RT Modeling of Radio-band Linear Polarization Data as a Probe of the Physical Conditions in the Jets of γ-ray Flaring Blazars

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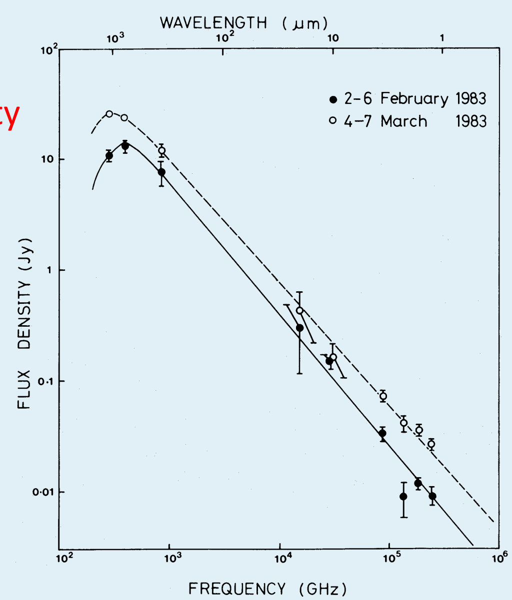
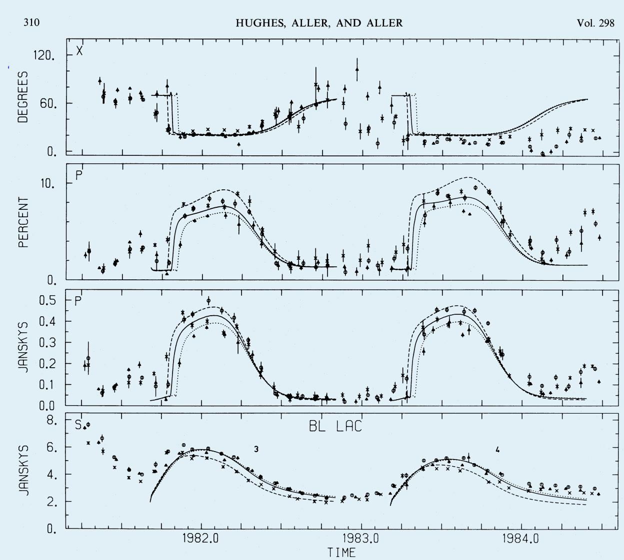
Shock-in-Jet Models

Flux density spectrum



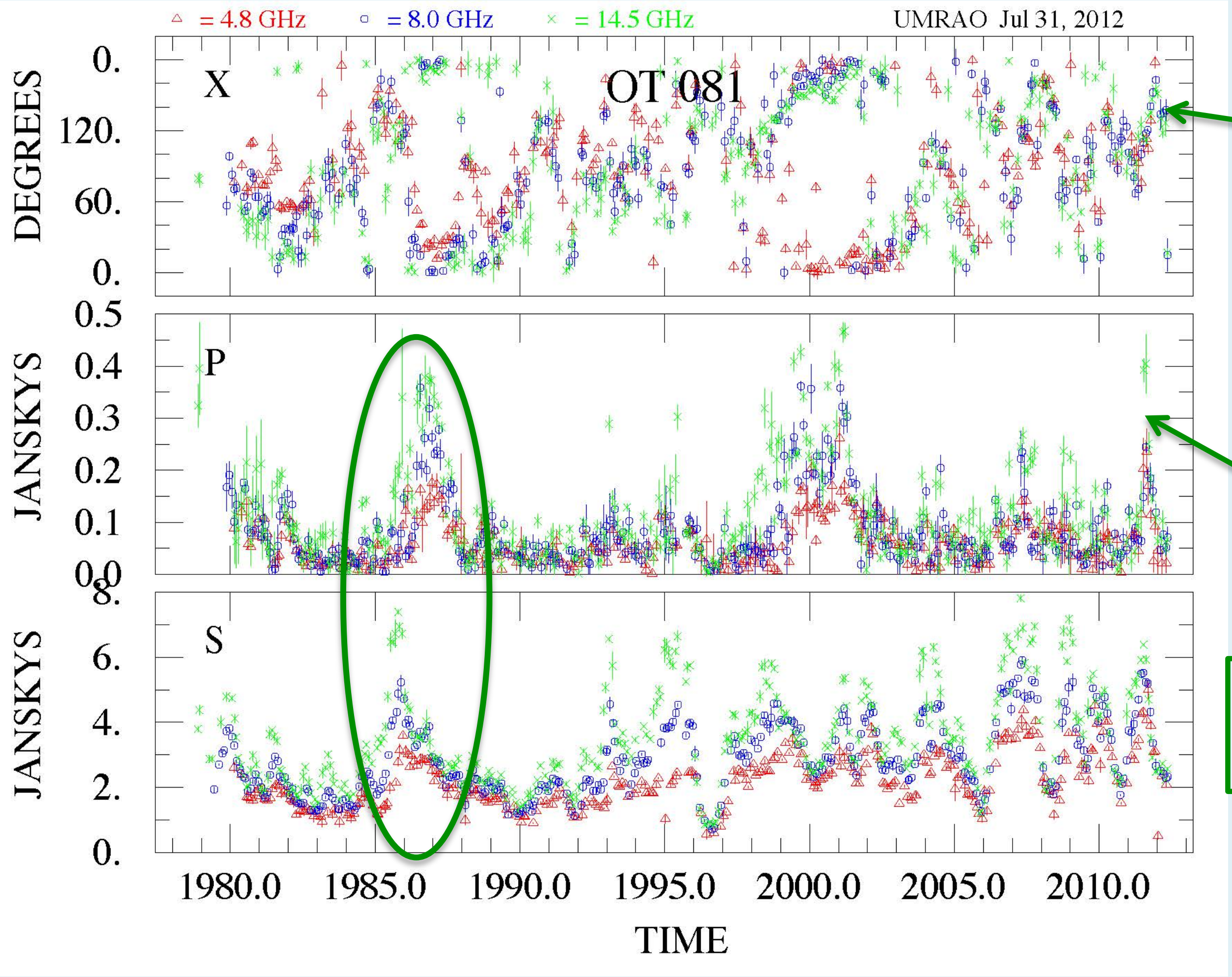
Marscher and Gear, ApJ, 298, 114 1985



Hughes, Aller, & Aller, ApJ, 298, 301, 1985

Cm-band S and LP spectral evolution

Spectral Variability in LP is the primary constraint for the UMRAO shock-in-jet model



Monthly-averaged triple frequency UMRAO Total Flux Density and Linear Polarization

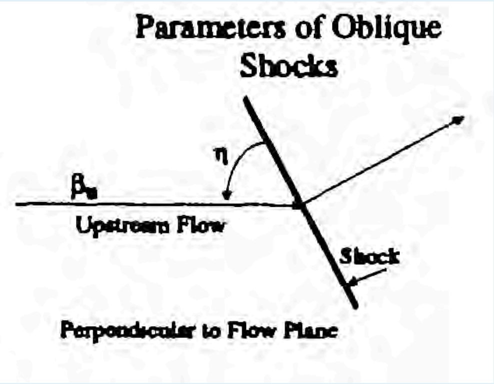
EVPA: ordered changes on timescales of a few years.

Outbursts in Polarized Flux: P% ranges from 1% to 15%.

S: Temporally well-separated outbursts (an envelope over individual flares).

