Blazars (Theoretical Aspects)

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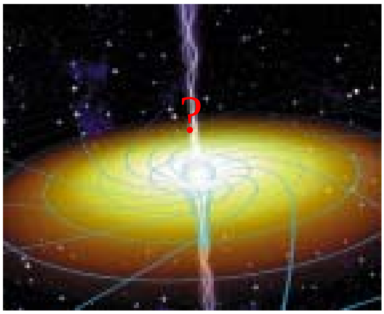
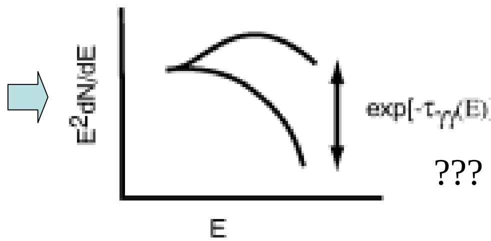
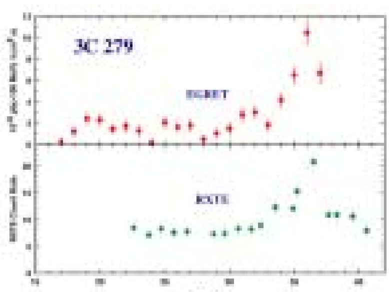
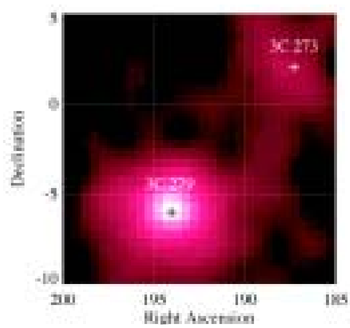
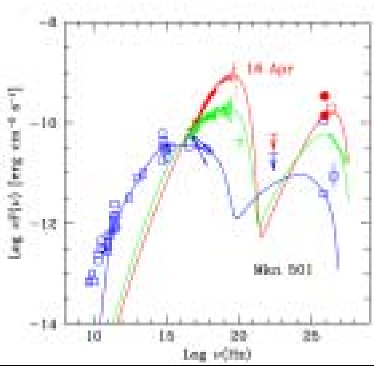
[Gamma-Ray Blazars: What?
How?
Can I Actually Learn Anything from Data?
SSC Modeling of TeV Blazars]

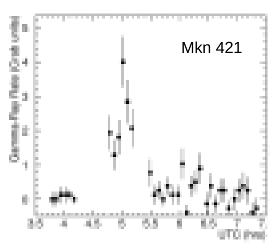


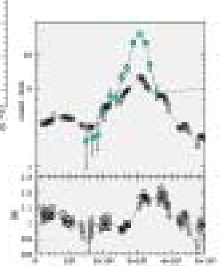


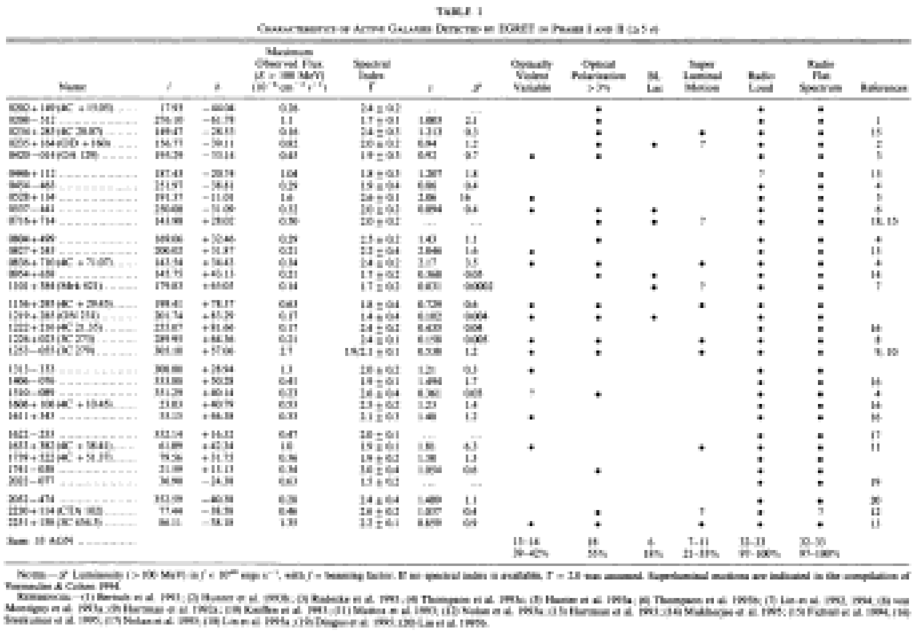












Cvm 1995

Main Observational Facts and Implications

Large Luminosity ⇨ -- efficient power source, e.g., accretion onto black hole?
black hole spin?

L_gamma>L_Edd?
Compactness Problem!
⇨ Relativistic Bulk Motion

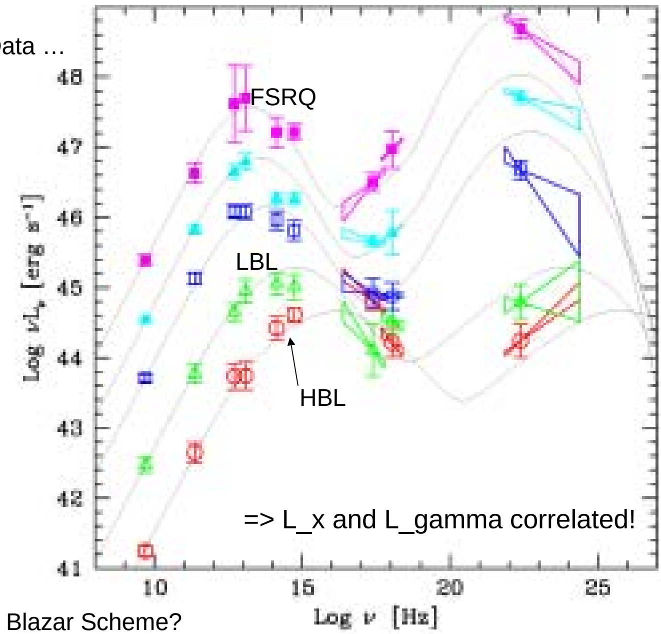
Rapid Variability ⇨ -- small source
-- source close to black hole?
-- rapid particle acceleration/creation and cooling/escape
↳ ~~hadronic~~ models, unless push source parameters

Double Peaked SED +
Good X-Ray/Gamma-Ray Correlation ⇨ -- same emission region for X-rays/gamma-rays?
-- same particle population responsible for emission at both energies (Occam's razor)?
↳ two peaks = (e+/e-) synchrotron + I.C.?
-- ***close analogy with galactic SNR!***
(similar GeV to TeV peaked sequence,
similar modeling issues and "discussions")

Optical/Radio ID = FSRQ, blazar ⇨ -- emission from relativistic **jet**
(like GRB: Doppler boosting, internal vs.
external shocks, etc.)

Many EGRET blazars show broad emission lines
⇨ strong ambient radiation field; messy systems; zone of avoidance

Add EGRET
Gamma-Ray Data …

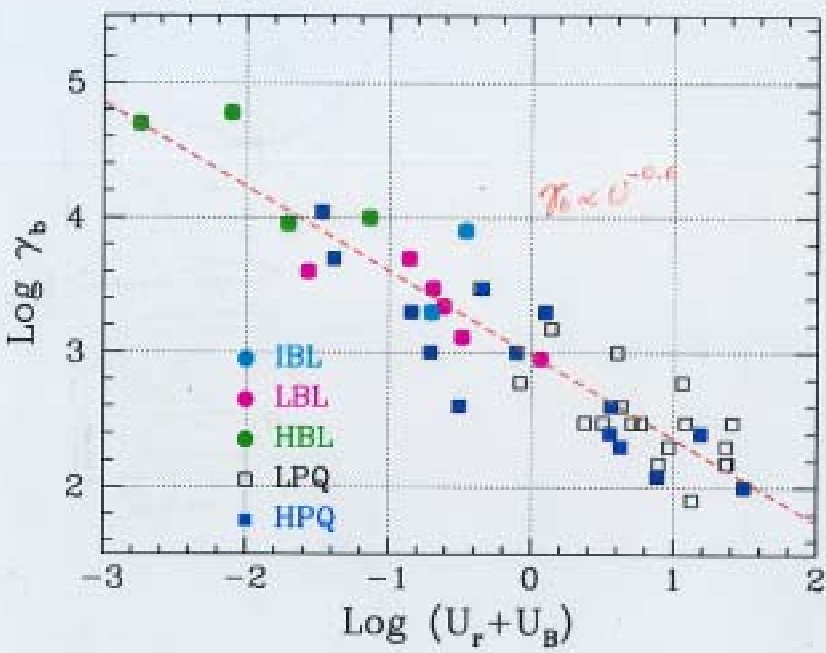


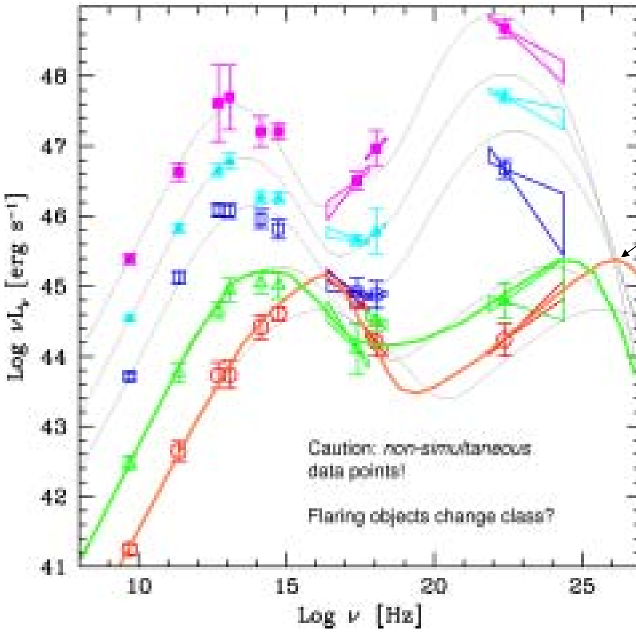
Grand Unified Blazar Scheme?

(synchrotron & Compton from SAME e+/e-?; $\gamma_{peak} \propto Lum^{-1}$?)

