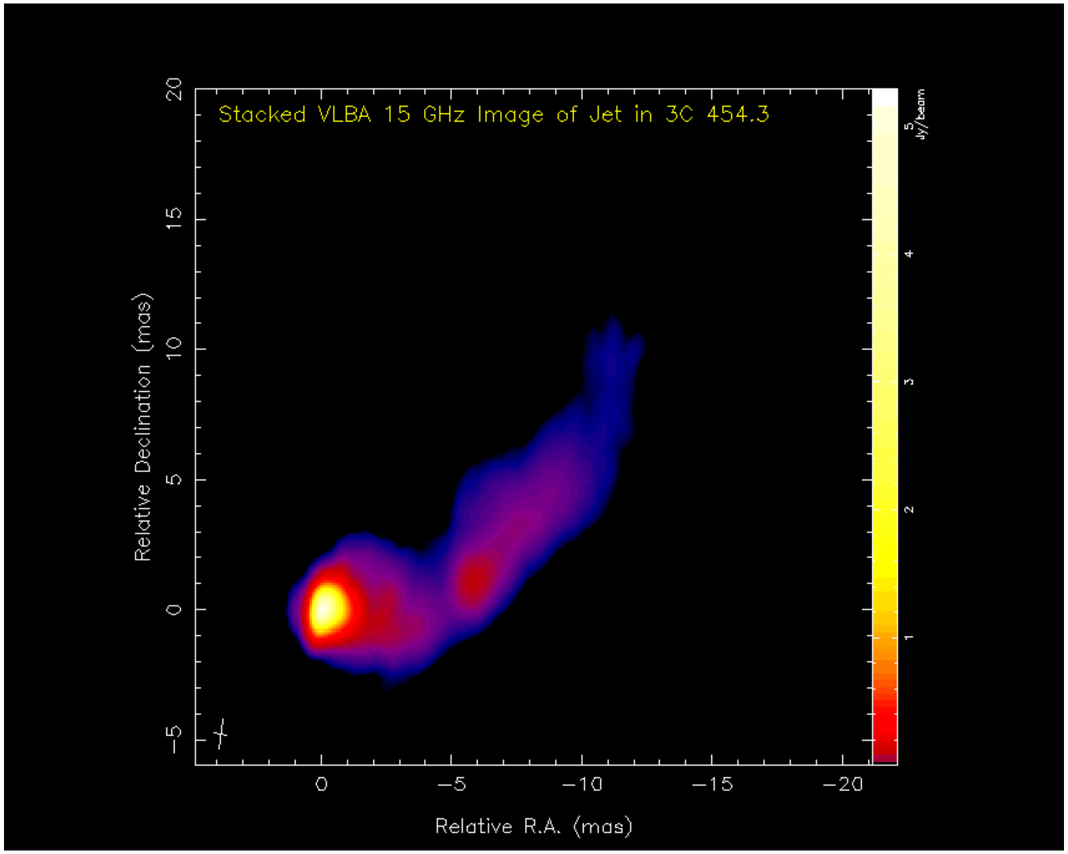
Gives distance to source, determines luminosities from fluxes



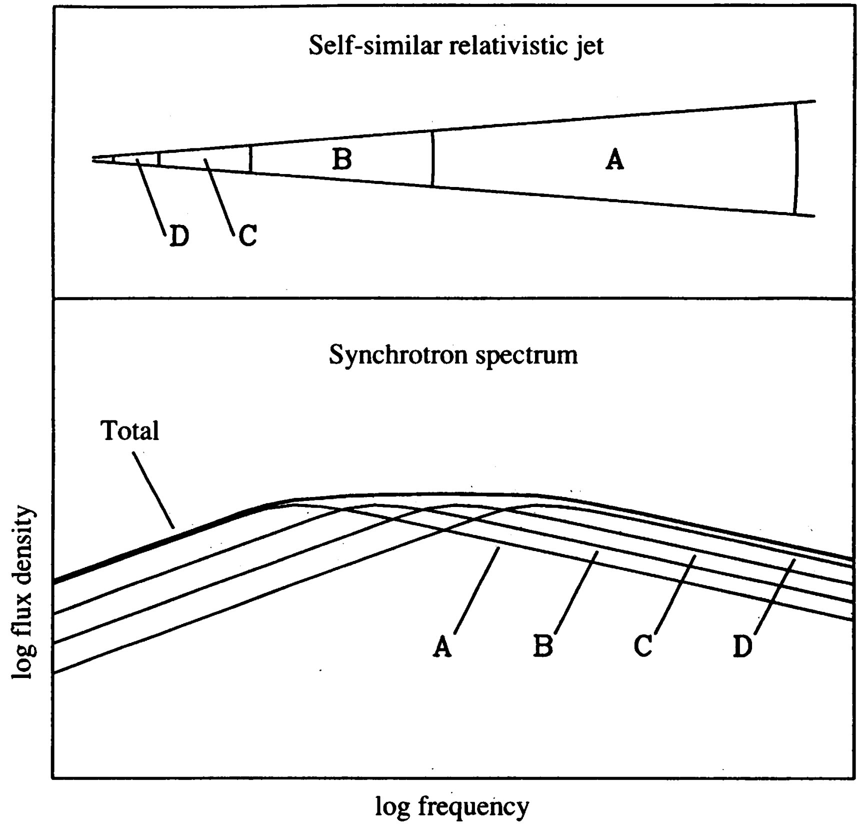
Shaw et al. (2012)

Core Flux Density

Core radio spectra seen in VLBI images are flat. BK model explains this as the superposition of several self-absorbed components. $F_\nu(\Gamma, \theta, \alpha, P_j)$. Also depends on electron distribution $N_e(\gamma) = N_{e0}\, \gamma^{-p}$.