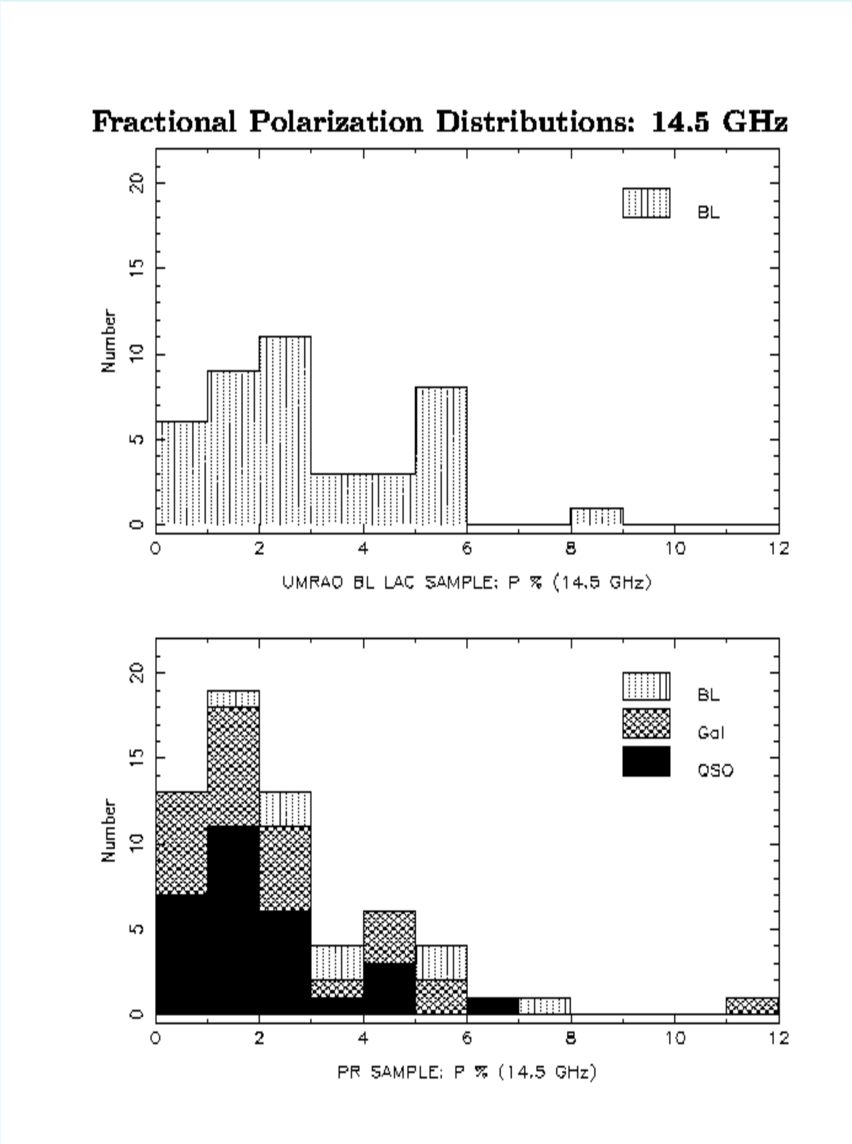
Model Framework for Recent Work (2011 - 2016)

- Magnetic Field: B in the emitting region is predominantly random before shock compression. Two ordered components are also included; one is axial, and the second may be helical.
- Shock Orientation: at arbitrary angle to the flow direction and spans the cross section of the flow. The orientation is specified by the obliquity (η) and the azimuthal direction of the shock normal (ψ).
- Shocked Flow: specified by a width, length, and a compression factor.
- Shock Propagation: the shock propagates at a constant speed (no acceleration or deceleration).



Evidence for Turbulent Magnetic Fields: Low P%

Histograms of <P%> from time-averaged Q and U for two flux-limited samples



UMRAO BL Lac Sample

<u>0≤P≤9%:</u> 41 objects observed 1979--

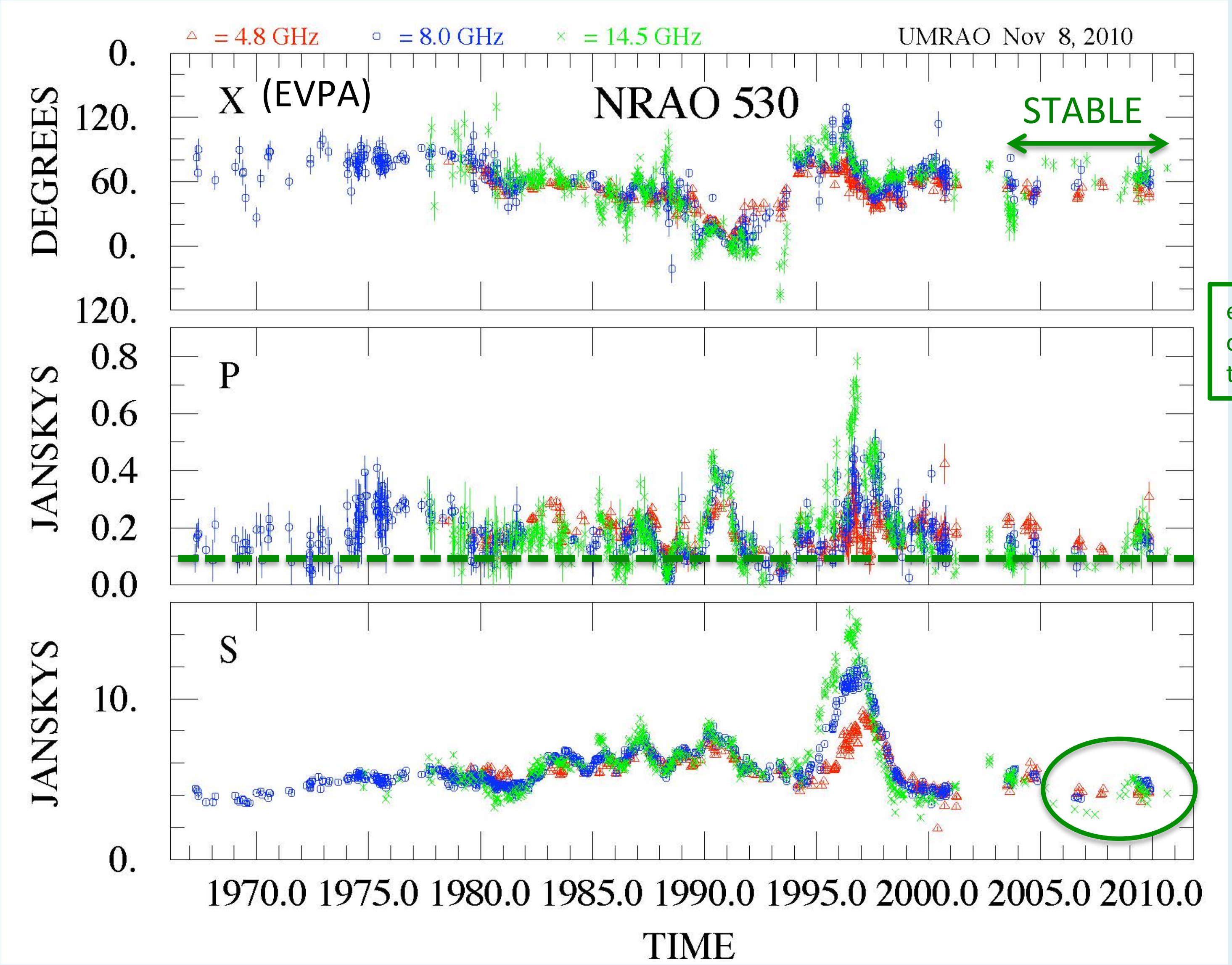
Pearson Readhead Sample

Primarily Q, G classes

<u>0≤P≤12%:</u> 62 sample members observed 1984 --

From source-integrated UMRAO data over decades: the distribution peaks ~2-3%, & the highest value in daily averages ~18% consistent with random B field

EVPA Stability During `Quiescence': A Weak Ordered Axial B Field



energy density in ordered component: 2% of that in the random component

Baseline level during quiescence

Free Parameters of Jet/Shock System & Data Constraints

MODEL PARAMETER	UMRAO DATA CONSTRAINT
Low energy cutoff (γ_i)	EVPA Spectral behavior
Axial B field (B_z)	EVPA and P%
Bulk Lorentz Factor (γ_f)	P%
Viewing Angle (θ)	P%
Shock obliquity (η)	ΔEVPA
Shock compression (κ)	ΔS and P%
Shock onset (t_o)	Start of flare in S or P
Shock length (l)	Duration of flare in S
Shock sense (F or R)	Doppler Factor and β_{app}

