

## Parsec-scale VLBI observations of TeV gamma-ray sources

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- EGRET sources
- Mkn 421
- Mkn 501
- 1ES 1959+650
- H1426+428

## EGRET sources

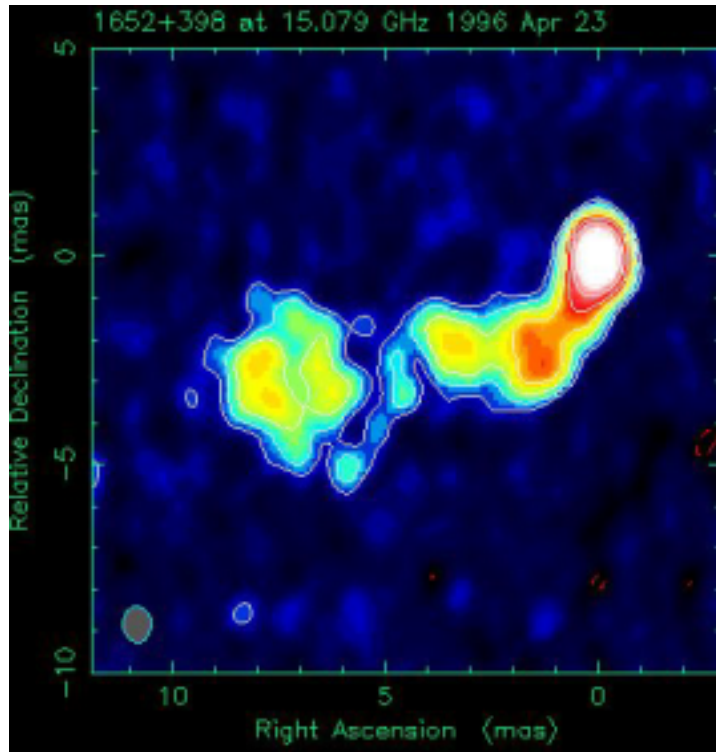
The apparent superluminal motions in gamma-ray sources are much faster than for the general population of bright compact radio sources.

(Jorstad et al. 2001, ApJS 134, 181)

Times of high gamma-ray flux coincide with ejections of superluminal components from the core in EGRET blazars [in a significant number of cases].

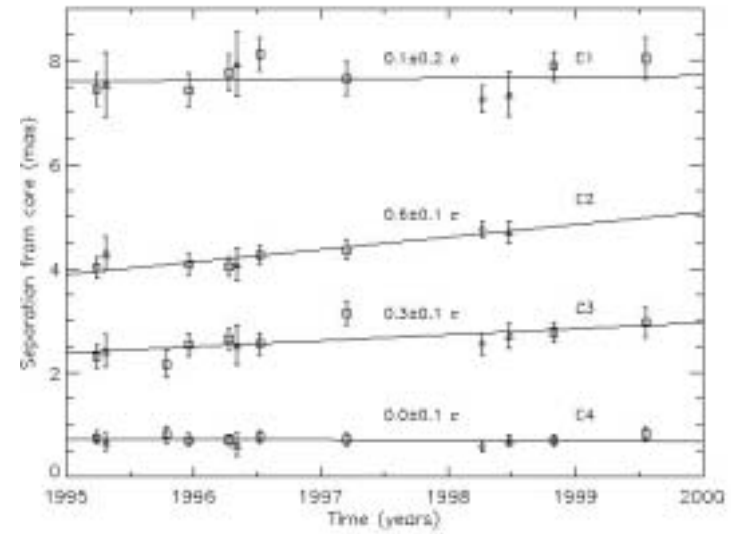
(Jorstad et al. 2001, ApJ 556, 738)

### Parsec-scale structure of Mkn 501



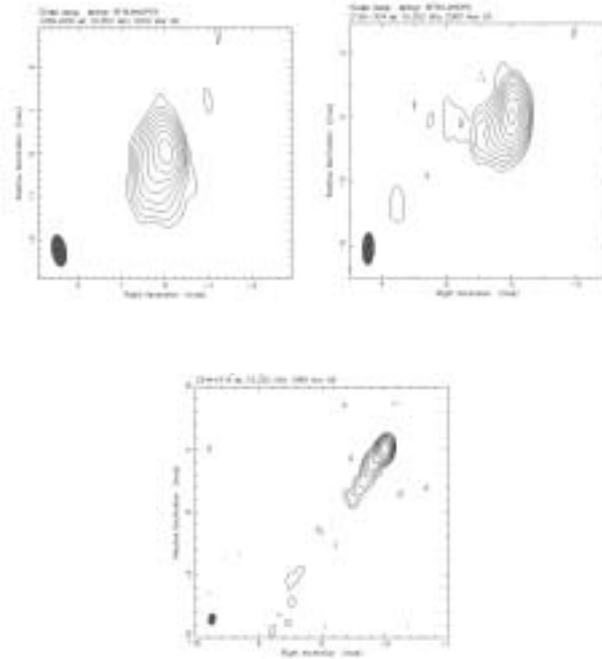
Edwards & Piner 2002

### Component speeds in Mkn 501



Edwards & Piner 2002

## Other TeV sources/candidates



Single epoch 15 GHz images. (see Piner et al. 2002)