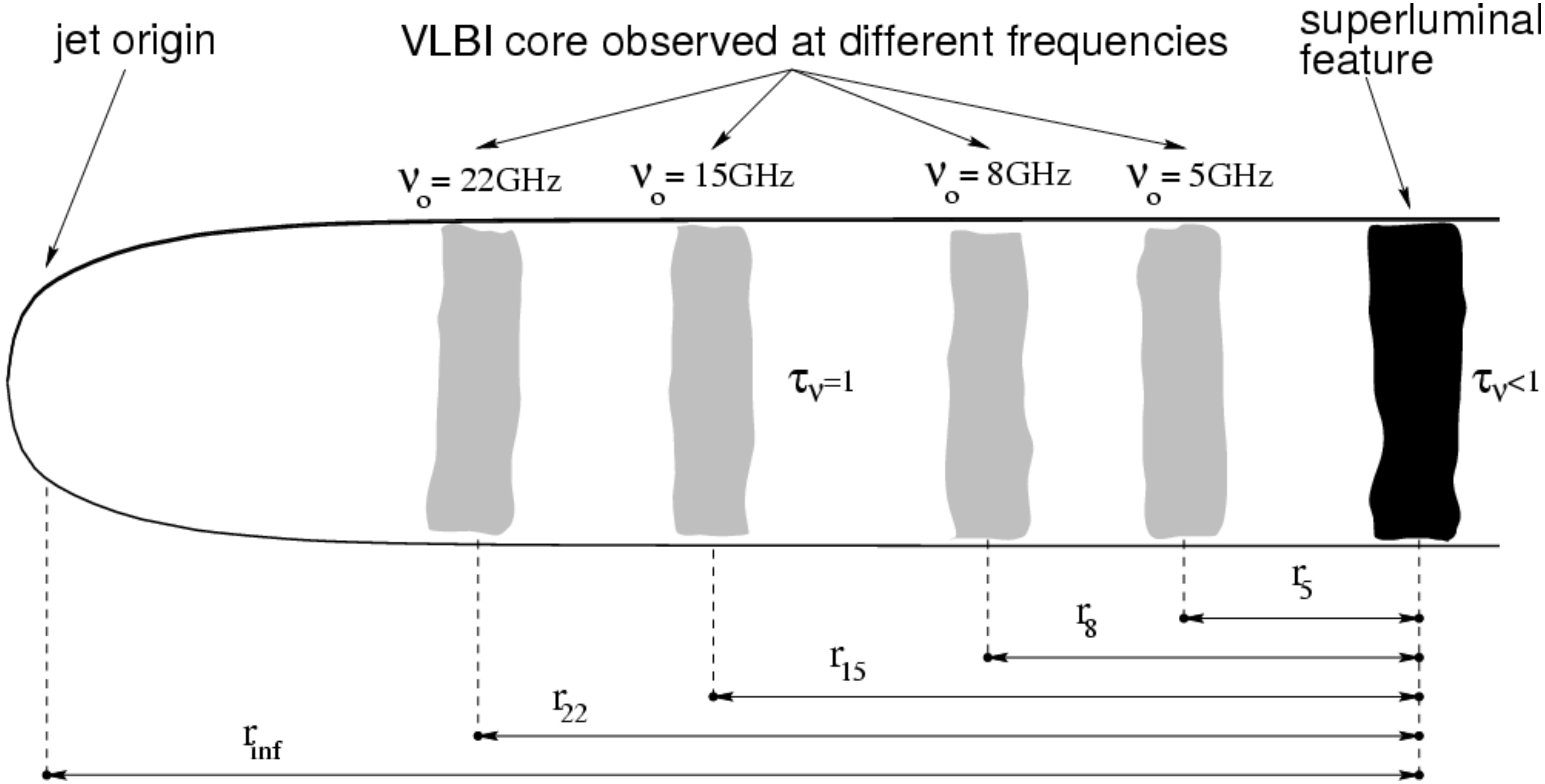
MOJAVE website
http://www.physics.purdue.edu/astro/MOJAVE/



Marscher (1995)

Core Shift

VLBI core position is dependent on frequency. Core's position "shifts" when viewed at different frequencies. $\Delta\varphi(\Gamma, \theta, \alpha, P_j)$. Also depends on electron distribution $N_e(\gamma) = N_{e0}\, \gamma^{-p}$.

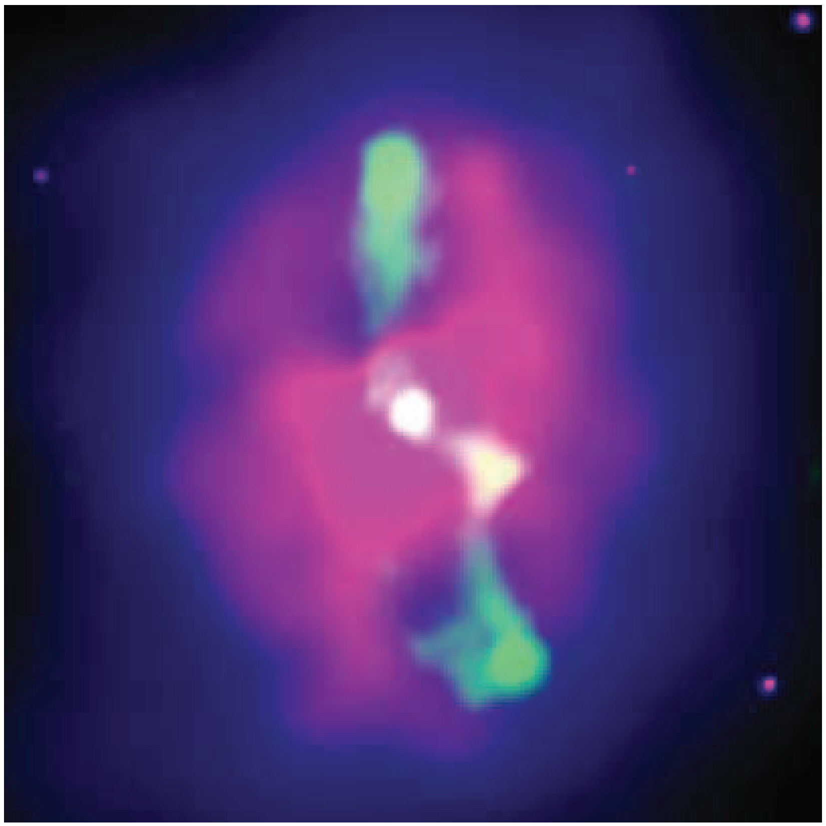


Kovalev et al. (2008)

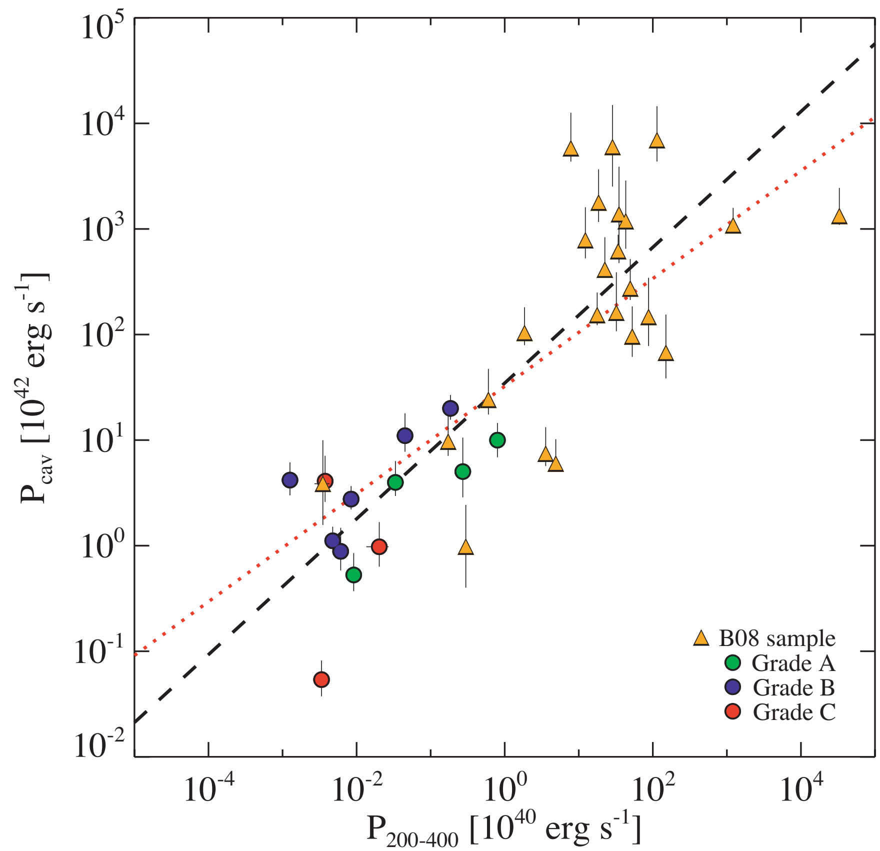
Extended Radio Flux and Jet Power

The Power needed to inflate cavities in hot ICM is well-correlated with extended radio luminosity. So measuring extended radio flux gives jet power.