Donati et al. 2001
(cf. Fossati el. 1998)

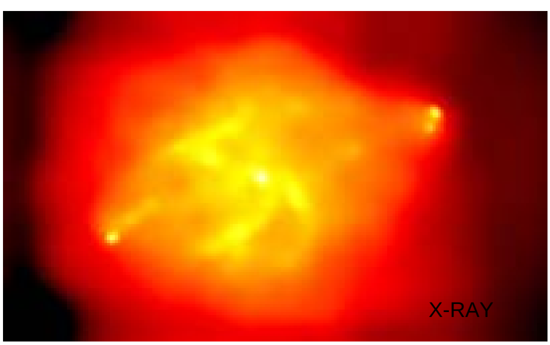
(Ghisellini et al. 1997)



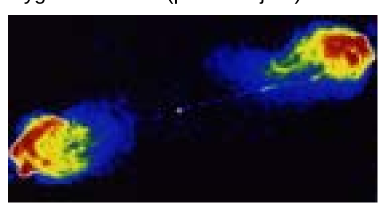


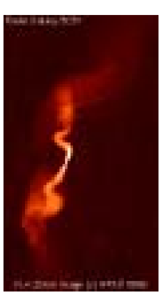
Don't forget absorption by infrared/optical background!

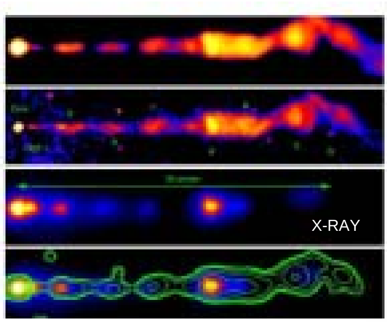
Extended X-Ray Emission from Jets!!



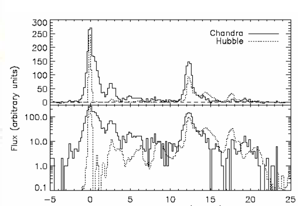
Cygnus A - FRII (powerful jet?)

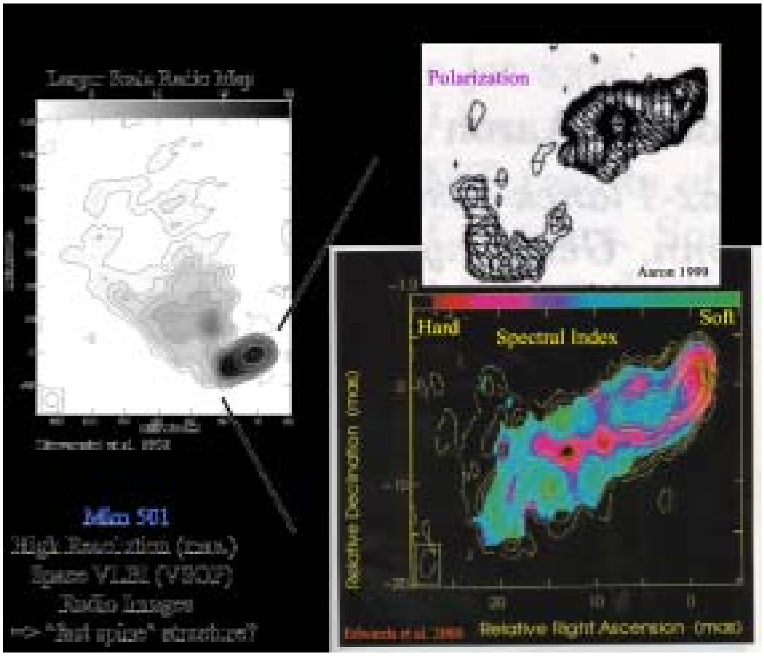






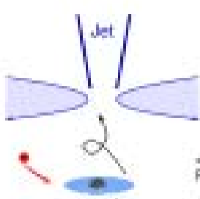
M87 – FRI (weak jet)





Jet Origin

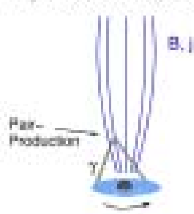
1.) Mass Accretion onto Black Hole



=> Extraction of up to 42.6% of Rest Mass Energy of Infalling Material

=> Accretion Disk => Jet Matter

2.) Extraction of Rotational Energy of Black Hole



=> Extraction of up to 29% of Rest Mass Energy of Black Hole

=> Electron/Positron Jet

=> Different Jet Matter
Different AGN Life Time

Theoretical Considerations [Complications]

Several excellent reviews already – e.g., see Sikora (astro-ph)

Global Energetics

$L_{rad} \lesssim L_{kinetic}$ at radio lobe (at least for FR II sources)

$\Rightarrow$ something dramatic happens to jet, but jet is not disrupted/stopped

$\Rightarrow$ ~~Compton drag/bulk Comptonization~~ of initially highly relativistic ($\Gamma \gg 1$) jet

Process(es) directly responsible for observed X-ray/γ-ray emission?

- Compton scattering ($e\gamma \rightarrow e\gamma$)
- synchrotron radiation ($eB \rightarrow eB\gamma$) — lowest order, most "efficient"
- Bremsstrahlung ($ee \rightarrow ee\gamma, pe \rightarrow pe\gamma$)
- π^0 decay ($\pi^0 \rightarrow \gamma\gamma$) — almost always accompanied by $\pi^{\pm} \rightarrow ...e^{\pm}$
- proton synchrotron ($pB \rightarrow pB\gamma$)

⇓

This theoreticians prejudice: $e^{\pm}$ probably involved (i.e., synchrotron/Compton)

Theoretical Considerations [Complications] II.

O.K. Where do we get required GeV/TeV electrons/pairs?

- Acceleration (bottom-up)

  Direct acceleration by $\vec{E}$ (e.g., pulsar)

  Stochastic shock/wave acceleration (e.g. 1^{st} / 2^{nd} order Fermi process)

  — "leptonic" models

- Creation at desired energies (top-down)

usually involves cascade (e.g., P.I.C.) with ultrarelativistic protons + photons

$$\left\{ \begin{array}{l} p\gamma \rightarrow pe^+e^- \\ (p/n)\gamma \rightarrow (n/p)\pi^{\pm} \rightarrow ..e^{\pm},\nu \\ \gamma\gamma \rightarrow e^+e^- \\ \gamma e \rightarrow ee^+e^- \end{array} \right.$$

or $pp \rightarrow pp\pi$ — "hadronic" models

don't need to be ultrarelativistic, e.g., SNR

but need large target matter densities

Neutrinos: "smoking gun" for hadronic models

Big advantage of hadronic models: protons easier to accelerate to very high energies
Big disadvantage … : protons harder to extract energy from

Theoretical Considerations [Complications] III.

If electrons/pairs are primary particles, what is acceleration energy spectrum?

$$\frac{dN}{dE} \propto E^{-\alpha}\,?$$

$E_{\max}$?

$E_{\min} / E_{peak}$?

(or just $t_{\rm cool}$ vs. $t_{\rm escape/expansion}$)

If they are instead secondary particles, similar considerations for primary protons ….
(relativistic e/p behave in same way for given energy)

Good questions!!

Relativistic shock theory $\Rightarrow \alpha \approx 2$, but $\exists$ range (1.7-2.4), depends on details like pitch angle diffusion ... (messy).

$E_{\max} = f(B, R_{shock}, t_{cool})$

e.g., if particle too energetic, $r_g > R_{shock}$ and particle escapes

often before get to this, though,

$t_{accel} \sim r_g / c \sim t_{cool} \propto E^2 B^2$ (synch. radn.)

(Bohm limit, $r_g = eB/mc$)

Maybe α reaches asymptotic value during strong flare, but would not be surprising to see $E_{\max}$ vary as source region varies....

Theoretical Considerations [Complications] IV.

Is the observed high energy cutoff in some objects intrinsic or simply due to photon-photon pair production (inside source or intergalactic)?

Depends on ambient radiation field, but for 3C279

γ-sphere: $r_{\rm emission} \lesssim 100\,R_g$ ($\approx 10^{15}$ cm), $\tau_{\gamma\gamma} > 1$ for E $\gtrsim$ 10 MeV

$r_{\rm emission} \lesssim 10^{17}$ cm (BLR), $\tau_{\gamma\gamma} > 1$ for E $\gtrsim$ 50 GeV

$r_{\rm emission} \lesssim$ parsecs (dust torus), $\tau_{\gamma\gamma} > 1$ for E $\gtrsim$ 1 TeV

[N.B. Estimates don't apply to Mrk 421/501 -- BL Lacs appear to have weak central radiation fields. Accretion disk underluminous for black hole mass]

What is the origin of the spectral breaks seen in X-rays/gamma-rays?

Superposition of different emission components? (next slide)
Transition from efficient to "inefficient" cooling (particles escape before cooling)?
(in SSC model, break/position position varies with source luminosity)
Large effective value of E_min from acceleration process?
(in SSC model, break not vary with luminosity unless acceleration mechanism changes)

Theoretical Considerations [Complications] V.

Assume simplest scenario:
e- directly accelerated, no protons, no photon-photon pair production.

⇒UV/X-ray = synchrotron
⇒GeV/TeV = Compton

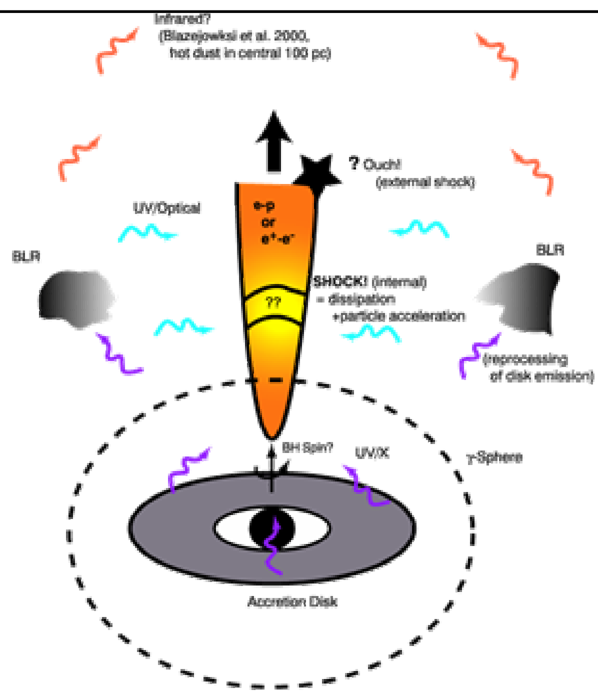
What are seed photons for Compton upscattering??

- Synchrotron Photons (SSC)
- Accretion Disk Photons (ERC)
- BLR Photons (reprocessed accretion disk photons) ..
- IR photons from hot dust in central region ..
- [Microwave background, probably not relevant, but always there] ..

All possible => **different** gamma-ray spectra for **same** e- distribution!

∴ Lots of uncertainty for generic blazar!!

If you think you can *a priori* predict a gamma-ray spectrum, I have a deal for you…

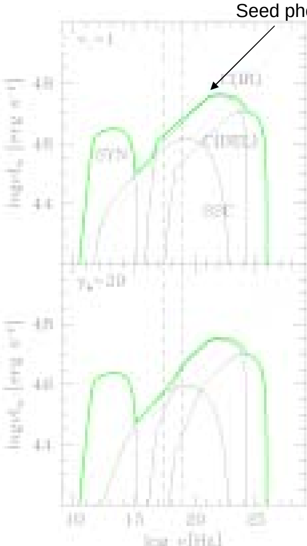


The central engine of a generic gamma-ray blazar is a MESSY place!