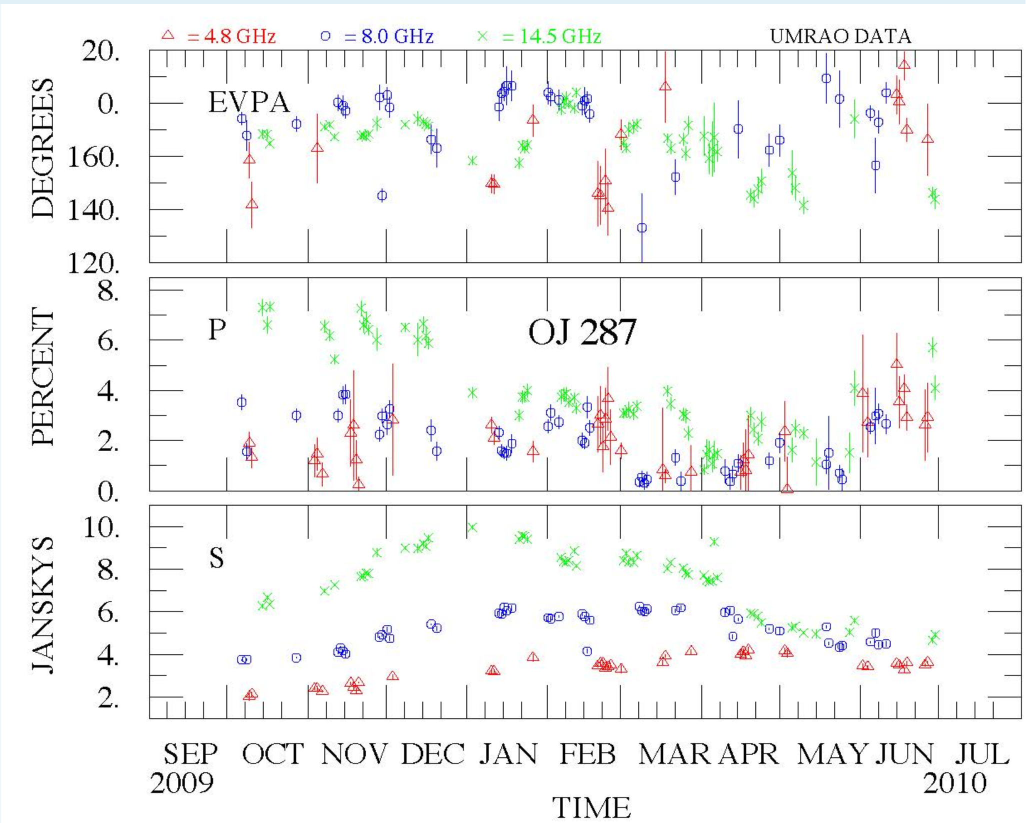
The free jet parameters

Observed variability in S and LP constrain the shock parameters

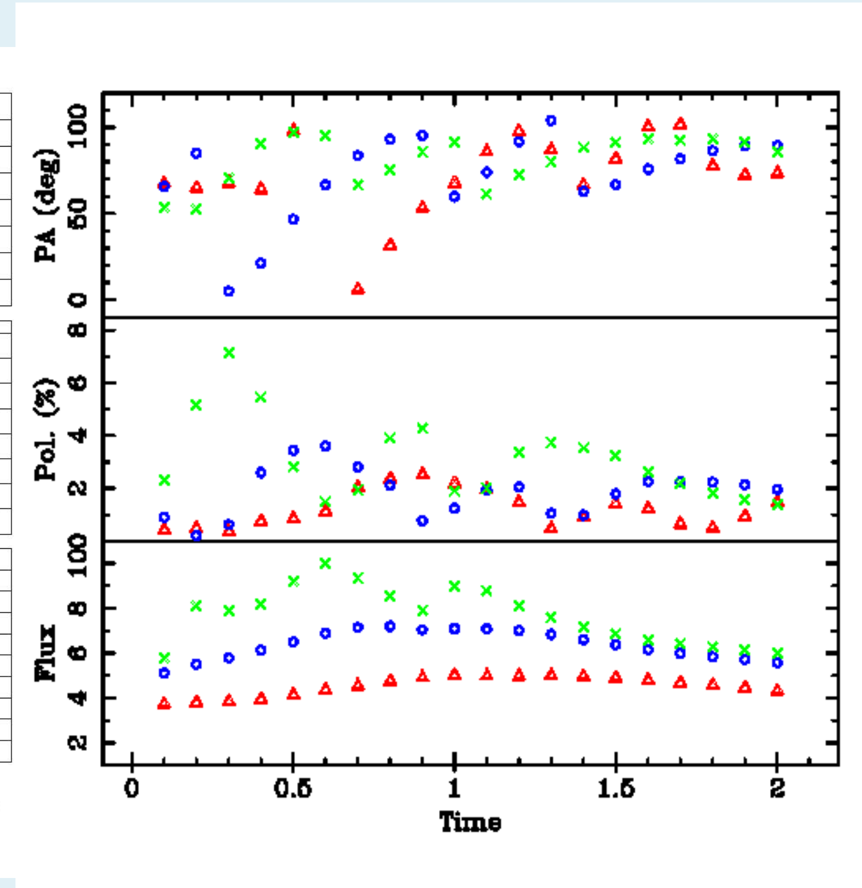
Procedure for obtaining shock parameters: Set number of shocks and onsets to match structure apparent in observed UMRAO S and/or P light curves. Duration is from the combined observed structure and the expected flare shape based on a library of simulations for a single shock. Shock obliquity is set by the range of change in the EVPA; transverse shocks are selectively picked for modeling, but one source, OJ 287, exhibits oblique shocks.

Shocks (Oblique): Data and RT Simulation for OJ 287

DATA



MODEL



Summary of observed characteristics reproduced by the simulation

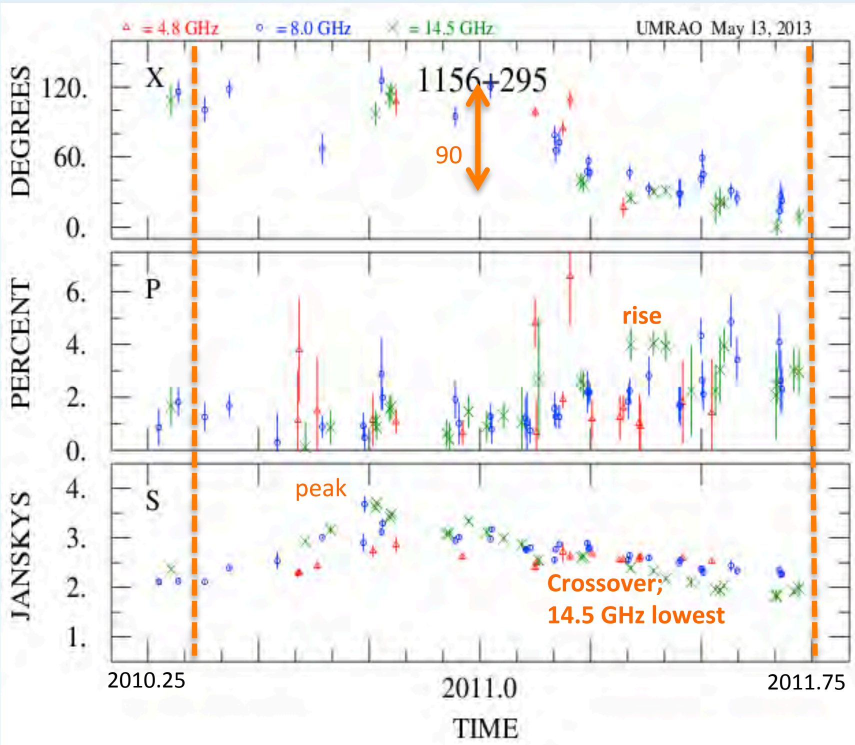
S: self-absorbed spectrum during rise with approximate time delay of peak; spectral behavior during the burst decline

P%: range of the variation and the peak value

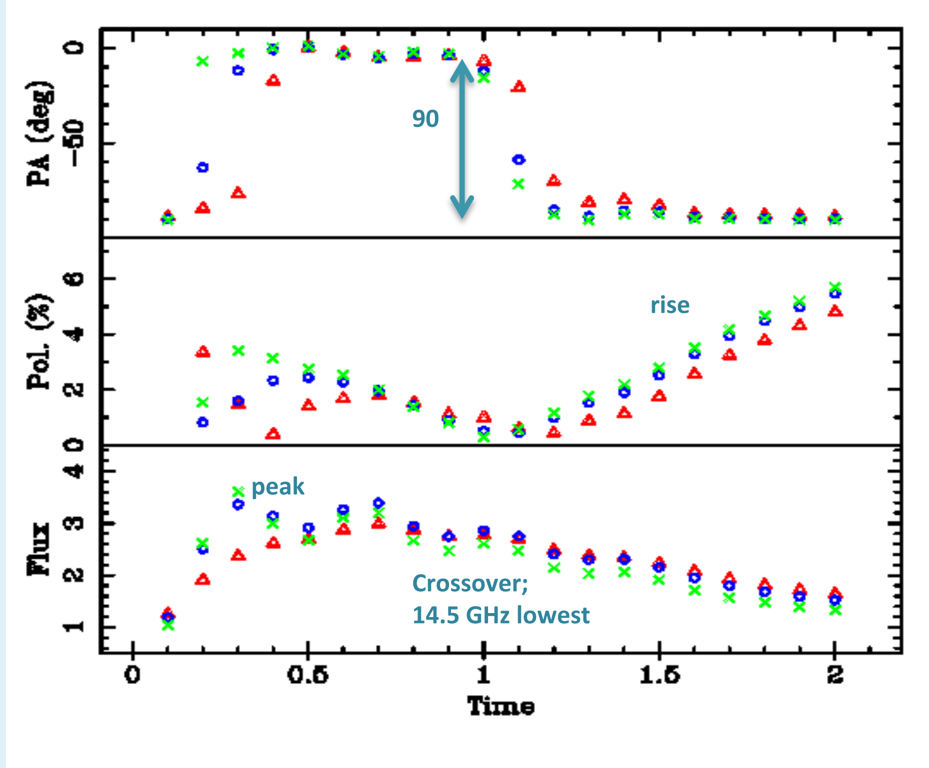
EVPA: ΔEVPA at 14.5 GHz, but the detailed spectral behavior is complex