MS 0735+7421 327 MHz



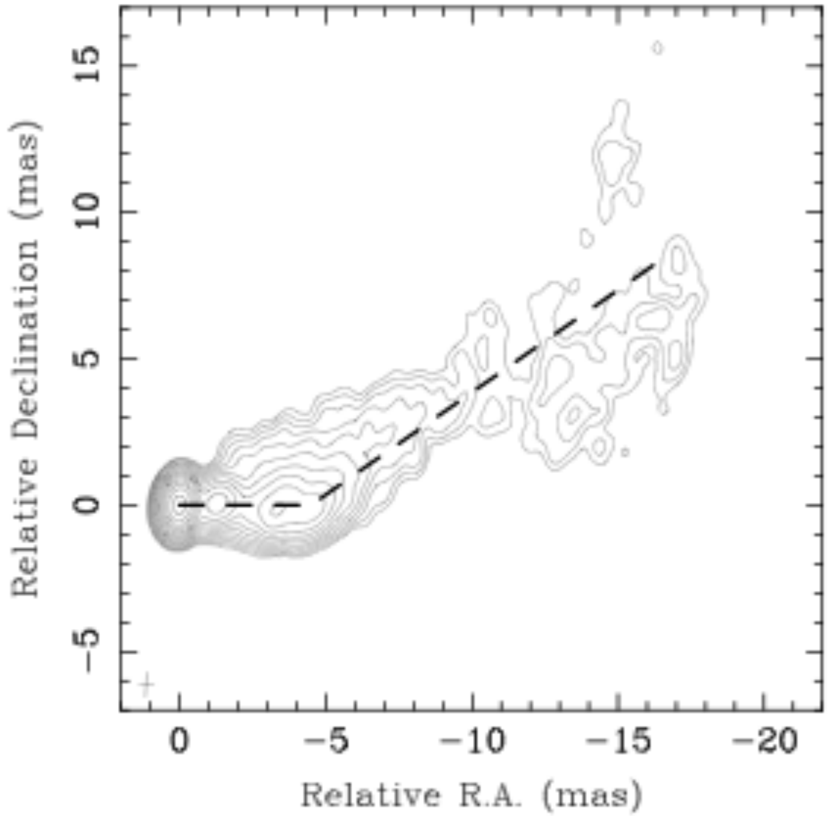
Birzan et al. (2008)



Cavagnolo et al. (2010)

Apparent Jet Opening Angle

Jet opening angle projected on the sky can be measured by analyzing transverse jet profiles from VLBI images. $\alpha = \alpha_{app} \sin\theta$



Pushkarev et al. (2009)

Finding Jet Parameters

Using observables, we can get two equations:

$F_\nu(\Gamma, \theta, \alpha, P_j) \rightarrow F_\nu(\Gamma, \theta, \alpha_{app}, L_{ext})$

$\Delta\varphi(\Gamma, \theta, \alpha, P_j) \rightarrow \Delta\varphi(\Gamma, \theta, \alpha_{app}, L_{ext})$

Two equations, two unknowns, can be solved for Γ and θ.

Once these are known, one can find:

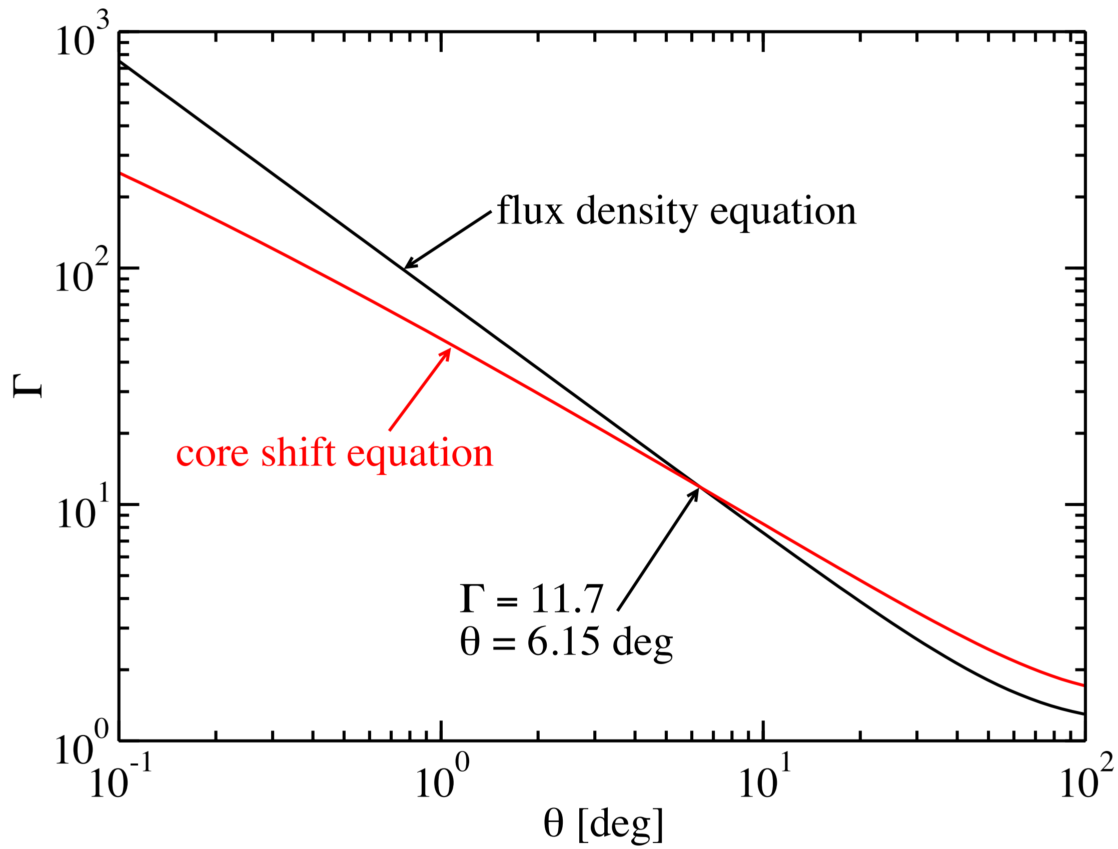
$\delta_D = [\Gamma(1-\beta\cos\theta)]^{-1}$