Which photon field(s) does jet interact with???

Boettcher et al. 2001

Seed photons: IR from dust



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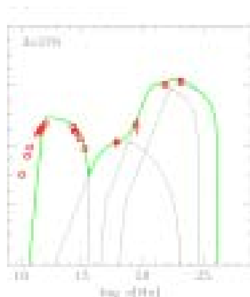
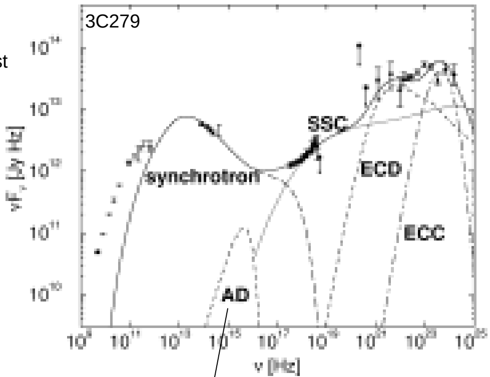
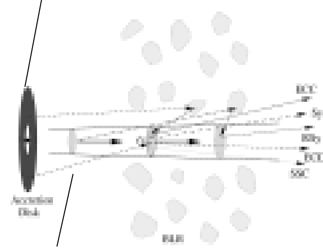


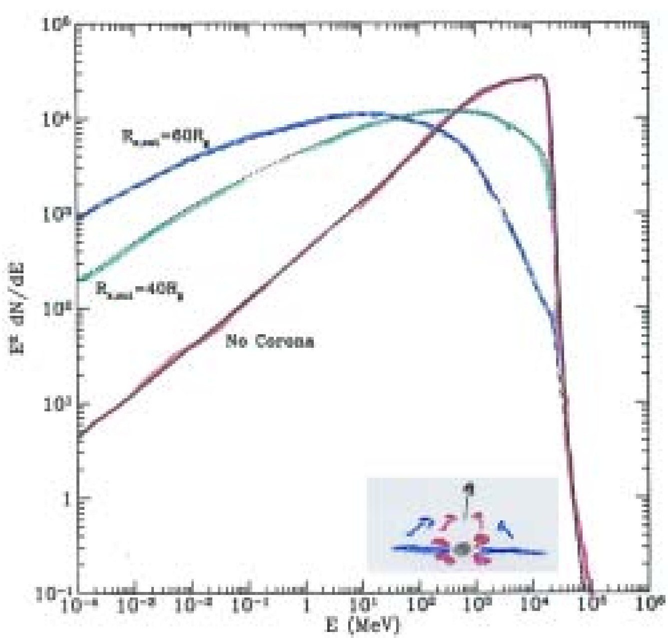




Blazejowski et al. 2000

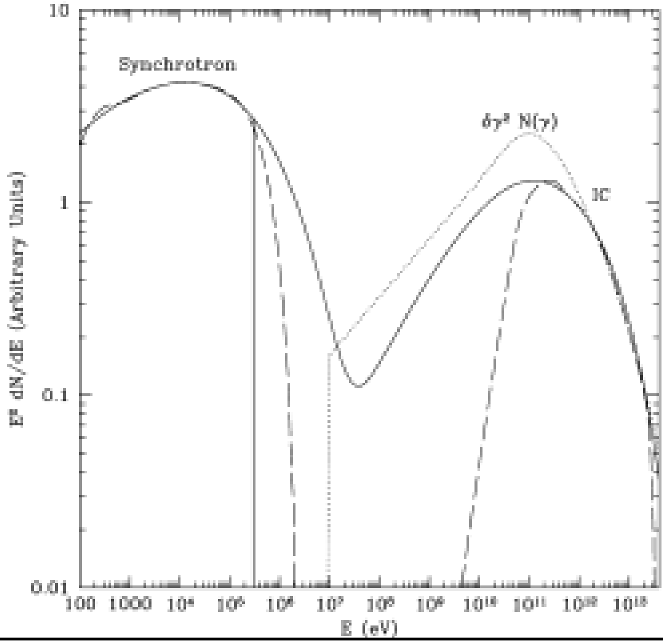
Beamed from behind, reduced efficiency?

Proton-Initiated Cascade in Accretion Disk + X-Ray Corona Radiation Field

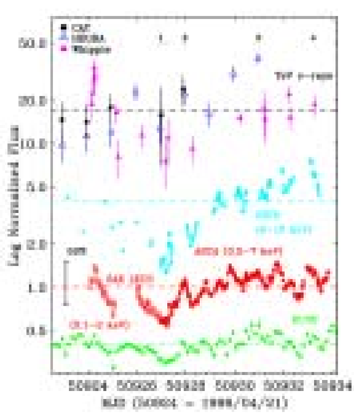


Coppi, Kartje, & Konigl 1993

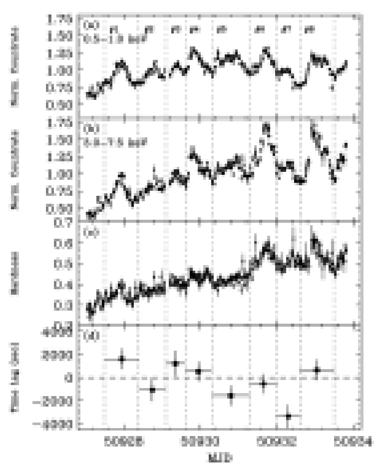
The advantages of TeV blazars…



Temporal Variability Contains Important Information – in Mkn 421, nothing simple works!



Takahashi et al. 2000



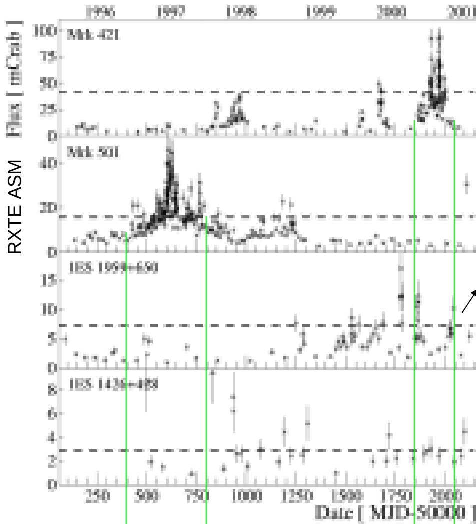
If cooling/acceleration slow,
SSC model predicts "hysteresis loops"
(due to lags)

Lags and Leads!?
(t_cool=t_accel= t_esc = R/c)

Also, IC target photons can only build up in R/c after increase in electron injection
=> gamma-rays lag X-rays

TIMESCALES (II):

TeV (and GeV) blazars appear to have discrete "flare" states…



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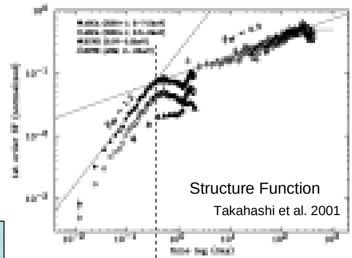


May-June 2002

1959 flares! (RXTE TOO)

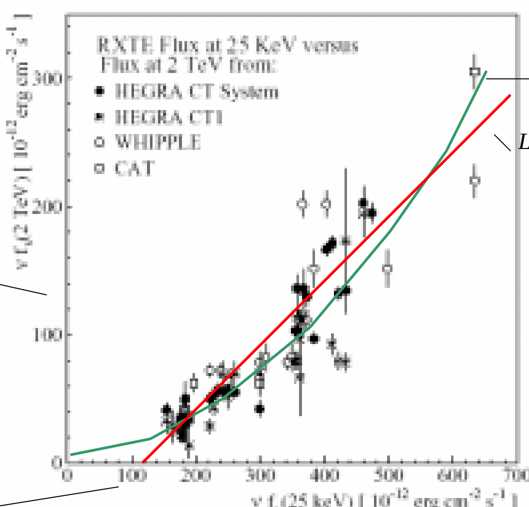
6 hr rapid variability timescale in Mrk 421??

Problem: In "standard model," single blob would be at $R \sim \delta^2 c\Delta t \sim 5\times10^{19}\delta_{25}^2\Delta t_{month}$ cm!

Unlikely....

$\Delta t \sim$ months??

The stability problem…



$L_{TeV} \propto L_x^2$ (naive SSC)

$L_{TeV} \propto L_x$ (ERC, SSC, hadronic model)

Linear Axes!

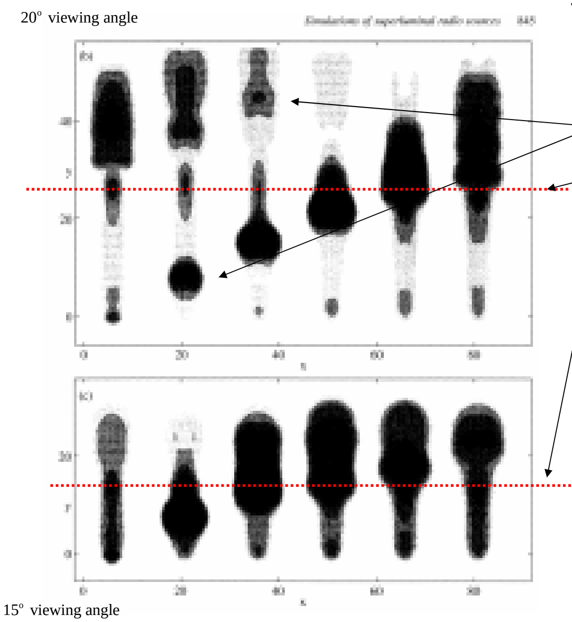
Steady X-Ray Component??

Figure 1. Correlation between X-ray (RXTE) and TeV Gamma-ray fluxes. The Gamma-ray fluxes are from CAT (squares), HEGRA CT System (solid points), HEGRA CT 1 (asterisks), and Whipple (open circles). Only observation pairs with less than 6 hrs time delay have been used.

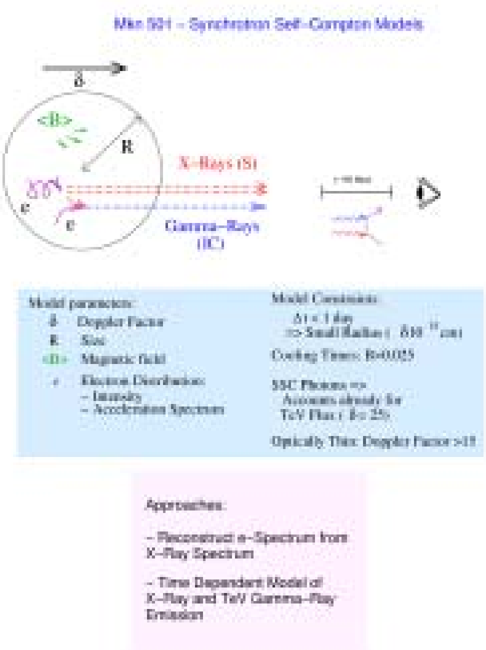
Key – 3 keV flux tracks TeV flux relatively poorly

N.B. June 1997 data (after main flaring) included!