Jet Parameters: Evidence for an Axial B Field (Bz)

DATA



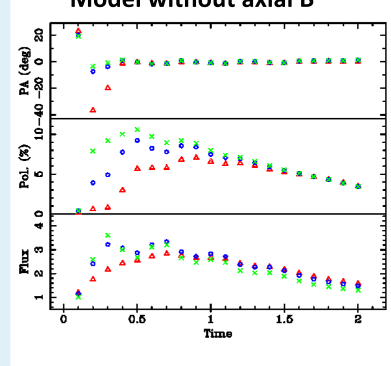
Adopted Model: with axial B



Primary Features Reproduced by Model WITH axial B field

S: peak value, spectral rise, crossover, and duration of decline
P%: max amplitude, and monotonic rise during decline in S
EVPA: swing thru 90° and spectral behavior

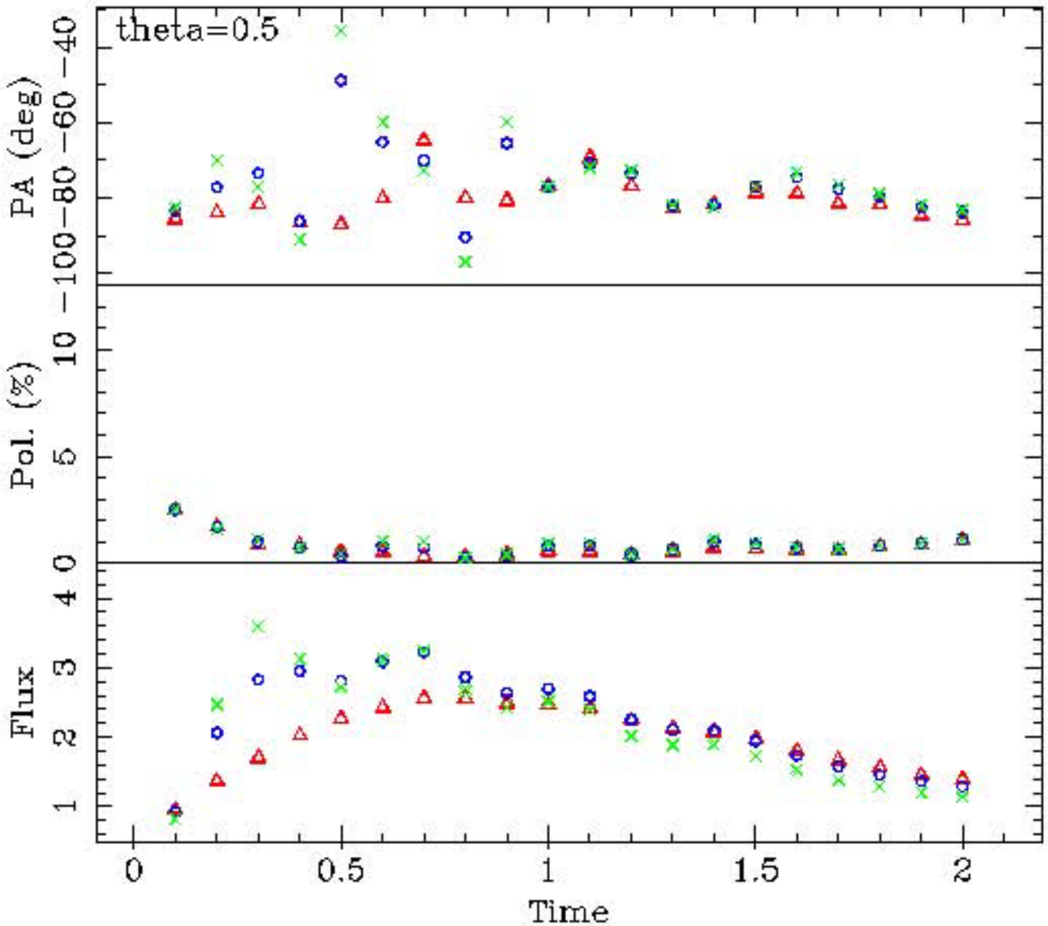
Model without axial B



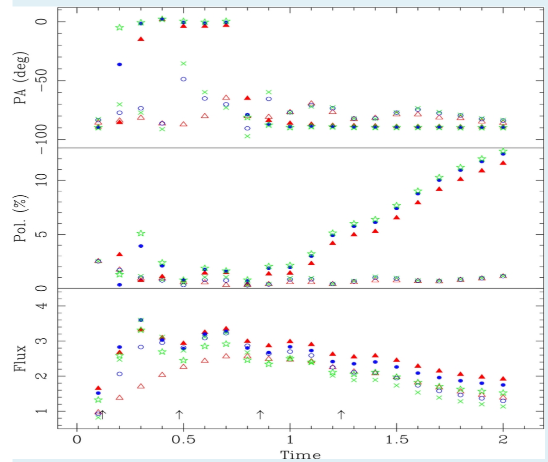
LP spectral behavior not reproduced

Effect of Jet Parameters on Model: Observer's Viewing Angle (θ)

1156+295: simulations for θ=0.5° to 3.5°



Start and end simulations illustrating range of change.



Θ=3.5

Θ=0.5

LP simulations are very sensitive to the choice of viewing angle, and this parameter is well-constrained.

From Hughes, Aller, & Aller 2015

Derived Parameters for 3 `Typical' Blazars Illustrating the Range of Values (all shocks forward relative to quiescent flow)

Parameter	0420-014	OJ 287	1156+295
Cutoff LF (energy)	50	10	50
Bulk Lorentz factor	5.0	5.0	10
Shock Sense	F	F	F
Number of shocks	3	3	4
Shock Obliquity	90° (transverse)	30° (oblique)	90° (transverse)
Shock Compression	0.65 to 0.8	0.5 to 0.7	0.5 to 0.8
Viewing angle	4°	2.5°	2.0°
Axial magnetic field*	16%	50%	50%

*% magnetic energy density which is a small quantity

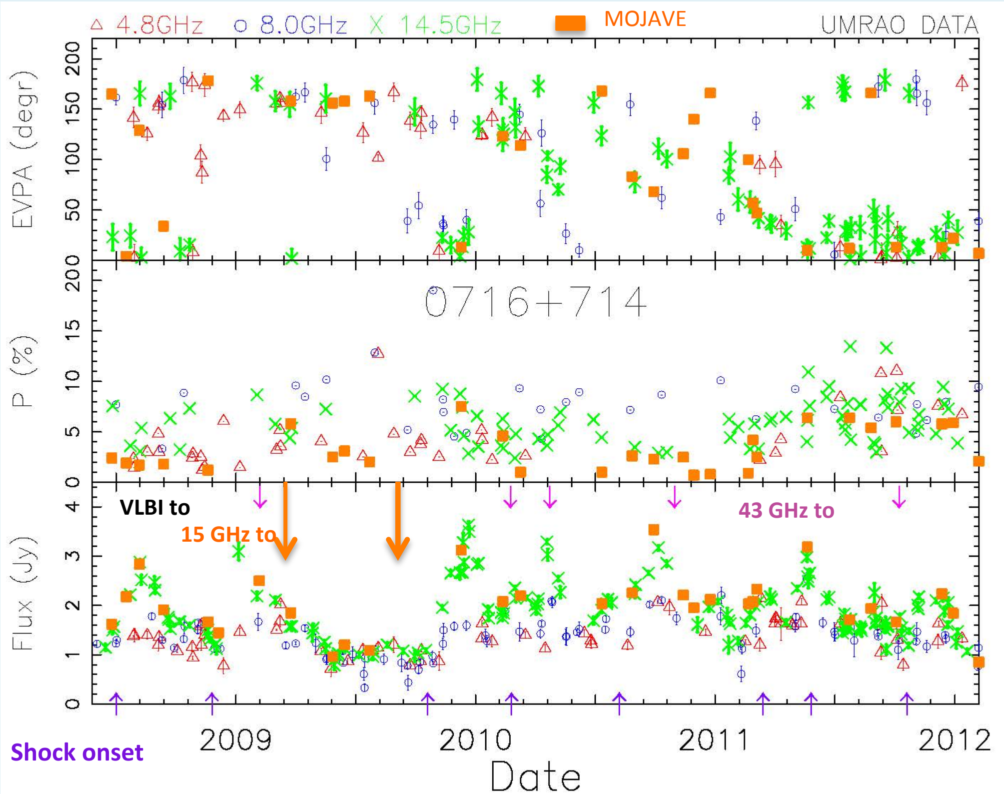
The derived parameters are well-constrained by the 3 frequency spectral data.