$\alpha = \alpha_{app} \sin\theta$

$\beta_{app} = (2\delta_D\Gamma - \delta_D^2 - 1)^{1/2}$

$B(1\ \mathrm{pc}) \sim P_j^{1/2}$

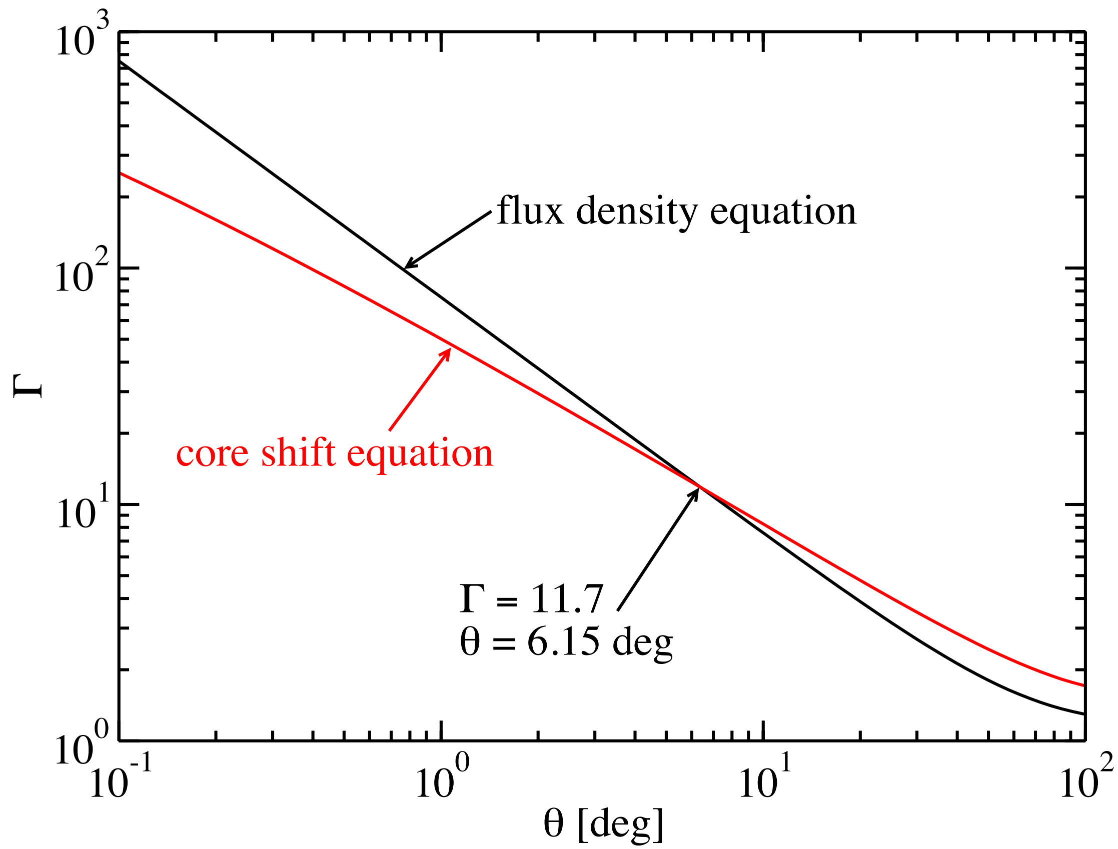
[$B \sim r^{-1}$ in BK model]



Finding Jet Parameters

Nuisance parameters drawn from flat priors:

1. electron distribution parameters
   1. log(γ_1): between 0 and 4.
   2. log(γ_2): between 3 and 7.
   3. p: between 1 and 5.
2. equipartition parameters
   1. log(ξ_e) = log(u_e/u_B): between -1 and 1.
   2. log(ξ_p) = log(u_p/u_B): between -4 and 1.



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Data

Observables taken from literature:

1. core flux density → MOJAVE website (e.g. Lister et al. 2009)
2. extended flux density → Meyer et al. (2011)
3. core shift → Pushkarev et al. (2012)
4. apparent opening angle → Pushkarev et al. (2009).

64 sources: 11 BL Lacs, 52 FSRQs, 1 NLSy1

TABLE 1
BLAZAR RADIO MEASUREMENTS

Source	Alias	Type[a]	z	$\log_{10}\left[\frac{L_{\rm ext}}{\rm erg\ s^{-1}}\right]$	F_ν(core) [Jy]	$2\alpha_{\rm app}$ [°]	$\Delta\phi$ [mas]
0133+476	DA 55	Q	0.859	41.93	1.781	21.7	0.099
0202+149	4C +15.05	Q	0.405	41.39	0.921	16.4	0.113
0212+735	S5 0212+73	Q	2.367	42.30	3.281	16.4	0.143
0215+015	OD 026	Q	1.715	43.52	1.170	36.7	0.111
0234+285	4C 28.07	Q	1.207	43.21	2.944	19.8	0.239
0333+321	NRAO 140	Q	1.259	42.98	1.343	8.0	0.276
0336−019	4C 28.07	Q	0.852	42.36	2.311	26.8	0.105

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Results

TABLE 2
Blazar Jet Parameter Results

Source	Alias	Γ	θ [°]	α [°]	B(1 pc) [G]	δ_D	$\beta_{\rm app}$
0133+476	DA 55	$7.5^{+36.6}_{-5.8}$	$3.6^{+12.6}_{-2.9}$	$0.7^{+2.4}_{-0.6}$	$0.7^{+3.1}_{-0.4}$	$8.2^{+25.7}_{-6.0}$	$4.6^{+28.5}_{-4.2}$
0202+149	4C +15.05	$5.4^{+20.2}_{-3.7}$	$9.1^{+23.2}_{-7.2}$	$1.3^{+3.1}_{-1.0}$	$0.4^{+0.9}_{-0.2}$	$4.2^{+10.6}_{-2.7}$	$3.8^{+14.5}_{-3.1}$
0212+735	S5 0212+73	$8.9^{+34.3}_{-6.8}$	$1.5^{+4.2}_{-1.2}$	$0.2^{+0.6}_{-0.2}$	$2.5^{+15.7}_{-1.9}$	$12.7^{+28.7}_{-9.3}$	$3.8^{+30.6}_{-3.7}$
0215+015	OD 026	$5.8^{+22.1}_{-4.1}$	$9.3^{+24.4}_{-7.5}$	$3.0^{+7.3}_{-2.4}$	$0.7^{+1.8}_{-0.4}$	$4.0^{+10.7}_{-2.6}$	$4.0^{+14.9}_{-3.2}$
0234+285	4C 28.07	$4.0^{+8.9}_{-2.5}$	$14.0^{+23.2}_{-10.2}$	$2.4^{+3.7}_{-1.7}$	$1.2^{+2.9}_{-0.7}$	$2.9^{+4.6}_{-1.6}$	$2.8^{+6.3}_{-2.2}$
0333+321	NRAO 140	$5.4^{+12.1}_{-3.4}$	$14.6^{+24.6}_{-9.7}$	$1.0^{+1.5}_{-0.7}$	$1.7^{+2.5}_{-0.9}$	$2.7^{+4.6}_{-1.5}$	$3.9^{+7.1}_{-2.7}$
0336−019	4C 28.07	$7.7^{+35.1}_{-5.9}$	$4.3^{+13.7}_{-3.5}$	$1.0^{+3.2}_{-0.8}$	$0.6^{+2.4}_{-0.4}$	$7.6^{+22.8}_{-5.5}$	$5.1^{+27.2}_{-4.5}$

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Results for all 64 sources.

Errors are quite large. Dominated by errors on core shift and unknown electron spectral index.