Jet Simulation:
variable, periodic piston at base of jet
+
external pressure gradient
=
Moving “internal” shocks
+
Quasi-stationary recollimation shock



Komissarov & Falle 1997



Krawczysnki, Coppi, & Aharonian 2002

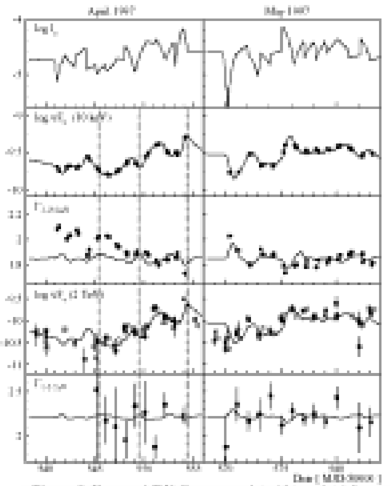


Figure 2. X-ray and TeV Gamma-ray data (data points) from April, 1997 (left column) and May, 1997 (right column) with SSC model B1 (lines). Here, model flares are caused for a time dependent $Q_0(t)$. The panels show from top to bottom: (i) the logarithm of the injection compactness L, (ii) the logarithm of the 10 keV X-ray energy flux (10^{-11} erg cm^{-2} s^{-1}), (iii) the X-ray 3-25 keV photon index, (iv) the logarithm of the 2 TeV energy flux (10^{-12} erg cm^{-2} s^{-1}), and (v) the 1-5 TeV photon index. The Gamma-ray fluxes are from CAT (squares), HEGRA CT System (solid points), HEGRA CT 1 (asterisks), and Whipple (open circles). TeV photon indices have only been published for the HEGRA group. The value for April 16 has been inferred from the average spectrum published by Djannati-Atai et al. (1999). The vertical dashed lines show the days with BeppoSAX observations (April 7, 11, and 16 which will be discussed in more detail further below. The model parameters are: $\delta_j = 45$, $R = 1.5\times 10^{16}$ cm, $B = 0.034$ G, $t_{esc} = 15\ R/c^{-1}$, $\gamma_{min} = 10^2$, $\gamma_{max} = 2.5\times 10^5$, $\xi = 0.5$, $\eta = 0.2$.

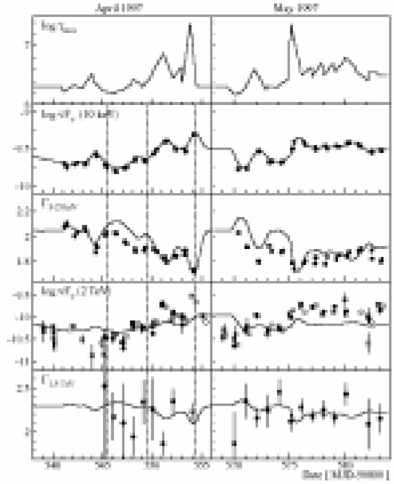


Figure 3. Same as in Fig. 2, but with flaring activity through a time dependent maximum Lorentz factor of accelerated particles $\gamma_{max}(t)$. The upper panel shows here $\gamma_{max}(t)$. The model parameters are: $\delta_j = 45$, $R = 1.5\times 10^{16}$ cm, $B = 0.039$ G, $t_{esc} = 3\ R c^{-1}$, $\gamma_{min} = 10^2$, $\xi = 0.5$, $\eta = 0.2$.

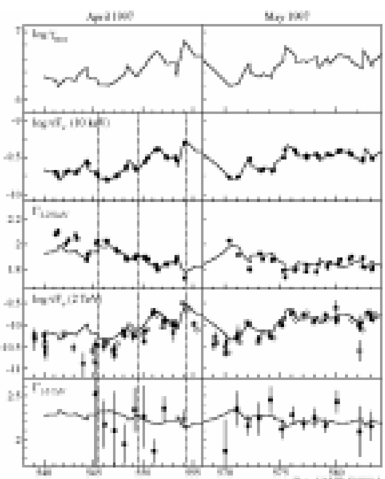


Figure 4. Same as in Fig. 3, but with flaring activity through time dependent $Q_0(t)$ and $\gamma_{max}(t)$ with $\gamma_{max} \propto Q_0^{\,2}$. The upper panel shows here $Q_0(t)$. The model parameters are: $\delta_j = 45$, $R = 3.2\times 10^{15}$ cm, $B = 0.035$ G, $t_{esc} = 3\ R c^{-1}$, $\gamma_{min} = 10^2$, $\xi = 0.5$, $\eta = 0.1$.

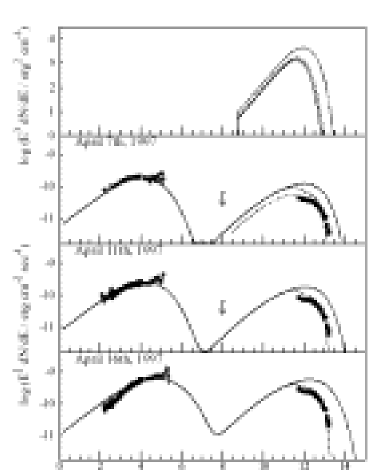


Figure 5. For the model of Fig. 3 the upper panel shows the electron energy spectra [illegible]

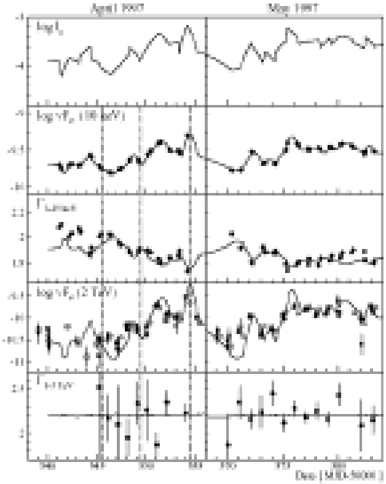


Figure 6. Fit of a SSC model with two emission components: (I) a quasi-stationary X-ray component, and, (II) a time variable X-ray/TeV Gamma-ray component, flares produced through $Q_{II}(t)$. Data and units are the same as in Fig. 2. The model parameters are $\delta_j = 45$, $R = 3.4 \times 10^{15}$ cm, $B = 0.014$ G, $t_{esc} = 3\,R\,c^{-1}$, $\gamma_{min} = 10^3$, $\gamma_{max} = 2.3 \times 10^7$, $\xi = 0.5$, $\eta = 0.6$.

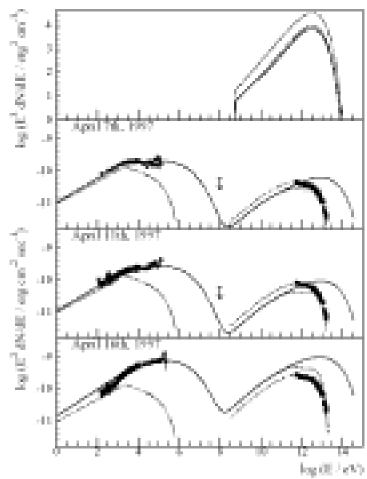


Figure 7. Same as in Fig. 3 but for the two-component model with time variable $Q_{II}(t)$ shown in Fig. 6. In the lower three panels, the dotted line shows the quasi-stationary X-ray component, and the dashed-dotted lines show the absorbed Gamma-ray energy spectra normalized at 2 TeV to the observed ones.

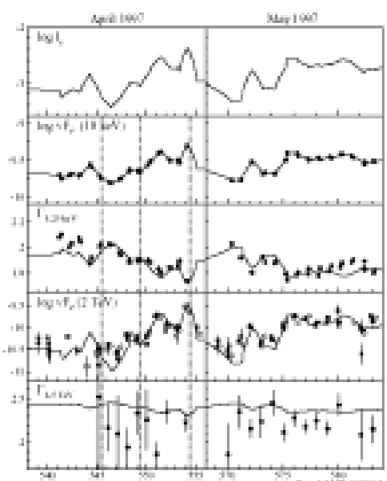


Figure 8. Same as in Fig. 6, but for the two-component model with $\gamma_{min} = 10^5$. The model parameters are $\delta_j = 45$, $R = 4.5 \times 10^{15}$ cm, $B = 1.1$ G, $t_{esc} = 10^4\,R\,c^{-1}$, $\gamma_{min} = 10^5$, $\gamma_{max} = 1.4 \times 10^7$, $\xi = 0.5$, $\eta = 0.00$.

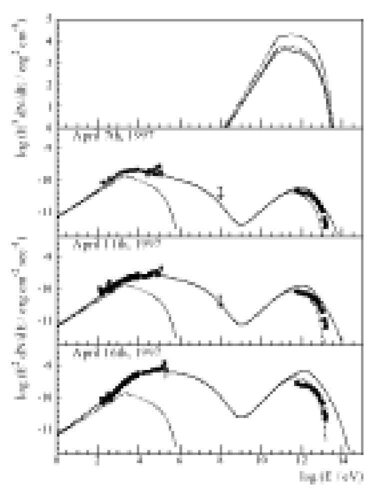
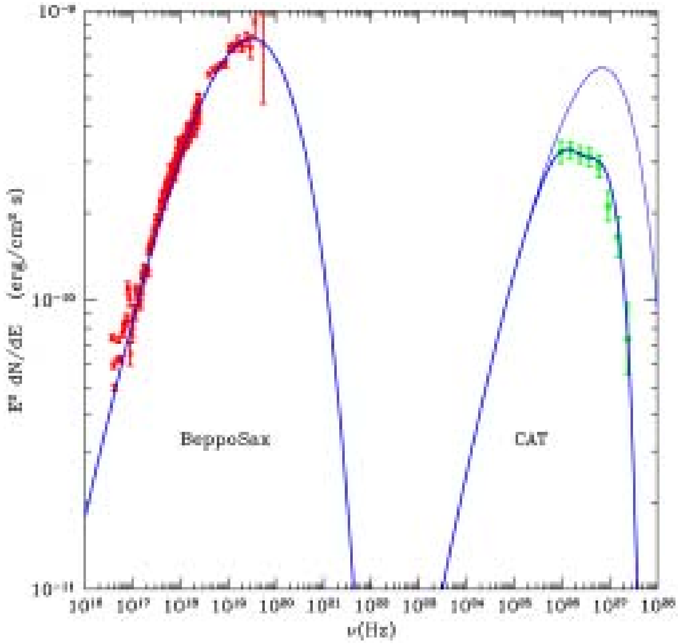


Figure 9. Same as in Fig. 7 but for the two-component model with $\gamma_{min} = 10^5$, shown in Fig. 8.



Simultaneous SSC fit to BeppoSax and CAT for Mrk 501 flare of April 16, 1997 using fully self-consistent model.