Shock properties	S, P%, EVPA (+VLBI as check on sense)
Axial B field (B_z)	EVPA and P%
Viewing Angle (θ)	P%
Low energy cutoff (γ_i)	EVPA Spectral behavior
Bulk Lorentz Factor (γ_f)	P%

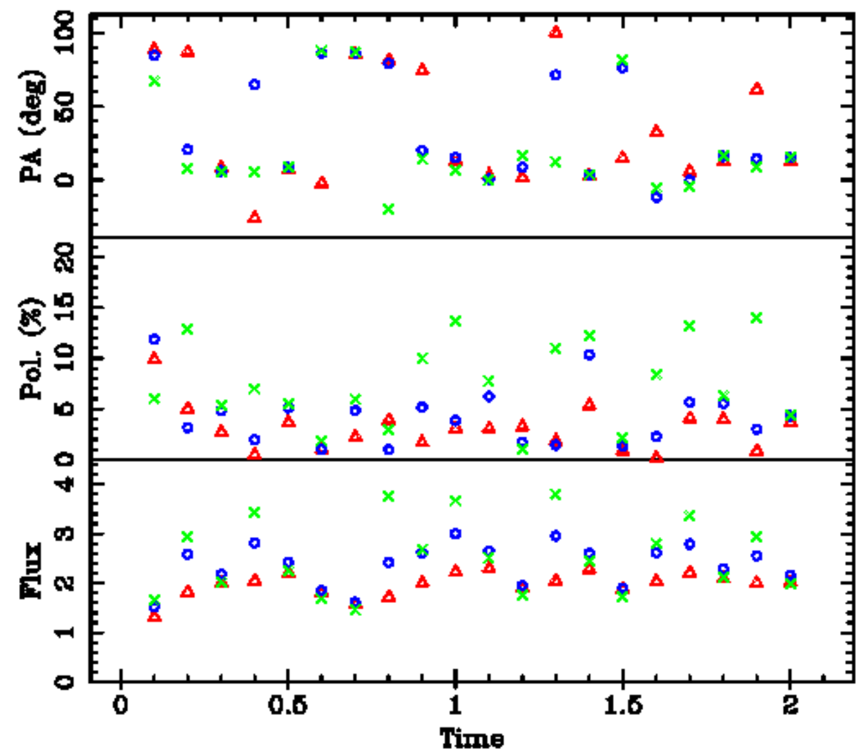
See Hughes, Aller, & Aller 2015 for additional movies.

0716+714: RT Modeling for an Extreme BL Lac Object

DATA: UMRAO + MOJAVE



Simulation with Adopted Model Parameters



Unusual features of the DATA:
1) the characteristic flare shape (quasi-triangular) indicates strong compression.
2) Pmax is high (14% compared to a few percent in typical blazar events modeled).

Note that a long segment of the data (3.6 yrs) has been simulated with a single set of jet parameters.

Shock and Flow Parameters: 0716+714 is different

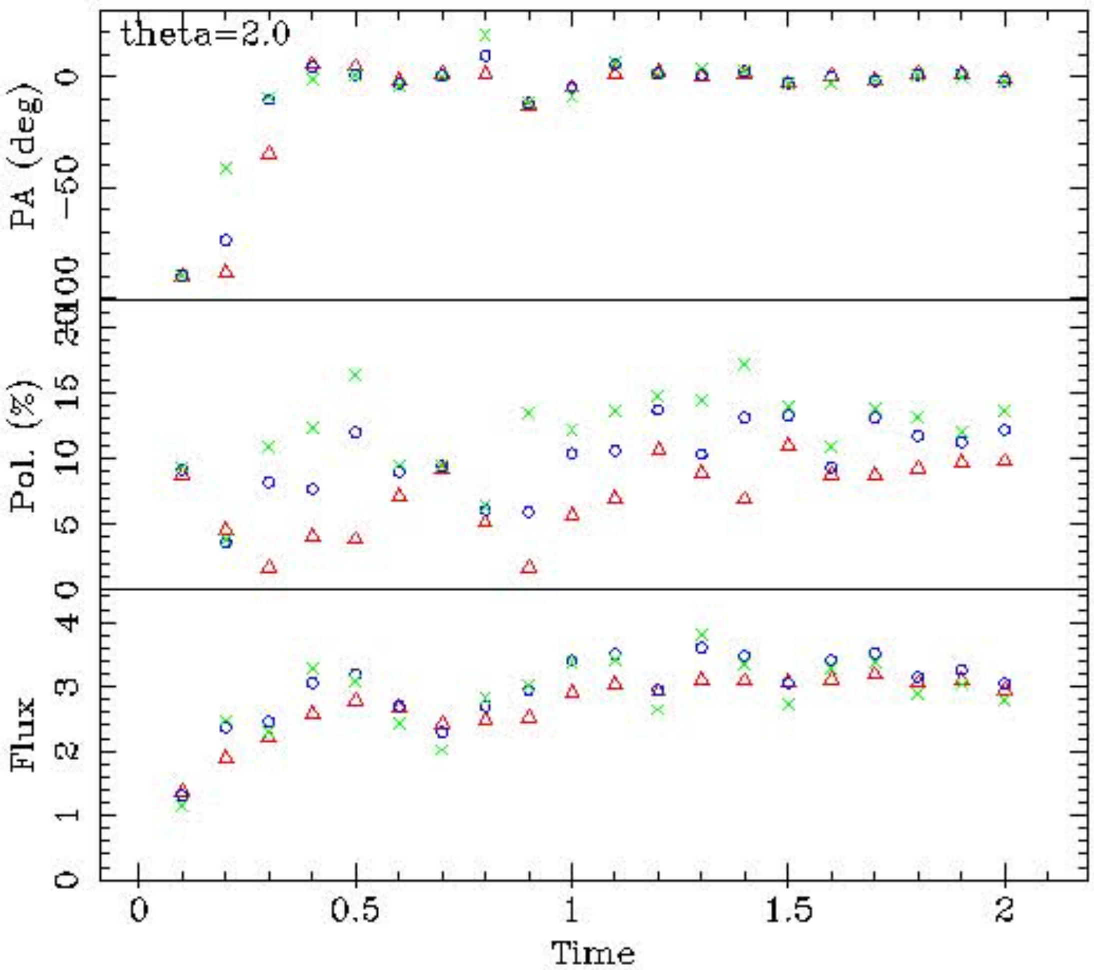
Parameter	0420-014	OJ 287	1156+295	0716+714
Cutoff LF (energy)	50	10	50	50
Bulk Lorentz Factor	5	5	10	20
Number of Shocks	3	3	4	8
Shock Obliquity	90°	30°	90°	90°
Shock Compression	0.65 to 0.8	0.5 to 0.7	0.5 to 0.8	0.17 to 0.27
Viewing Angle	4°	2.5°	2.0°	12°
Axial Magnetic Field (energy density in B)	16%	50%	50%	36%

Unusual derived parameters of 0716+714 from the modeling:
1) the bulk Lorentz factor is high (20 compared to 5-10 for other modeled sources).
2) The shocks are strong (κ=0.2).
2) the value of θ (12°) is high and outside the critical cone.
Θ and the LF are higher than those obtained in analyses based on VLBI data and analytic expressions.

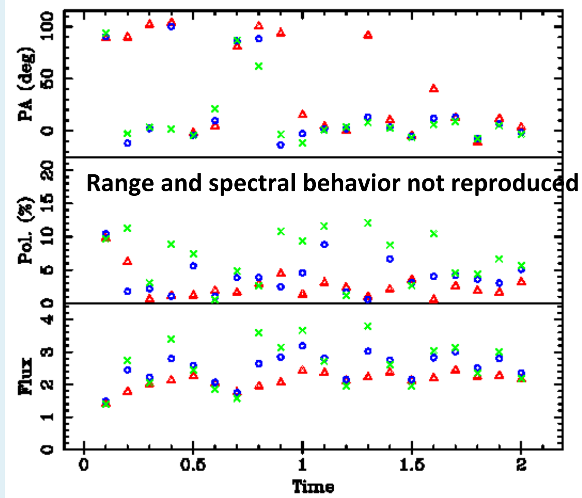
Does a shock model with lower θ and the adopted parameters reproduce the data?