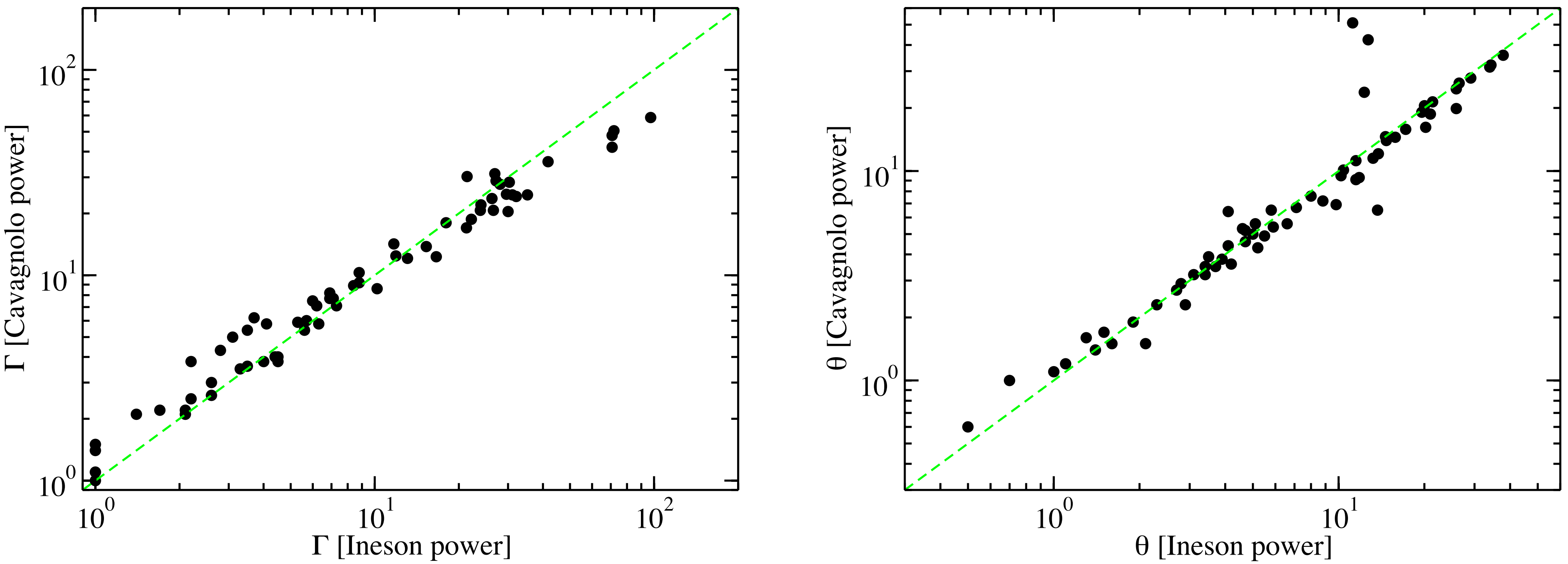
Results

TABLE 2
Blazar Jet Parameter Results

Source	Alias	Γ	θ [°]	α [°]	B(1 pc) [G]	δ_D	β_{app}
0133+476	DA 55	$7.5^{+36.6}_{-5.8}$	$3.6^{+12.6}_{-2.9}$	$0.7^{+2.4}_{-0.6}$	$0.7^{+3.1}_{-0.4}$	$8.2^{+25.7}_{-6.0}$	$4.6^{+28.5}_{-4.2}$
0202+149	4C +15.05	$5.4^{+20.2}_{-3.7}$	$9.1^{+23.2}_{-7.2}$	$1.3^{+3.1}_{-1.0}$	$0.4^{+0.9}_{-0.2}$	$4.2^{+10.6}_{-2.7}$	$3.8^{+14.5}_{-3.1}$
0212+735	S5 0212+73	$8.9^{+34.3}_{-6.8}$	$1.5^{+4.2}_{-1.2}$	$0.2^{+0.6}_{-0.2}$	$2.5^{+15.7}_{-1.9}$	$12.7^{+28.7}_{-9.3}$	$3.8^{+30.6}_{-3.7}$
0215+015	OD 026	$5.8^{+22.1}_{-4.1}$	$9.3^{+24.4}_{-7.5}$	$3.0^{+7.3}_{-2.4}$	$0.7^{+1.8}_{-0.4}$	$4.0^{+10.7}_{-2.6}$	$4.0^{+14.9}_{-3.2}$
0234+285	4C 28.07	$4.0^{+8.9}_{-2.5}$	$14.0^{+23.2}_{-10.2}$	$2.4^{+3.7}_{-1.7}$	$1.2^{+2.9}_{-0.7}$	$2.9^{+4.6}_{-1.6}$	$2.8^{+6.3}_{-2.2}$
0333+321	NRAO 140	$5.4^{+12.1}_{-3.4}$	$14.6^{+24.6}_{-9.7}$	$1.0^{+1.5}_{-0.7}$	$1.7^{+2.5}_{-0.9}$	$2.7^{+4.6}_{-1.5}$	$3.9^{+7.1}_{-2.7}$
0336−019	4C 28.07	$7.7^{+35.1}_{-5.9}$	$4.3^{+13.7}_{-3.5}$	$1.0^{+3.2}_{-0.8}$	$0.6^{+2.4}_{-0.4}$	$7.6^{+22.8}_{-5.5}$	$5.1^{+27.2}_{-4.5}$
1101+384	Mrk 421	$1.4^{+2.7}_{-0.4}$	$51.0^{+26.5}_{-41.1}$	$6.7^{+1.9}_{-5.2}$	$0.1^{+0.9}_{-0.1}$	$1.1^{+0.4}_{-0.6}$	$0.8^{+0.8}_{-0.7}$
1652+398	Mrk 501	$1.5^{+2.1}_{-0.5}$	$42.4^{+30.1}_{-38.2}$	$6.3^{+2.8}_{-5.6}$	$0.1^{+1.3}_{-0.1}$	$1.1^{+0.7}_{-0.5}$	$0.8^{+1.0}_{-0.8}$

For Mrk 421, Mrk 501 and other TeV blazars, Γ, δ_D and β_{app} are low, consistent with observations of jet components.