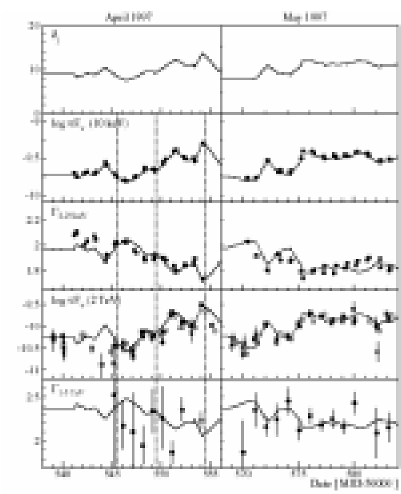


Figure 10. Fit of a SSC model with two emission components: (I) a quasi-stationary X-ray component, and, (II) a time variable X-ray/TeV Gamma-ray component, flares produced through $\delta_j(t)$. The upper panel shows here $\delta_j(t)$, and the other data and units are the same as in Fig. 3. The model parameters are: $R = 10^{15}$ cm, $B = 0.18$ G, $t_{esc} = 10\,R\,c^{-1}$, $\gamma_{min} = 4.3\times10^5$, $\gamma_{max} = 2.0\times10^7$, $\xi = 0.3$, $\eta = 0.06$.

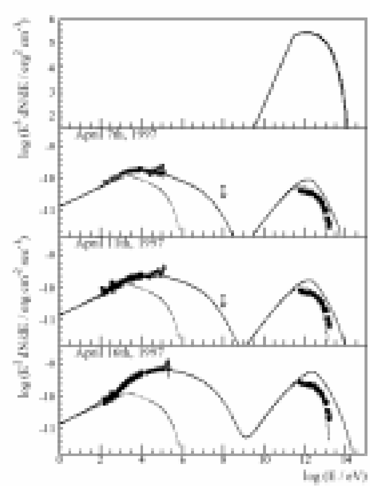


Figure 11. Same as in Fig. 7 but for the two-component model with time variable $\delta_j(t)$ shown in Fig. 10.

Table 1. Selected Blazar SSC Models relevant to this paper

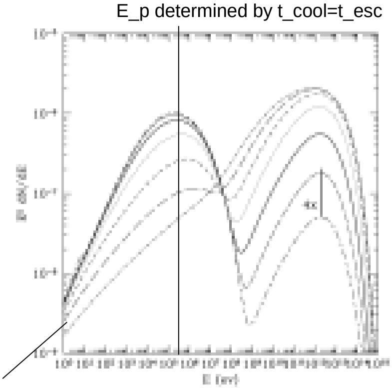
Authors	Objects Studied	Time Dependent?	SED Peak Determined By	Flare Mechanism
Inoue & Takahara (1996)	3C 279, Mrk 421	No	Cooling vs. Particle Escape	Not specified
Bednarek & Protheroe (1997, 1999)	Mrk 421, Mrk 501	No	Not specified	Not specified
Böttcher et al. (1997)	Mrk 421	No	γ_{min}	B, γ_{min}
Mastichiadis & Kirk (1997)	Mrk 421	Yes	Cooling vs. Particle Escape	Q_0, γ_{max}, B
Pian et al. (1998)	Mrk 501	No	γ_{min}	γ_{min}, γ_{max}
Dermer et al. (1998)	generic	Yes	Cooling vs. Particle Escape and Plasmon Deceleration	δ_j
Chiaberge & Ghisellini (1999)	generic	Yes	Cooling vs. Particle Escape	Q_0
Coppi & Aharonian (1999)	generic	Yes	Cooling vs. Particle Escape	Q_0, B
Kirk & Mastichiadis (1999)	generic	Yes	Cooling vs. Particle Escape	Q_0
Kataoka et al. (2000)	PKS 2155-304	Yes	Cooling vs. Particle Escape	γ_{max}
Petry et al. (2000)	Mrk 501	No	Cooling vs. Injection Time Scale	p
Kusunose et al. (2000)	generic	Yes	Cooling vs. Particle Escape	γ_{max} (through t_{acc} and t_{esc})
Tavecchio et al. (2001)	Mrk 501	No	Not specified	Change of γ_b
Krawczynski et al. (2001)	Mrk 421	Yes	Cooling vs. Particle Escape	γ_{max}
Sikora et al. (2001)	3C 279, PKS 1406-076	Yes	Cooling vs. Injection Time Scale or γ_{min}	Q_0
Kino et al. (2002)	Mrk 421, Mrk 501, PKS 2155-304	No	Cooling vs. Particle Escape	Not specified
This work	Mrk 501	Yes	Cooling vs. Particle Escape or γ_{min}	Q_0, γ_{max}, δ_j

Table 2. Parameters of Models Shown in Figures

Time Dependent Parameter	Comments	δ_j	R [cm]	$\log_{10}$ (B/1 G)	t_{esc} [$R\,c^{-1}$]	γ_{min}	γ_{max}	ξ	q	n_e/n_p	L_0 [erg s^{-1}]
$Q_0(t)$	1-component	45	1.1×10^{15}	-1.55	10	1000	2.5×10^7	0.5	0.2	600	1.2×10^{44}
$\gamma_{max}(t)$	1-component	45	1.5×10^{15}	-2.05	5	1000	$1.8\text{-}25\times10^6$	0.5	0.2	1200	1.7×10^{44}
$\gamma_{max}(t) \propto Q_0(t)^2$	1-component	45	3.2×10^{15}	-1.45	5	1000	$1.6\text{-}6.3\times10^6$	0.5	0.1	600	6.3×10^{43}
$Q_0(t)$	2-component	45	3.0×10^{15}	-1.55	5	1000	2.2×10^7	0.5	0.4	7470	1.3×10^{44}
$Q_0(t)$	2-component, high γ_{min}	45	4.5×10^{15}	0.05	10000	1.8×10^5	1.4×10^7	0.5	0.80	290	5.6×10^{42}
$\delta_j(t)$	2-component, high γ_{min}	20	10^{15}	-0.6	10	4.3×10^5	2.8×10^7	0.5	0.04	2970	2.8×10^{43}

TeV Blazars: Self-Consistent Modeling &
Klein-Nishina Correction to Thomson Cross-Section Important!

E_p determined by t_cool=t_esc

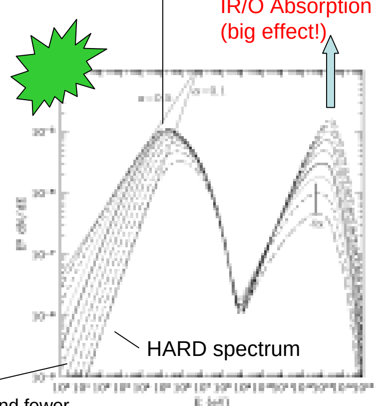


Lots of soft target photons

Response to variations in electron acceleration luminosity.

E_p determined by E_min
(t_esc=infinity)

IR/O Absorption
(big effect!)

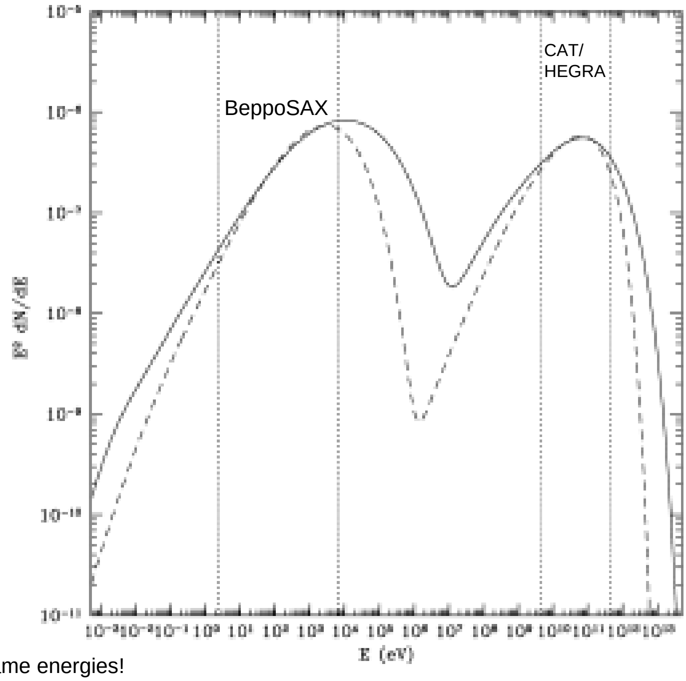


HARD spectrum

Solid line models: Both fit April 16th Mrk 501 CAT gamma-ray and BeppoSax data above 2 keV equally well…

Fewer and fewer soft photons

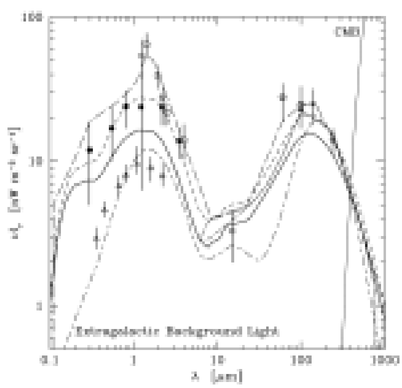
Fits BeppoSAX < 2 keV X-ray Better!!



Jet Frame energies!

Absorption by the EBL – Important!

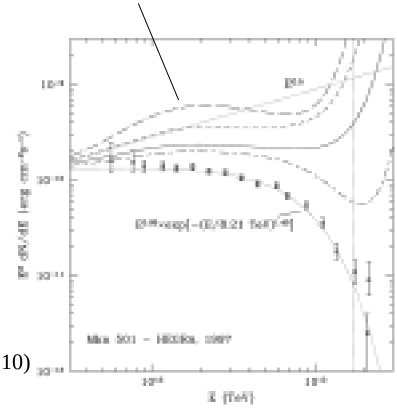
Might not seem too important, but…



$E_{peak} \propto (\delta / B)^{1/2}$

EBL Abs: $E_{peak}^{true} \approx 3 \times E_{peak}^{observed}$

$\Rightarrow \delta \uparrow B \downarrow$ by up to factor ~ 9!