## Summary of observed speeds

### Apparent Component Speeds (Piner et al. 2002)

Source	Component <sup>a</sup>	$\beta_{app}$ <sup>b</sup> ( <i>c</i> )
Mrk 421	C4	$0.2 \pm 0.3$
	C5	$0.3 \pm 0.1$
	C6	$-0.1 \pm 0.1$
Mrk 501	C1	$0.1 \pm 0.2$
	C2	$0.8 \pm 0.1 \rightarrow 0.6 \pm 0.1$
	C3	$0.3 \pm 0.1$
	C4	$0.0 \pm 0.1$
1ES 1959+650	C1	$0.1 \pm 1.1$
	C2	$-0.2 \pm 0.8$
PKS 2155-304	C1	$4.6 \pm 3.8$
1ES 2344+514	C1	$1.3 \pm 0.8$
	C2	$0.5 \pm 0.8$
	C3	$-0.2 \pm 0.8$

*a*: Components are numbered C1, C2, ... from the outer-most component inward.

*b*: for  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

Apparent speed for C2 of Mrk 501 revised by Edwards & Piner 2002

## Why are the jets sub-luminal?

Doppler factors ( $\delta = [\gamma(1 - \beta\cos\phi)]^{-1}$ ) of  $\sim 10$  or more are inferred from TeV variability.

### A Small Angle to the Line-of-Sight?

Subluminal motion arises because the VLBI jet is aligned within  $1^\circ$  of the line-of-sight.

### A Changing Doppler Factor?

Change in  $\delta$  between the  $\sim 10^{-4}$  pc TeV emitting region and  $\sim 1$  pc VLBI region.

Bends in jets are observed on the parsec scale, but are not sufficient to reduce  $\delta$  without reduction in bulk Lorentz factor also.

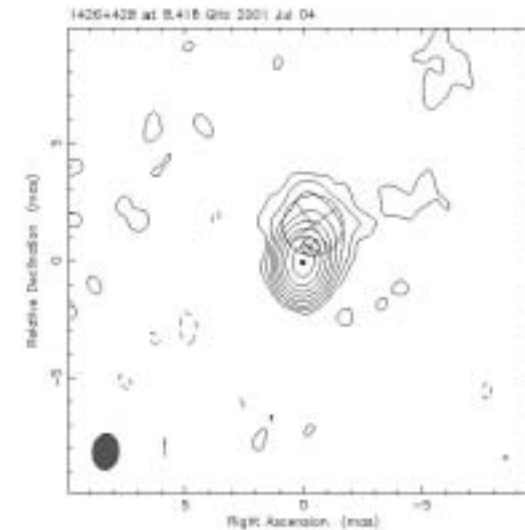
In an electron-positron dominated jet, high energy electrons lose energy very efficiently to synchrotron radiation and I.C. scattering, and so most of the energy and momentum can be lost close to the base of the jet (Marscher 1999).

### Unequal “Pattern” and Bulk Flow Speeds?

Vermeulen & Cohen (1994) show that ratios of pattern to bulk Lorentz factors ranging from  $\sim 0.5$  to  $\sim 5$  can fit the observed  $\beta_{app}$  distribution of core-selected quasars.

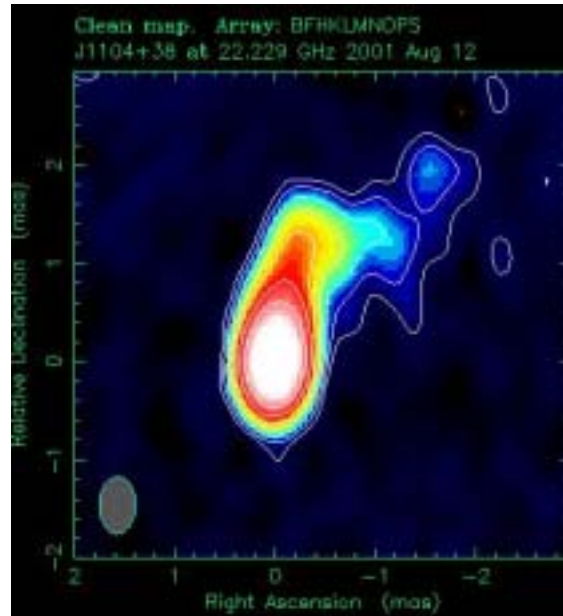
Stationary components are an example of this.

## First epoch observation of H1426+428



Compare with 1991 observation of Kollgaard et al. (1996)!

TeV high states and new VLBI components?



First of four epochs of Mkn 421 at 22 GHz

Shameless promotion



<http://www.astronomy2003.com>

## Conclusions

The apparent speeds of parsec-scale jet components for TeV gamma-ray sources are subluminal.

The distribution of speeds differs significantly from that for EGRET sources.

Small angle to line-of-sight?  
Changing Doppler factor?  
Unequal pattern and bulk speeds?

Also, unlike EGRET sources, there appears to be no emergence of new components associated with TeV high states.

Studies of H1426+428, and Mkn 421 after the 2001 TeV high state, are continuing.

Please find some more extra-galactic TeV gamma-ray sources!

## More details

1. "VSOP and Ground-based VLBI Imaging of the TeV Blazar Markarian 421 at Multiple Epochs,"  
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3. "The Parsec-Scale Structure of TeV Blazars",  
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4. "The parsec-scale jets of extra-galactic TeV gamma-ray sources",  
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5. "The Sub-Luminal Parsec-scale Jet of Mkn 501"  
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*Astrophysical Journal Letters*, in press (2002).