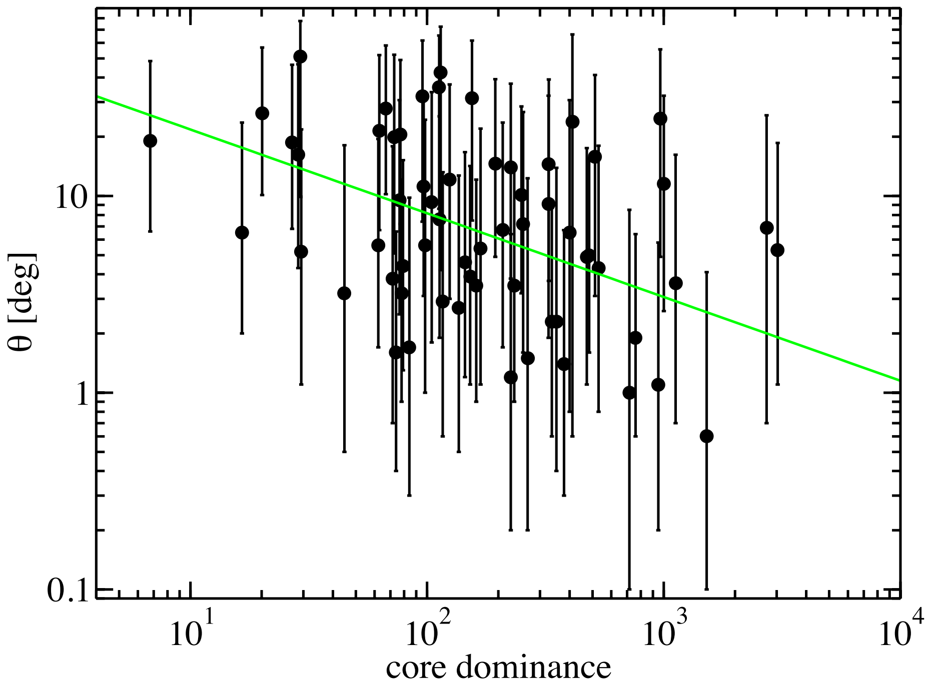
Expressions for Jet Power

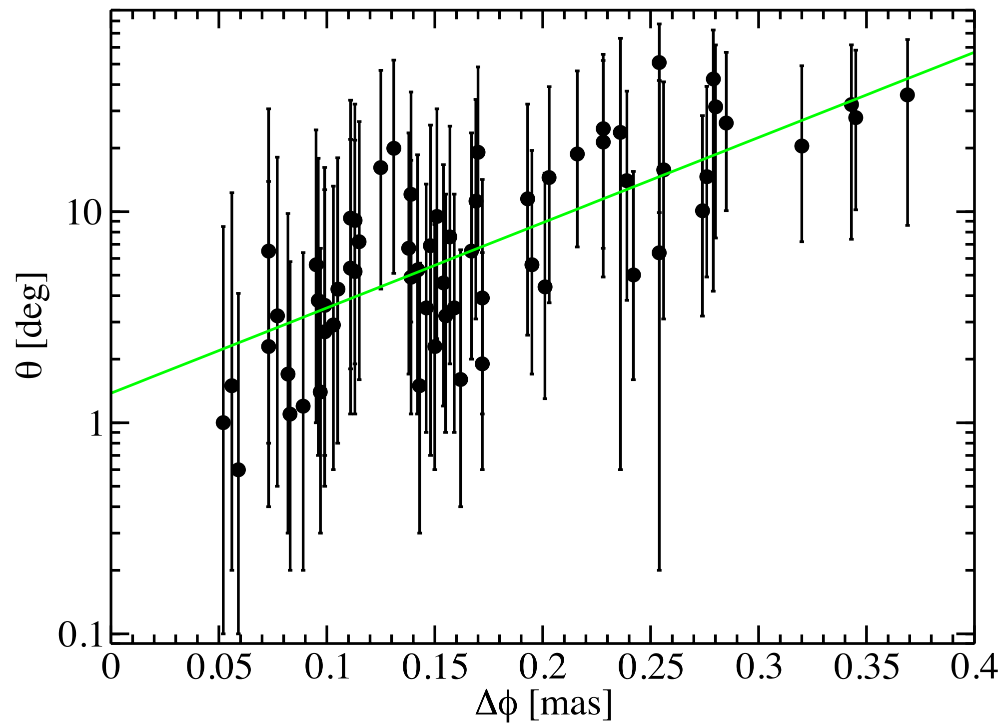


Relation between jet power and extended radio luminosity is controversial (e.g., Godfrey & Shabala 2016). Different expressions for jet power don't have strong effect on results.

Cavagnolo et al. (2010) versus Ineson et al. (2017).

Proxies for jet angle





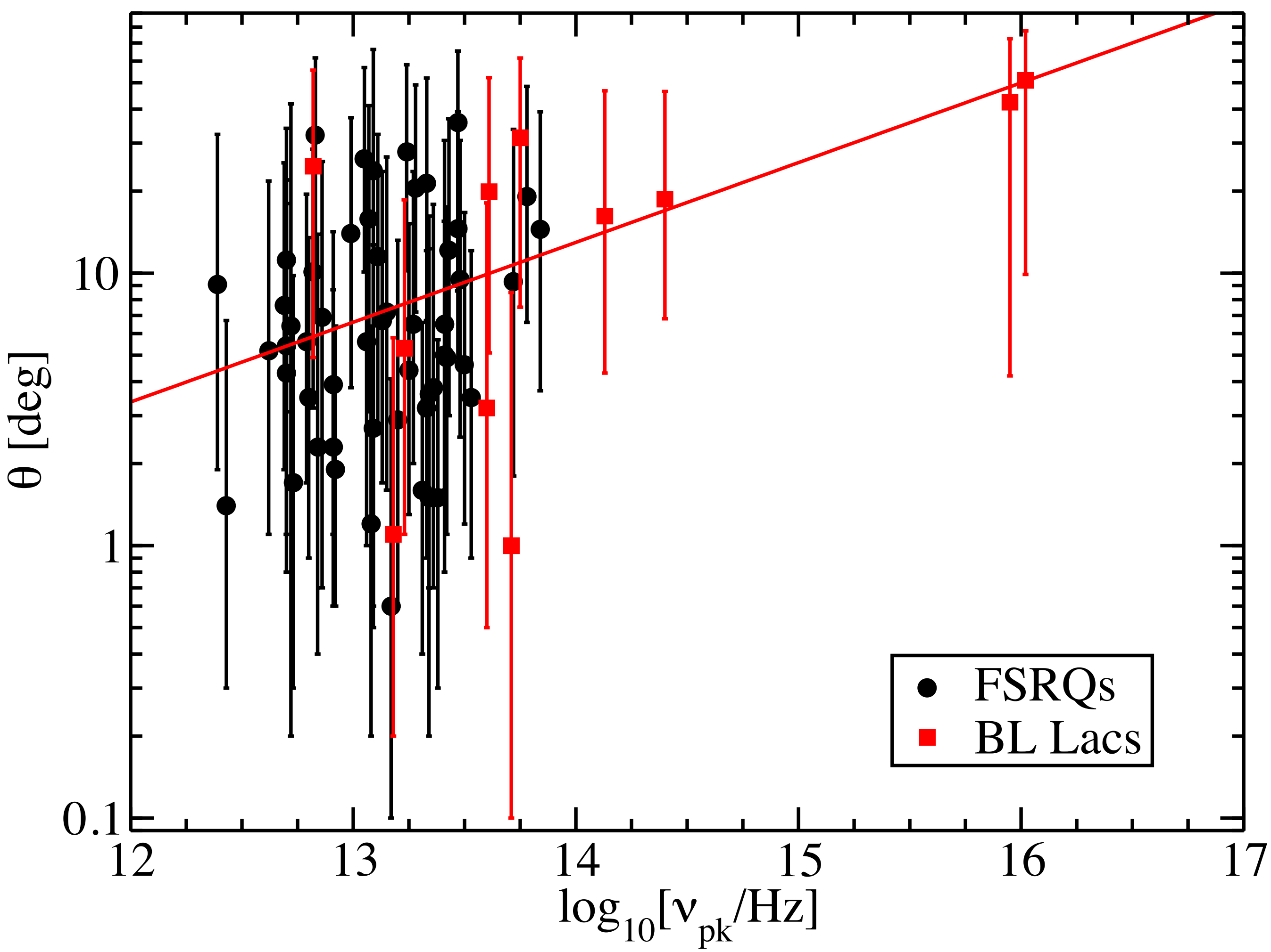
Core dominance: ratio of core to extended radio flux.

Not significantly correlated with observing angle ($< 4\sigma$).