More: E_{peak} larger $\Rightarrow$ Higher γ_{peak}

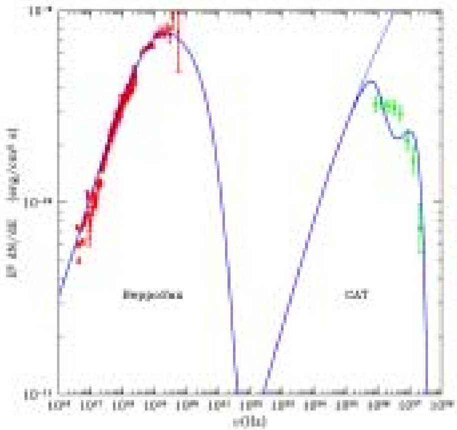
$\Rightarrow$ More in KN limit $\Rightarrow$ lower IC component

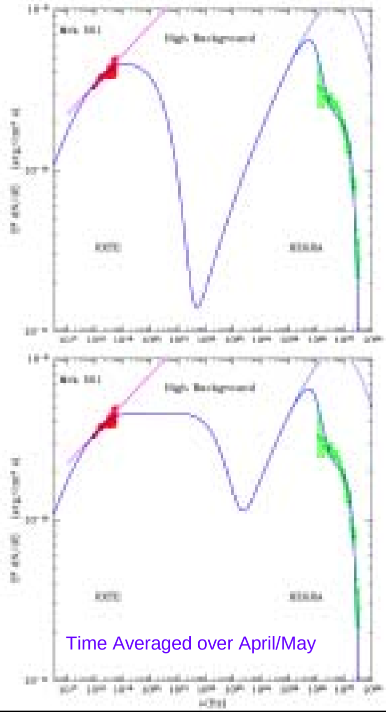
BUT... EBL abs. also $\Rightarrow$ $L_{IC} \uparrow \Rightarrow R \downarrow$ (another factor ~ 10)

$\Rightarrow L_{kinetic} \uparrow$! $U_B / U_{e-} \downarrow$ (very out of equipartition)

SSC fits (e- distribution obtained by “inverting” X-rays) to quasi-simultaneous (< 6hr difference) data for Mrk 501 April-May flare.

April 16, 1997





Using Mrk 501 April 1997 data can start to constrain DEBRA models – if SSC hypothesis is correct.

Key which allows this is simultaneous, broadband X-ray and TeV data.

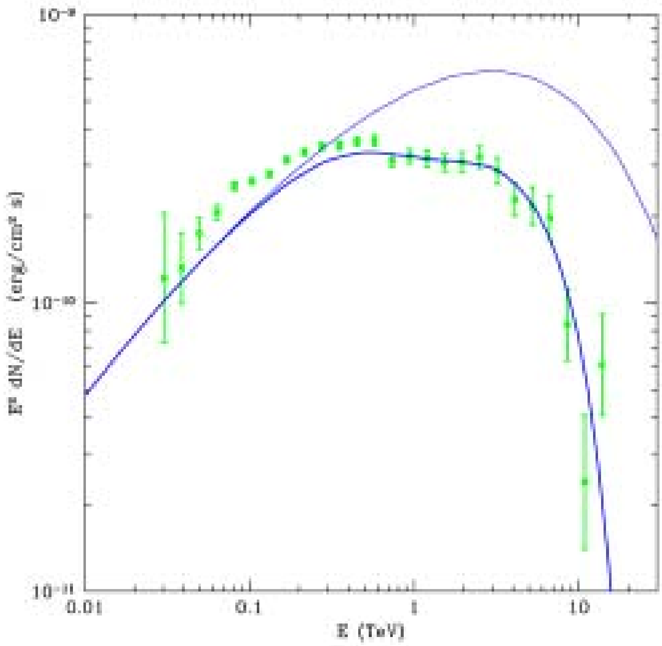
Better data on the way!

Table 1. Joint RXTE-HEGRA Fits for Various DEBRA Models

Assumed DEBRA	χ^2/dof	Chance Probability	$\delta_K^{min}/\delta_R^{min}$	$B_{\delta_{min}}$	$R^{15}_{\delta_{min}}$	(model-data)/σ_{data}
High, no shift	76/20	1.7×10^{-8}	25/86	0.0124	1.57	-2.5,-4.8,-3.2,-2.8,-2.9
High, shift	47/20	5.2×10^{-4}	21/48	0.015	3.56	-0.49,-3.0,-1.6,-1.7,-2.5
Kennicutt, no shift	58/20	1.4×10^{-5}	37/220	0.0089	0.54	-2.2,-4.3,-2.5,-2.3,-2.6
Kennicutt, shift	30/20	0.069	26/78	0.0125	2.3	-1.0,-3.1,-1.3,-1.3,-2.2
Salpeter, no shift	33/20	0.035	28/78	0.0125	2.8	-1.1,-3.2,-1.4,-1.3,-2.1
Salpeter, shift	21/20	0.41	24/47	0.015	5.9	0.20,-1.9,0.02,-0.04,-1.3
TT02, no shift	12/20	0.91	19/22	0.019	17	0.70,-0.96,1.4,1.5,-0.026
TT02, shift	18/20	0.60	16/13	0.028	20	0.79,-0.74,1.8,2.2,0.70
No Background	39/20	6.8×10^{-3}	9.0/2.3	0.16	12	0.78,-0.50,2.4,3.2,2.0

Table 2. Joint BeppoSAX-CAT (April 16, 1997) Fits for Various DEBRA Models

Assumed DEBRA	χ^2/dof	Chance Probability	$\delta_K^{min}/\delta_R^{min}$	$B_{\delta_{min}}$	$R^{15}_{\delta_{min}}$
High, no shift	43/5	3.3×10^{-8}	12/7.7	0.043	16
High, shift	53/5	4.4×10^{-10}	44/930	0.0062	0.059
Kennicutt, no shift	11/5	0.044	24/78	0.012	1.5
Kennicutt, shift	14/5	0.014	17/27	0.018	6.8
Salpeter, no shift	3.4/5	0.64	13/10	0.032	17
Salpeter, shift	4.3/5	0.51	5.8/11	0.056	14
TT02, no shift	3.7/5	0.59	12/7.7	0.043	16
TT02, shift	3.7/5	0.59	10/4.6	0.053	13
No Background	2.8/5	0.73	8.5/2.3	0.15	11



Example of Data Quality for Next Generation Instruments – Simulated 5hr observation of April 16,1997 Mrk 501 flare as as seen by HESS. Model used for simulation is slightly different at low energies compared to fit model used in previous slide. Both models give excellent to current data – but will be able to distinguish (blue curve is fit model of last slide).

Summary

Gamma-ray emission from blazars still not well-understood.

Leptonic models "preferred," but hadronic models not ruled out (need more work though! especially temporal variability signatures).

Complex environment in GeV blazars may hinder progress in understanding them, even with arrival of GLAST. When detailed modeling required, e.g., for IR background constraints, focus on TeV blazars: simpler (?) and better matched to detectors (GLAST area small).

TeV blazars may not be as boring as we once thought.

High Doppler boost factor (>20?) => multi-component jet structure? [relativistic spine?]

(Too) large jet kinetic energy? K_e,p order unity? Jet very inefficient radiator? Interaction with local environment, e.g., recollimation shock, may be important.

External photon fields may still be important in TeV blazars (in Mrk 501, can significantly lower energetics). Radical hypothesis: main difference with GeV blazars is higher electron energies and importance of Klein-Nishina effects??

Fossati et al.-type unification scheme really o.k.? (especially after correct for absorption)

With good broad band, time-resolved X-ray AND gamma-ray data, detailed modeling possible =>interesting constraints. Activity just starting … lots of data already in hand (e.g., Mrk 421 2000 flare) and some starting to becoming public ☺.

Better data coming soon – one simultaneous observation of an April 16 Mrk 501-type flare by HESS/VERITAS and ASTROE-2 has potential to measure 1-80 micron IR background (but may first cause headaches for modelers – data too good!).

Modeler HEALTH WARNING

With better data, even factors 2-3 will matter in the future!

Don't ignore Klein-Nishina effects:
- -- use correct cross-sections/solve full kinetic equations.
- -- in TeV blazars, factor 10 in gamma-rays corresponds to factor 100 in X-rays!

Use self-consistent models:
- -- even if accelerated particle distributions are power laws(?), cooled distributions (and emitted photon spectra) are usually not!
- -- often seem to be in "moderate" Klein-Nishina regime => asymptotic approximations poor.
- -- don't assume synchrotron and Compton spectral indices match.
- => do not use phenomenological "power law" models or constraints derived from such models (e.g., Tavecchio et al. 1998).
- => no more "eyeball" theorist fits…

In estimating source parameters, don't ignore absorption by infrared/optical background! (B,R, L_kin can change by factor 10!)

Don't forget time dependence of problem/finite cooling times of particles.

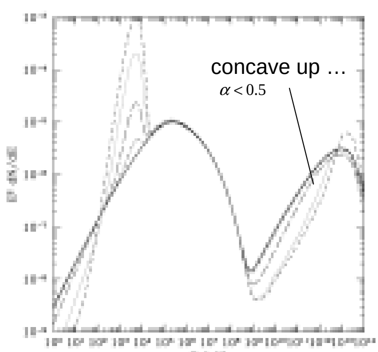
Several emission regions may be active at any given time => confusion, especially at low (keV) energies => watch for big flares, focus on hard X-rays.

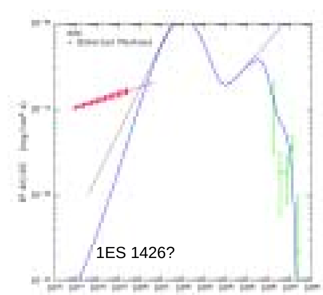
If you don't have sensitivity/energy coverage to track curvature/peak in both X-ray/gamma-ray spectra as well as emission from *same* electrons, don't bother…

Summary for Eli Dwek (low-energy background people):

If SSC model applies to Mrk 501, April 1997 flares (in particular April 16), your best-fit detected values are probably too high!
[15 micron background resolved, IR warm galaxies must be rare at low z, don't leave out PAHs in background models. Stellar models: 1 micron background too high => 2-3 micron also too high?]

On the other hand, the TeV guys don't really know what they're doing yet …
(simple SSC model correct???? SSC model parameter "systematic" uncertainties, poor data quality w/unknown systematics) => treat TeV limits with appropriate grain of salt
… but much better data and hopefully more sources are coming.





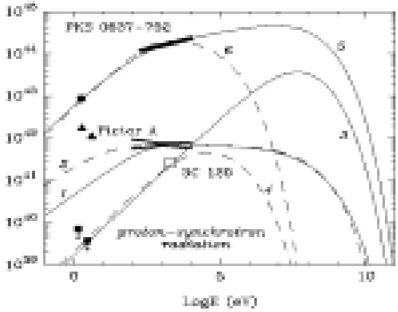


Figure 1. Proton synchrotron luminosities of jet features in Pictor A (western radio hot spot), 3C 120 (25" radio knot), and PKS 0637-752 (the outer jet component). The model parameters are described in the text. The optical and X-ray data are from Wilson et al. (2001) for Pictor A; Harris et al. (1999) for 3C 120; Schwartz et al. (2000) for PKS 0637-752.