Sensitivity of the 0716+714 Simulation to Changes in θ

0716+714: simulations for θ=2° to 12°

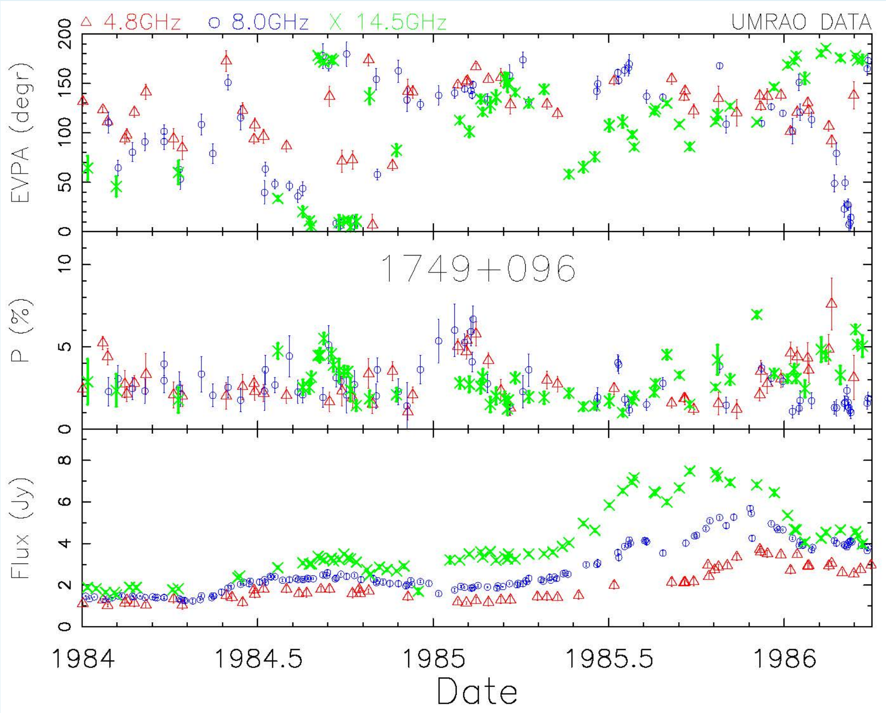


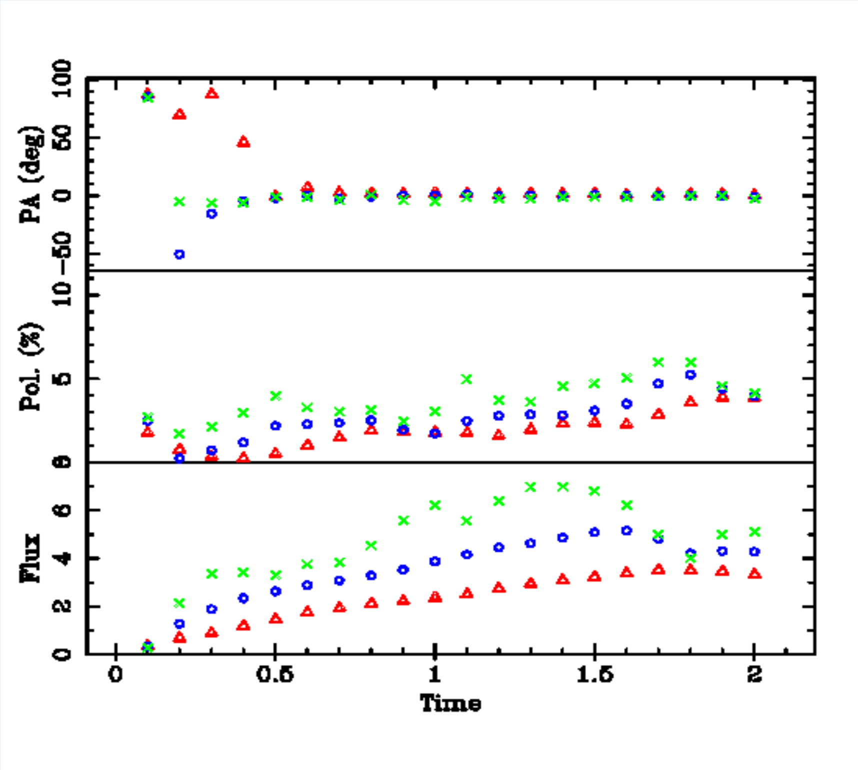
0716+714 model with θ=5°



We cannot rule out θ=5°, but θ=12° better reproduces the observed spectral variability.

Changes in the Flow on Decadal Time Scales: OT 081 Epoch 1 (1984.5-1986) Remodeled

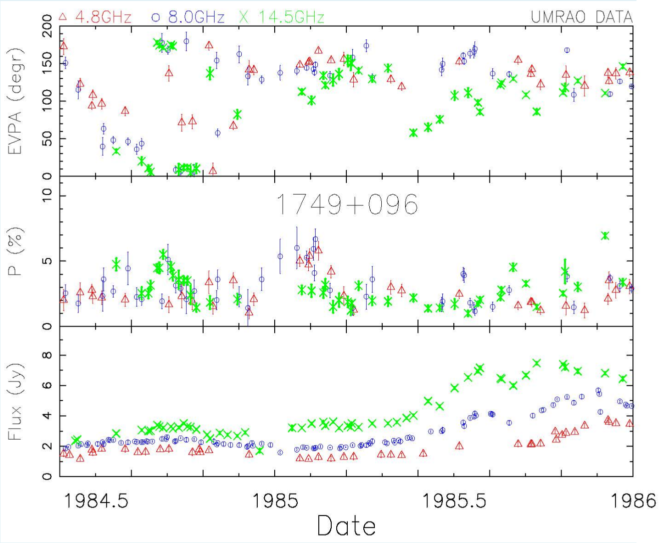




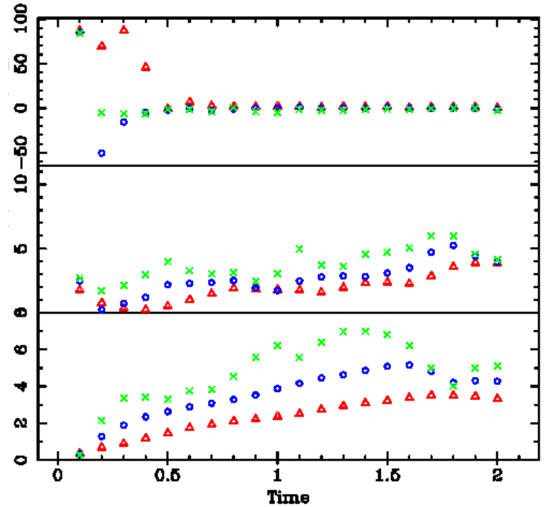
Model	# shocks	κ	Sense	Obliquity	θ	βapp
NEW	5	0.28-0.40	F	90°	1.7°	10.4 c
OLD	5	0.28-0.60	R	90°	40°	1.7 c

β_{max} (MOJAVE)=7.89 c but includes few features. β_{max}(15 GHz, to=1996.9)=10.2 c & β_{max}(22 GHz, to=2003.2)=21.0 c (Lu+ 2012).
VLBA data are an important complementary constraint.

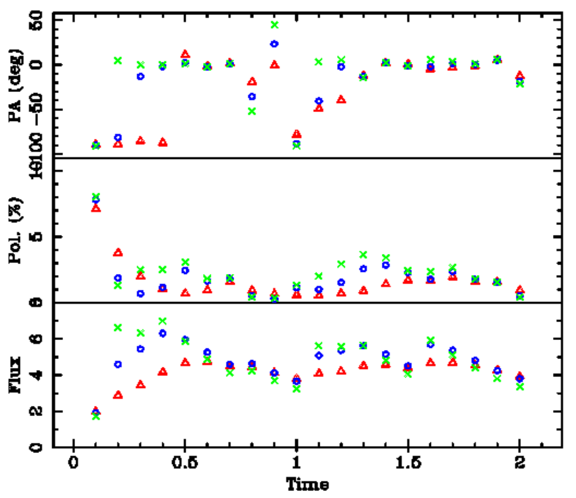
Variation in the Flow on Decadal Time Scales: OT 081

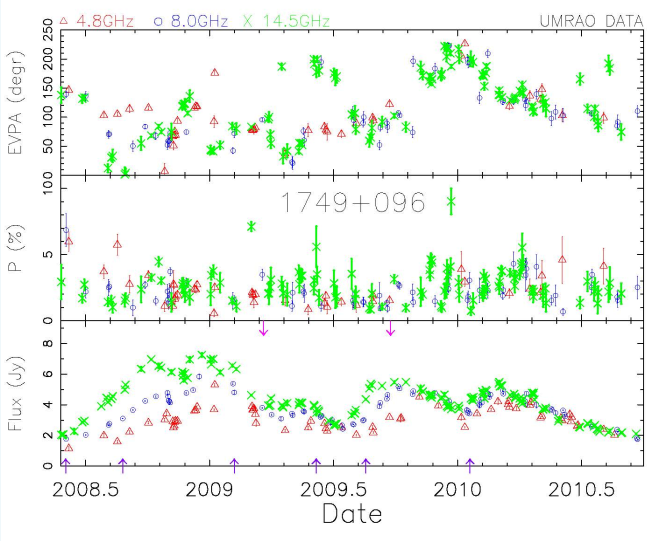


Outburst 1985.0-1986.0: Simulation for T1



Outburst 2008.4-2010.7: Simulation for T2





Features reproduced

S: spectral character and max. amplitude
P: small flare near 1984.6 & Pmax
EVPA: near constant value during most of modeled period, but variability complex

Significant changes in the flow have occurred since 1985. These cannot be reproduced by scaling.