Core Shift

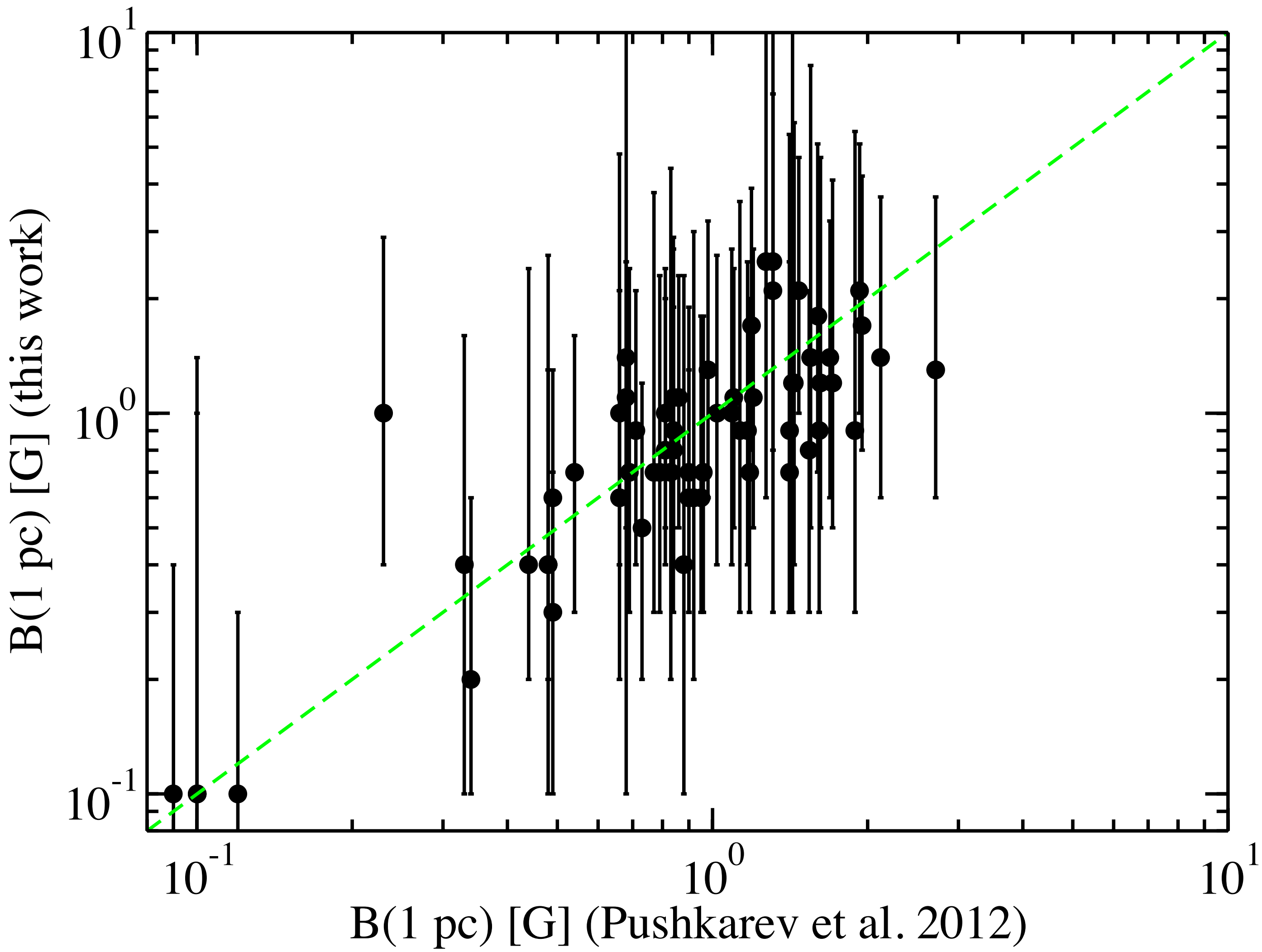
Significantly correlated with observing angle. ($>5\sigma$)

θ and ν_{pk}



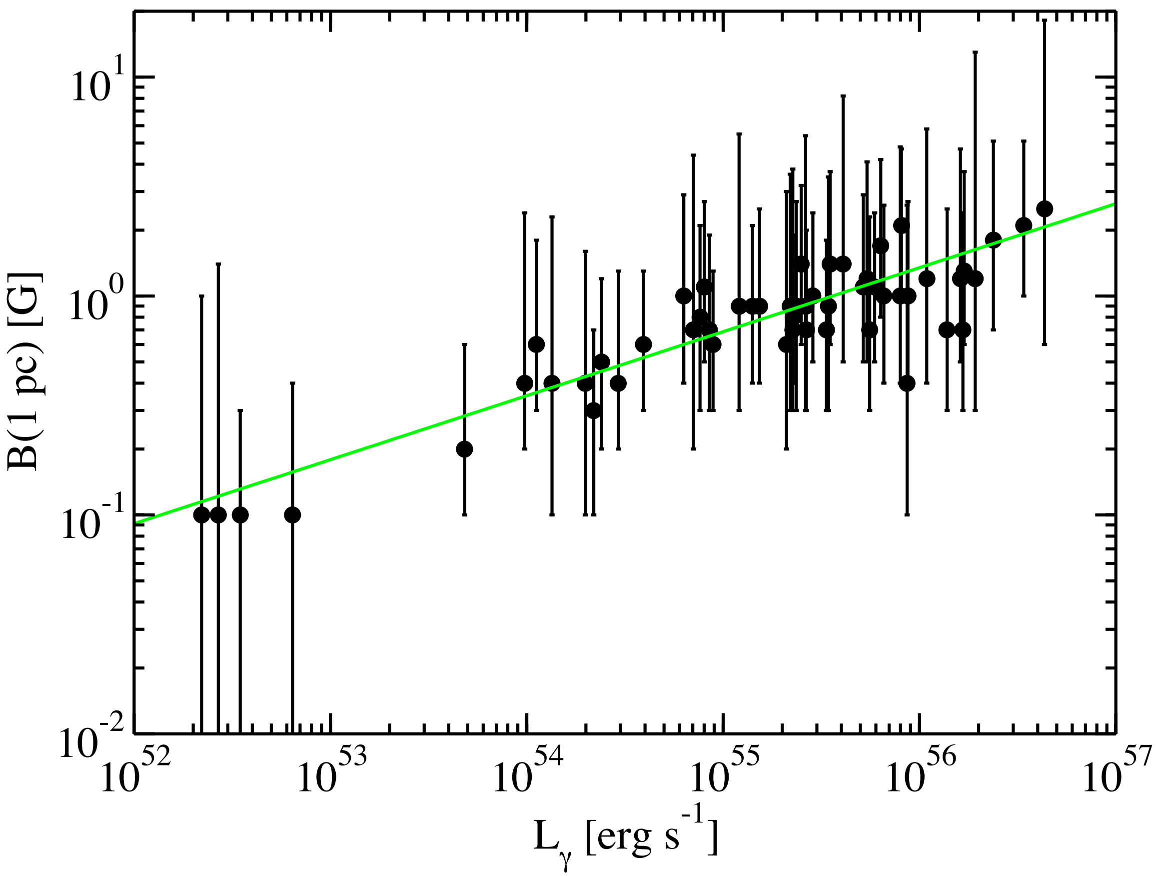
Some expectation that θ and ν_{pk} are correlated for BL Lacs (Meyer et al. 2011). Did not find significant evidence for this (but large errors and few sources).

Magnetic Field



My magnetic field values are consistent with values found by Pushkarev et al. (2012) using a different method.