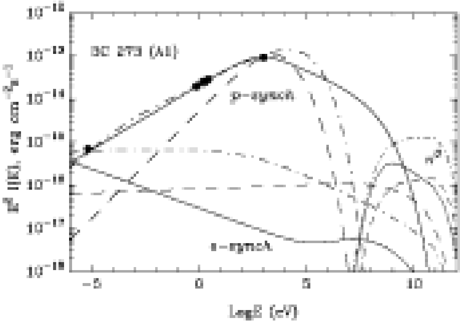
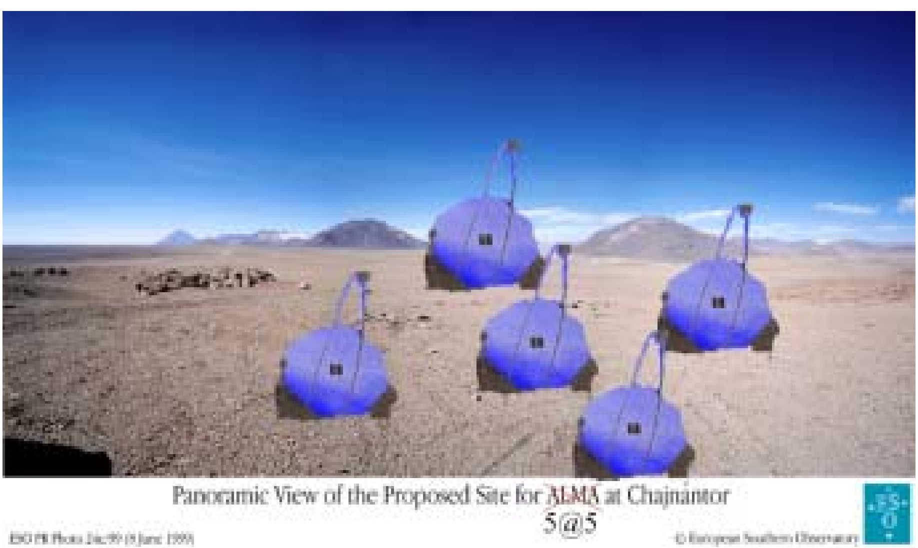
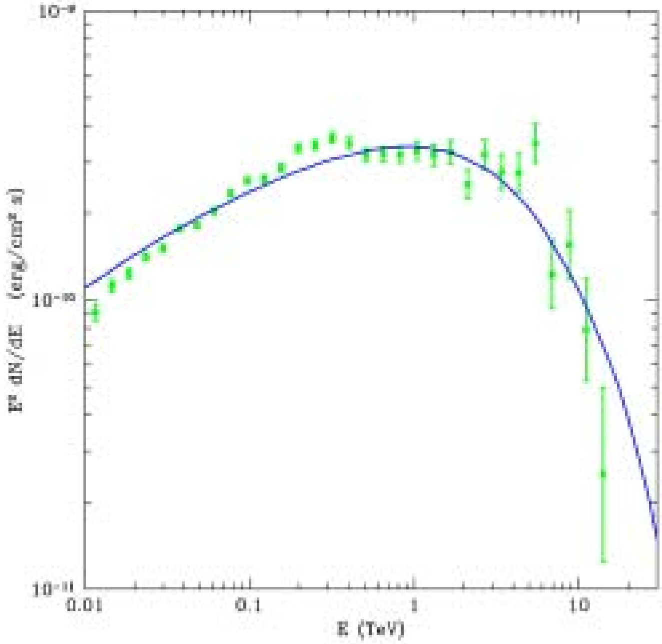


Figure 3. The spectral energy distribution of the knot A1 in 3C 273. The radio, optical and X-ray fluxes are from Marshall et al. (2001). The solid, dashed and dot-dashed curves correspond to 3 different sets of model parameters discussed in the text. The heavy, standard and thin lines represent the fluxes of (1) synchrotron radiation of protons, (2) synchrotron radiation of secondary electrons produced in $p\gamma$ and pp interactions, and (3) π^0-decay γ-rays produced at pp interactions, respectively.

What if you put VERITAS/HESS at 5000m?

5 GeV Threshold!

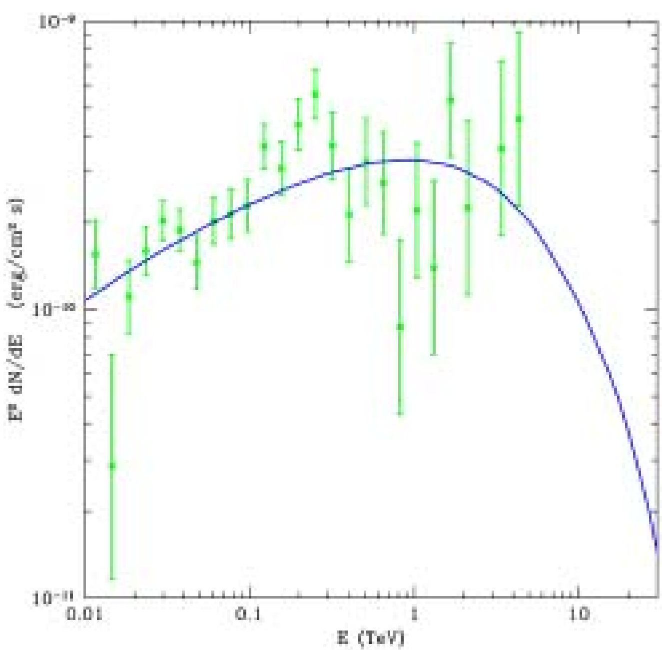




Even better!

Same as last slide, except simulated for response of the proposed 5@5 (5 GeV threshold) instrument.

Blue is curve is best-fit no absorption SSC model – strongly ruled out! (“Salpeter” DEBRA absorption assumed in generating faked data.)

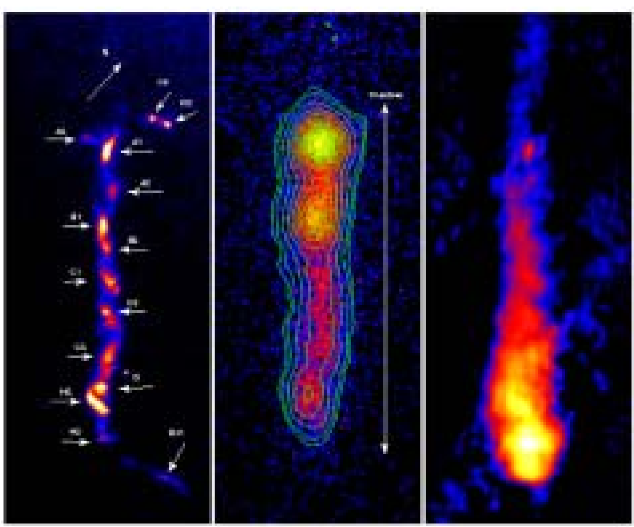


A 5@5 instrument would have sensitivity even on ***5 minute*** timescales – although now one cannot rule out no-absorption model.

Still, very useful for probing possible SSC model dynamics or signatures, e.g., looking for gamma-ray vs. X-ray lags, etc.

Coppi & Aharonian 1999

Lag/lead loops!



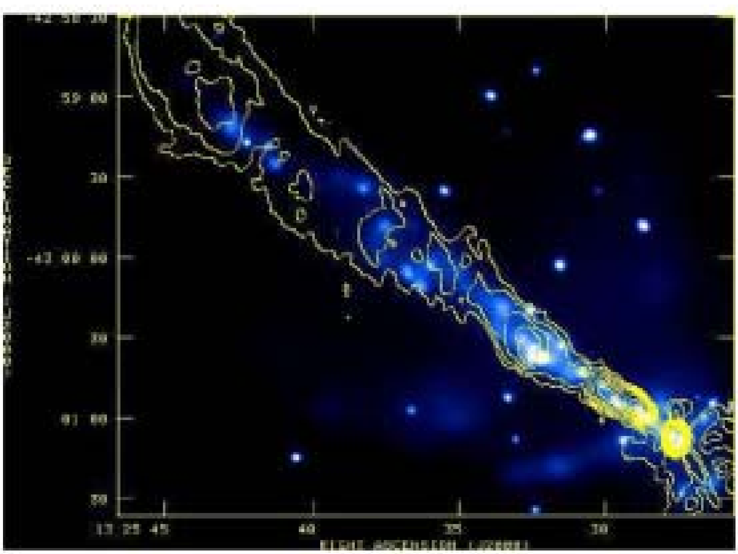


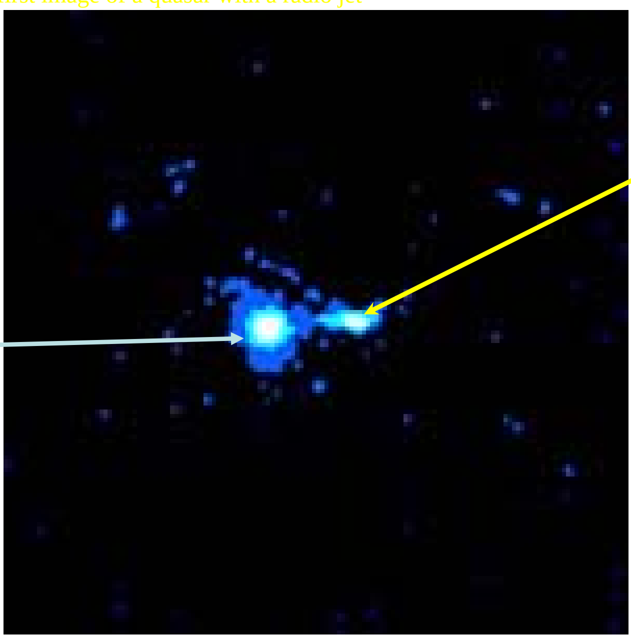
Fig. 10.— Adaptively smoothed, coadded X-ray image in the 0.4-2.5 keV bandpass of the jet in Centaurus A with 3.6 cm radio contours overlaid. North is up and east is to the left. The radio beam is 3.39" (RA) × 4.70"(DEC).

Cygnus A Radio Jet

Approx. 1 Megaparsec!

(our Galaxy size -- approx. 20 kiloparsecs, 50x smaller!)

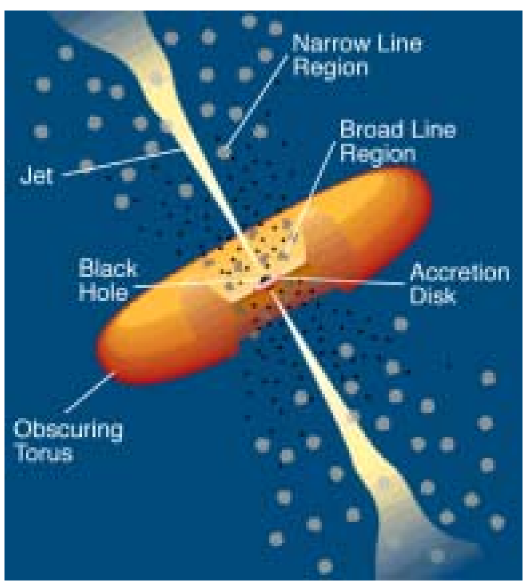
Chandra's first image of a quasar with a radio jet



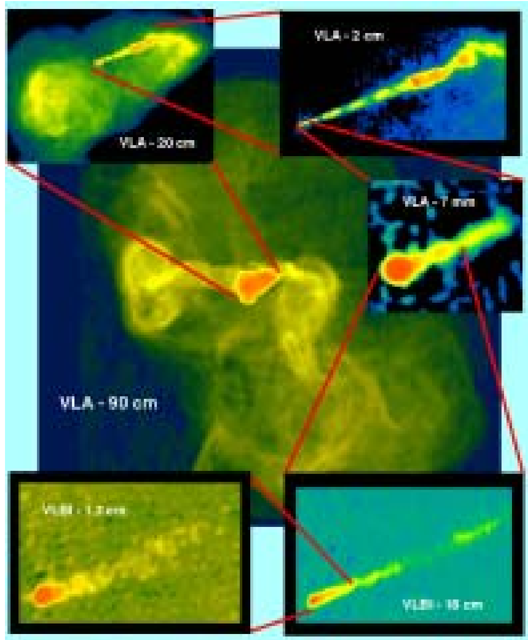
Strong X-ray emission 200,000 light years down the jet..oops.