Features reproduced

S: spectral character and maximum amplitude
P: generally low levels (under 5%)
EVPA: flat spectrum and complex variation

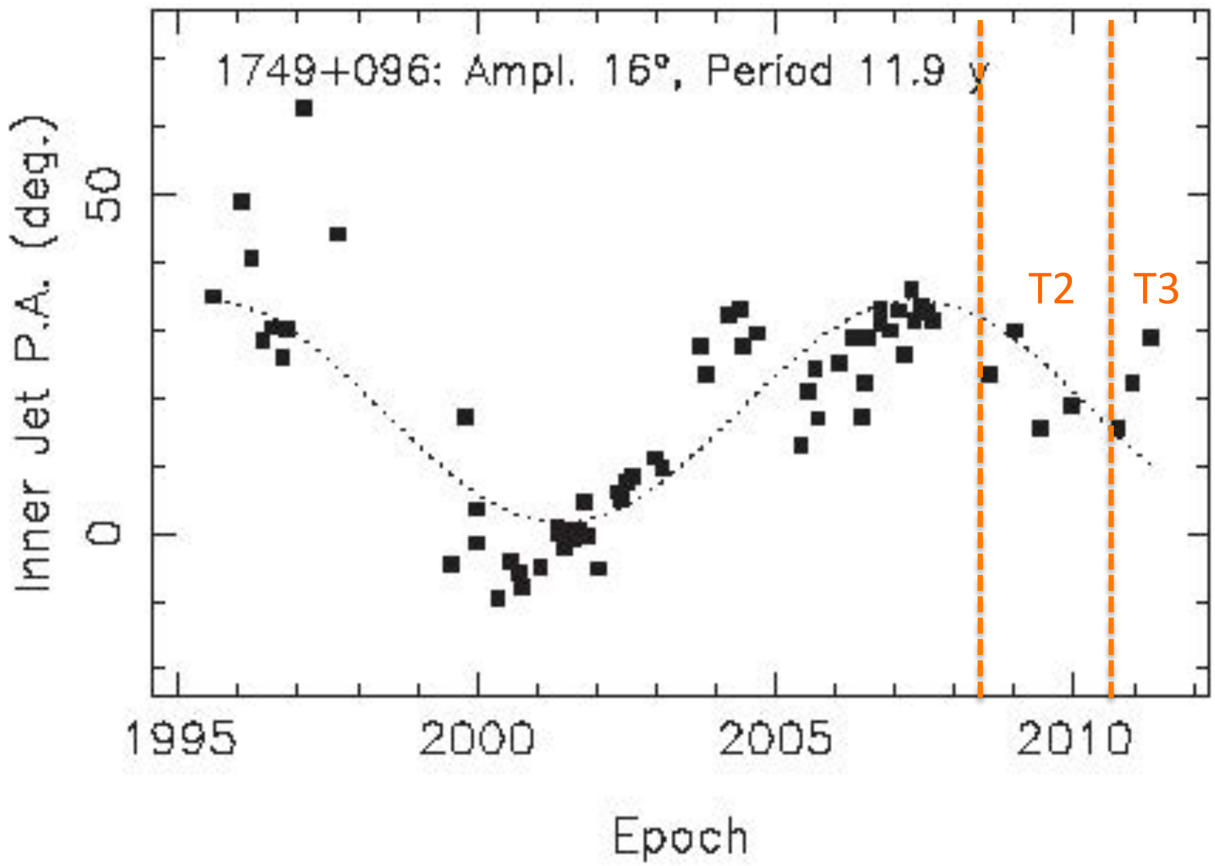
Evolution of the Flow From Modeling 3 Epochs of OT 081: Changes in Derived Parameters

Parameter	T1 (1985-1986)	T2 (2008-2010)	T3 (2011-2012)
Low energy cutoff (γ_i)	50	50	50
Axial B Field (B_z)	25%	64%	56%
Bulk Lorentz factor	5	10	10
Viewing Angle (θ)	1.7°	1.4°	1.1°
Shock Sense	F	F	F
Number of shocks	5	6	3
Shock Obliquity	90°	90°	90°
Shock Lorentz Factor	14.5	24.7	27.3
Shock $\beta_{\mathbf{app}}$	10.4	21.8	22.5

Are these temporal changes due to a difference in viewer's orientation so that different segments of the flow are seen, or are they the result of intrinsic changes in the flow??

Evidence for Changes in the Inner Jet PA from MOJAVE

15 GHz projected inner jet PA versus time



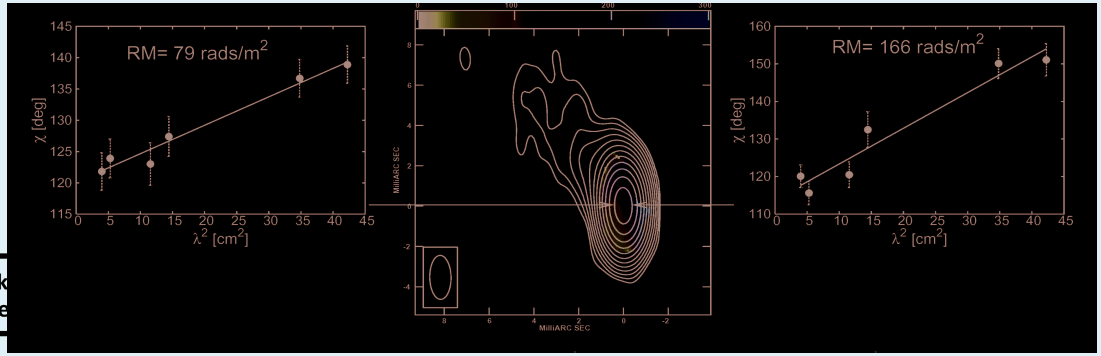
Lister et al. 2013

Projected inner jet PA versus time shows a swing through a minimum between T2 and T3 suggesting that orientation and geometrical effects play some role.

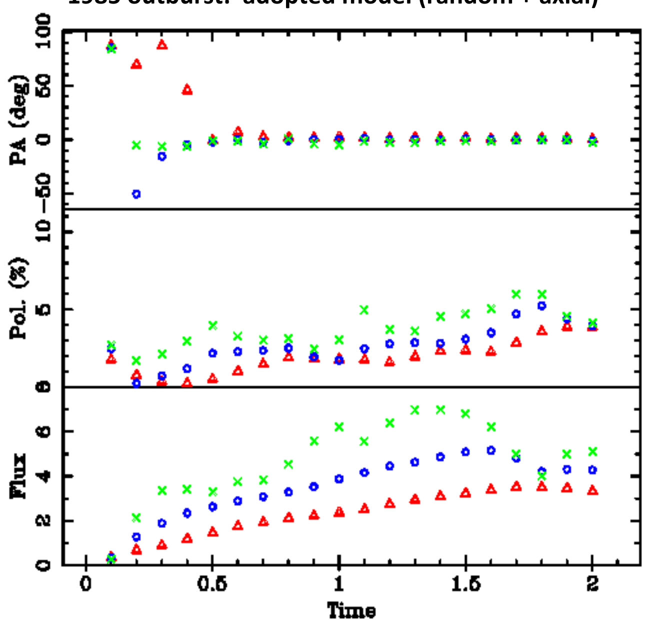
Effect on the OT 081 Simulation of Adding a Helical B Field

OT 081: the case for a toroidal/helical B field at pc scales from VLBI imaging

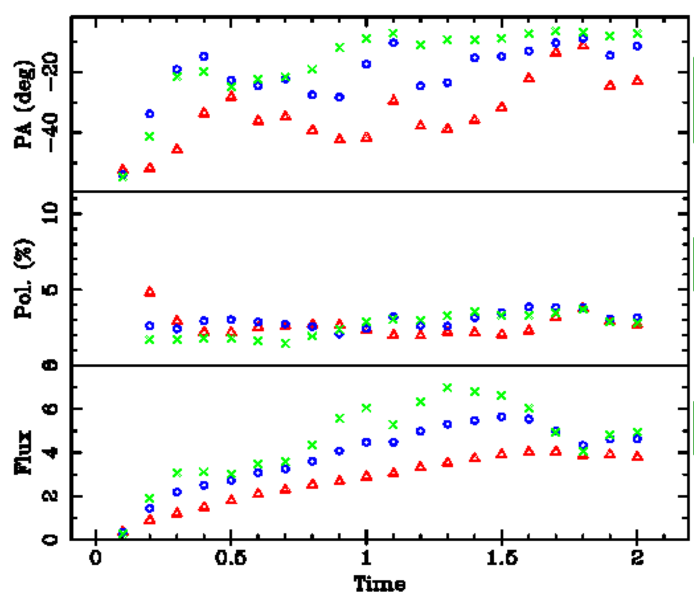
Stok
6 fre



1985 outburst: adopted model (random + axial)