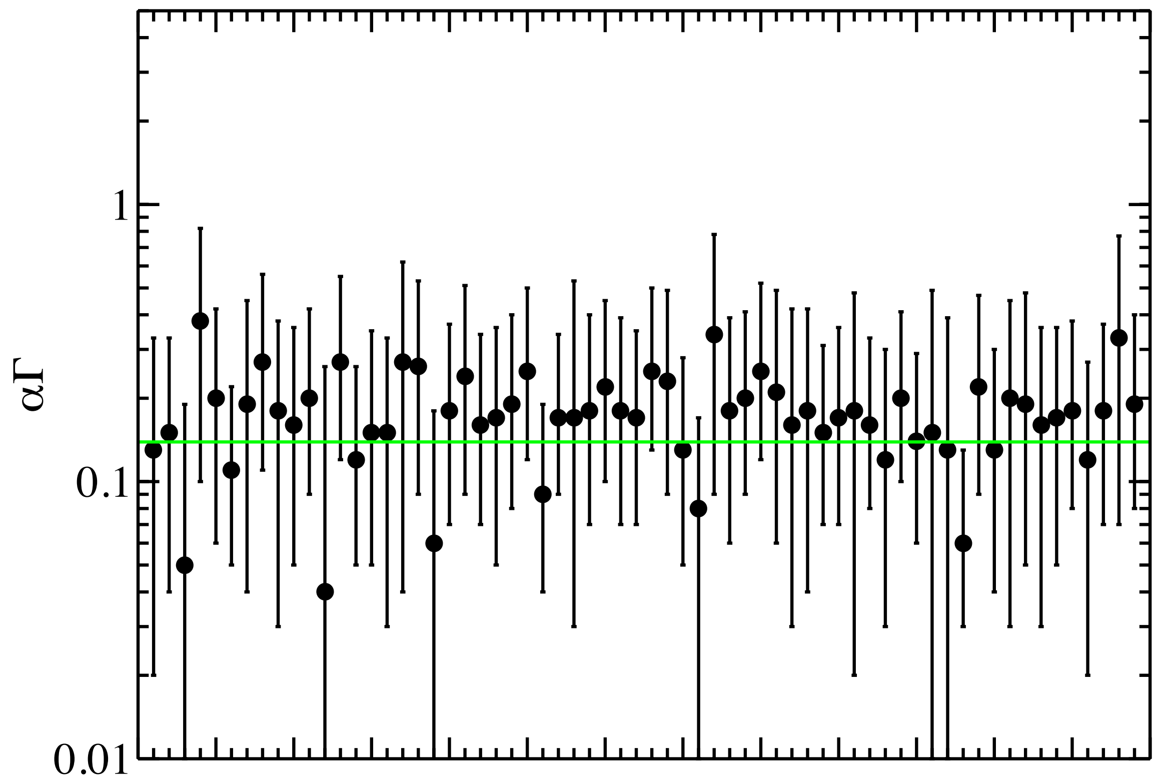
γ-ray luminosity



Of all the parameters I determine, magnetic field is best-correlated with γ-ray luminosity (> 5σ).

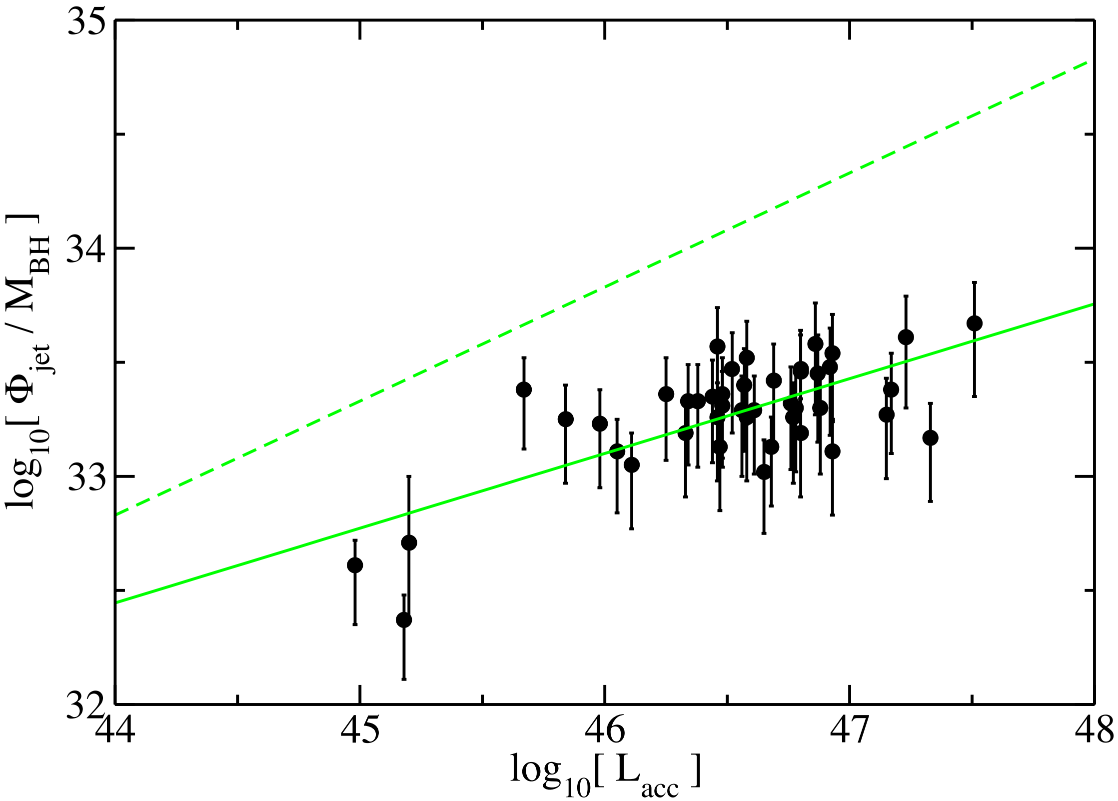
But is this a selection effect?
$P_j \sim \alpha\Gamma B^2$

Γ and α



My results are consistent with a constant αΓ, i.e., α ~ 1/Γ. Similar results found by others (e.g., Jorstad et al. 2005, 2017; Clausen-Brown et al. 2013; Pushkarev et al. 2009, 2017) .

Jets from Magnetically-Arrested Disks



Following Zamaninasab et al. (2014)
Parsec-scale magnetic flux can be computed from:

$$\Phi_{\rm jet} = 1.2 \times 10^{34}\ \Gamma\alpha \left[\frac{M_{\rm BH}}{10^9\ M_\odot}\right] \left[\frac{B(1\ {\rm pc})}{1\ {\rm G}}\right]\ {\rm G\ cm^2}$$

Expectation from jets launched from MADs:

$$\log_{10}\left[\Phi_{\rm jet}/M_{\rm BH}\right] = 0.5 \log_{10} L_{\rm acc} + 34.4$$

This is ***not*** consistent with my results. May be due expression above assuming a~1 and η=0.4 for all sources.

Summary

- I describe a method to determine parameters of parsec-scale blazar jets from observable quantities.
- I compute properties for 64 sources.
- Errors are large. Errors dominated by error in core shift measurement and uncertainty in electron spectral index (p). Variability is another issue.
- Properties are consistent with previous results. Results are consistent with slow β_{app} for many TeV BL Lacs.
- Find little evidence for MAD-launched jets, or scenario of Meyer et al. (2011) (θ and ν_{pk} correlation for BL Lacs).
- A promising method for studying jets, especially if ways can be found to reduce errors!