N.B. Our galaxy is only 60,0000 light years in size...

Nuclear emission



Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus



http://hea-www.harvard.edu/XJET (Dan Harris et al.)

RADIO SOURCES WITH JET RELATED X-RAY EMISSION

Generic Name	R.A. (J2000) hh:mm	Dec. (J2000) dd:mm	z	Class	Dist. (H=50) (Mpc)	kpc/" (H=50)	Assoc. radio	Assoc. optical	PA w.r.t. core
3C 15	00:37	-01:09	0.0730	FRI RG	453	1.91	knots	knots	-30
3C 31	01:07	+32:25	0.0167	FRI RG	101	0.47	jet	no	-20
B2 0206+35	02:09:38.56	+35:47:50.92	0.0369	FRI RG	225	1.02	Y	N	-46
3C 66B	02:23	+43:00	0.0215	FRI RG	130	0.61	jet	jet	45
3C 120	04:33	+05:21	0.0330	Sy I	201	0.91	25" knot	no	NW
3C 123	04:37	+29:40	0.2177	FRII RG	1448	4.74	hs	no	110
3C 129	04 49 09.06	+45 00 39.34	0.0208	FRI RG	126	0.587	Y	N	14
Pictor A	05:19	-45:46	0.0350	FRII RG	214	0.97	W hs	yes	-90
PKS 0521	05:25	-36:27	0.055	BL Lac	338	1.475	knots	yes	NW
PKS 0637	06:35	-75:16	0.653	CDQ	5197	9.22	knots	yes	-90
3C 179	07 28 11.65	+67 48 47.5	0.846	LDQ	7223	10.27	knots, hs	N	274
B2 0755+37	07:58:28.11	+37 47 11.81	0.0428	FRI RG	262	1.17	Y	Y	+112
3C 207	08:40:47.5	+13:12:23.0	0.68	LDQ	5463	9.38	knot, hs	?	90

Blazars (Theoretical Overview)
P. Coppi, Yale

- 10+ years after discovery of strong gamma-ray emission from blazars, still do not conclusively know the mechanism(s) responsible for the emission.
- If had to bet, strong x-ray/TeV correlation (in TeV blazars at least) + rapid variability timescales + Occam's razor favor a synchrotron-Compton model where the SAME electrons are responsible for x-rays and gamma-rays.
- Although TeV blazars are commonly fit with SSC models, not obvious that "external" photons are not important in these objects too (as they are in GeV blazars).
- SC/SSC models make detailed predictions that can be tested by *simultaneous, broadband* x-ray/gamma-ray observations. Some good data already in hand. More coming with arrival of next generation telescopes + x-ray instruments like Astro E2, JEM-X.

- Example fitting exercise to April 1997 Mrk 501: simple SSC model ruled out! Need quasi-steady, extra X-ray emission component to explain X-ray spectral variability. If add this, then constraints become quite loose.
- Puzzle: month-long Mrk 501 flare sequence fits one "blob" model where all parameters except for electron injection rate are *constant.* What is reason for apparent "stability" (tight X/TeV correlation)? Preferred location of emission region (recollimation shock)? Not obviously expected in internal shock models.
- If want to fit SSC models, use self-consistently derived models or else can get unphysical nonsense.

- In TeV blazars,do not ignore gamma-ray absorption by infrared/optical photons. Effect large given current background models, e.g., position of Compton peak goes (delta/B)^(1/2). Factor two shift in peak from absorption => factor 4 in delta or B.
- After absorption correction, Fossati et al. (1998) trend of L_gamma/L_UVX scales as (L_UVX+L_gamma) not so obvious…
- Spectral + absorption modeling => high Lorentz factors (>25), U_B/U_e- << 1 (even more out of equipartation than speculated by Takahara et al.), and E_jet is huge: 10^44 erg/s kinetic power for pure e-/e+ jet, to 10^46+ for e/p jet. => have completely understimated FR1 jets? => multi-velocity jet flow structure? SC models wrong?

- SC model gamma-ray spectra *NOT* simple powerlaws. Intrinsic spectrum can look just like absorbed spectrum , e.g., with exponential cutoff, and can have alpha_x, alpha_gamma < 0.5 => WATCH OUT when “constraining” IR/optical background absorption. Use real models!
- My talk may be completely different after HESS/VERITAS/MAGIC/GLAST… we live in interesting times.

Messy – TeV
Blazar, still although cleaner
Too many x-rays, cascade

Break, nature cool vs. injection

Compactness parameter

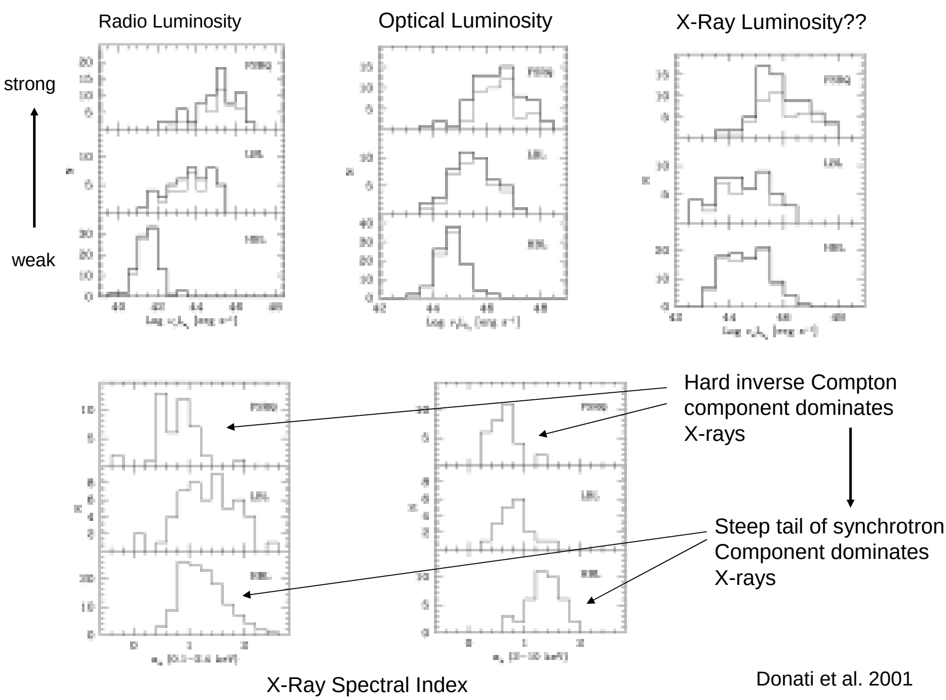
Lags, leads, synch, ssc99 paper figure, thin shock

Particle accel, internal shock model, sikora rev, proton time

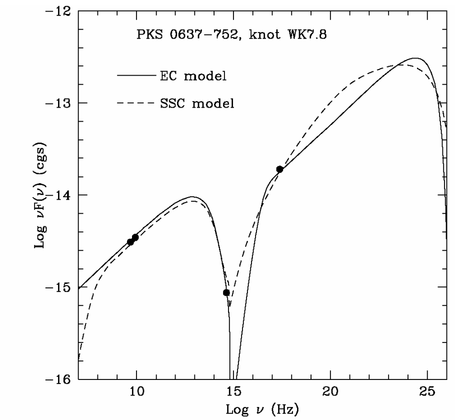
Blazejoswki, vs. simple SSC

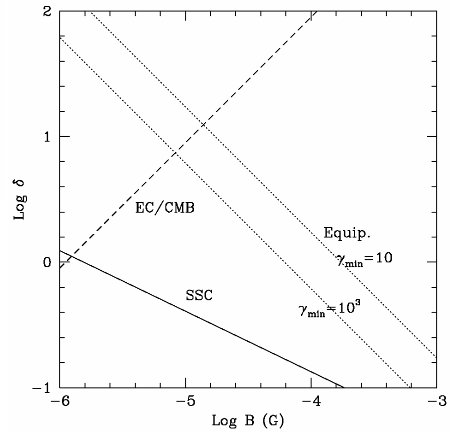
Proton synch, very fast accel to gamma>10^10, high B, push limits
And very large jet energetics, L_j > 10^46

Nature of jet, e+e-, but when work out energetics protons still dominate
L_bol, how much in radn, deceleration,

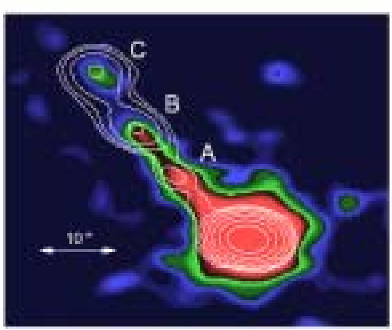


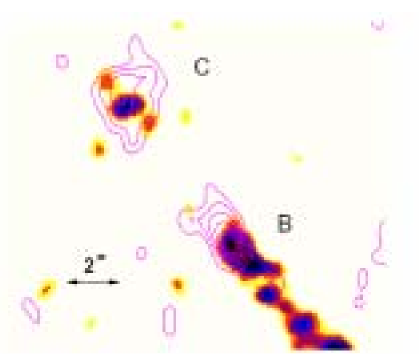
Donati et al. 2001

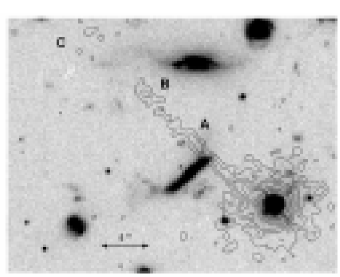

PKS 0637−752, knot WK7.8
EC model
SSC model
Log νF(ν) (cgs)
Log ν (Hz)
−12
−13
−14
−15
−16
10
15
20
25


EC/CMB
Equip.
γmin=10
SSC
γmin=10^3
Log δ
Log B (G)
2
1
0
−1
−6
−5
−4
−3

PKS 1127-145


C
B
A
10"


C
B
2"


C
B
A