1985 outburst: adopted model + strong ordered helical field (flux rope)



EVPA: spectral evolution inconsistent with UMRAO data

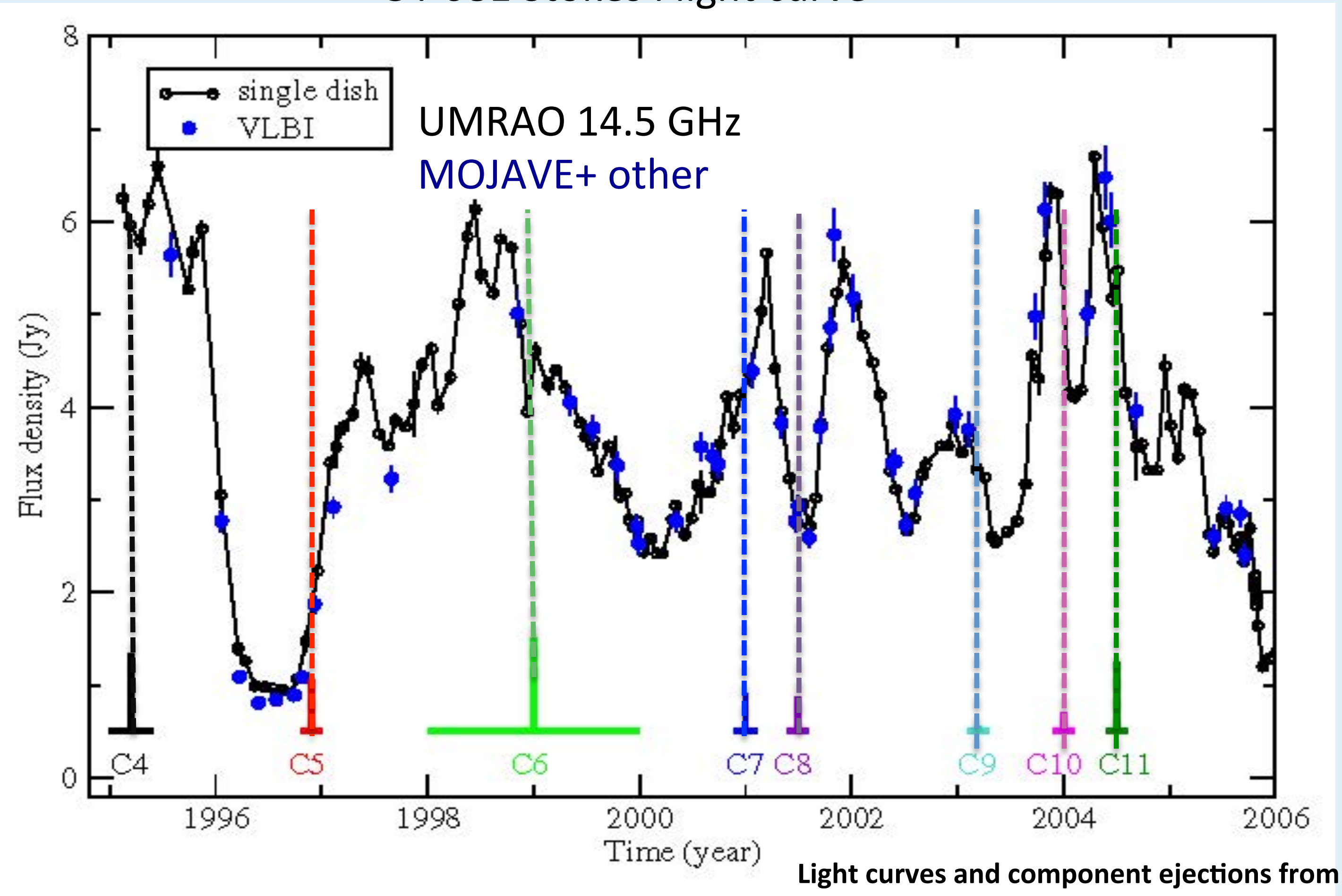
Structure suppressed in P%

Small change in S!

The B field in OT 081 is not dominated by a helical component. However, inclusion of a modest helical B field improves the fit during the 1985 flare. Inclusion of both a turbulent and an ordered helical B field are consistent with the data.

Flare Onsets/Shocks and Component Ejections

OT 081 Stokes I light curve

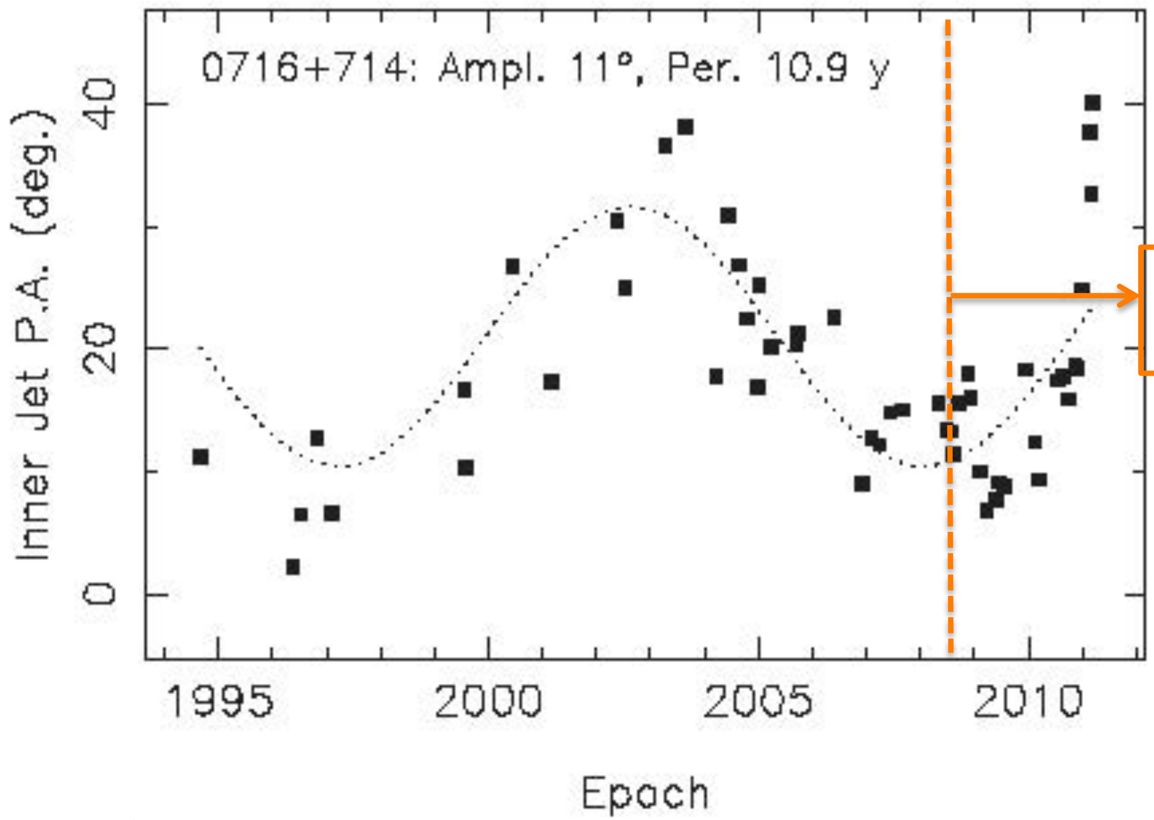


Light curves and component ejections from Lu et al. 2012

Single dish and VLBA flux densities agree, but component ejections occur at a variety of outburst phase. Are flares and component ejections physically related, and what does this tell us about the character and evolution of the flow?

Intrinsic Changes Versus Orientation

Projected inner jet PA versus time (15 GHz)



Lister et al. 2013

Time segment simulated with the **same** model parameters. (Affect of changes in θ smaller?)

Can we unambiguously distinguish intrinsic changes in the jet flow from changes in orientation?

Conclusions

- Selected outbursts exhibiting S and LP variability in centimeter-band data have successfully been fit with shock-in-jet models to obtain both the jet flow and the shock parameters.
- The primary constraint in the modeling is the spectral variability in the linear polarization.
- While simple analytic approaches can restrict the range of permissible parameters in the jet flows, detailed modeling is required to limit these ranges, especially when extreme flow conditions may exist.
- The long term UMRAO data are consistent with particle-dominated flows with an embedded, passive magnetic field containing both turbulent and ordered components, one of which may be helical in character.