Probing the inner jet structures of blazar S5 0716+714 and OJ 287 using exceptionally dense optical observations

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In Collaboration with
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Whole Earth Blazar Telescope (WEBT)

Shining from the heart of the darkness: Black hole accretion and jets,
Kathmandu, Nepal, 2016

Introduction

i. Blazar exhibit rapid variability on the timescales ranging from minutes up to days.

ii. Blazar jets aligned near line of sight Doppler boosted non-thermal emission mostly swamps the thermal emission

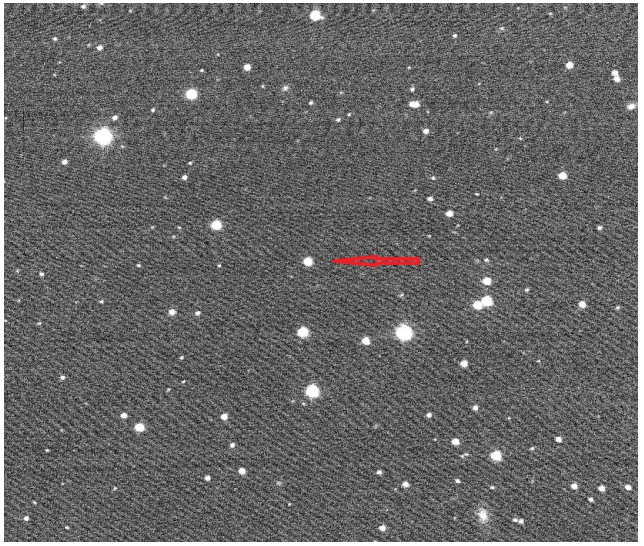
iii. Study of the Optical variability is one of the most important tools to probe the inner jet structures of the blazar.

iv. The study can be used to the constrain the internal (sub)-structure of blazar jets as well as the dominant particle acceleration processes shaping the rapid variability.

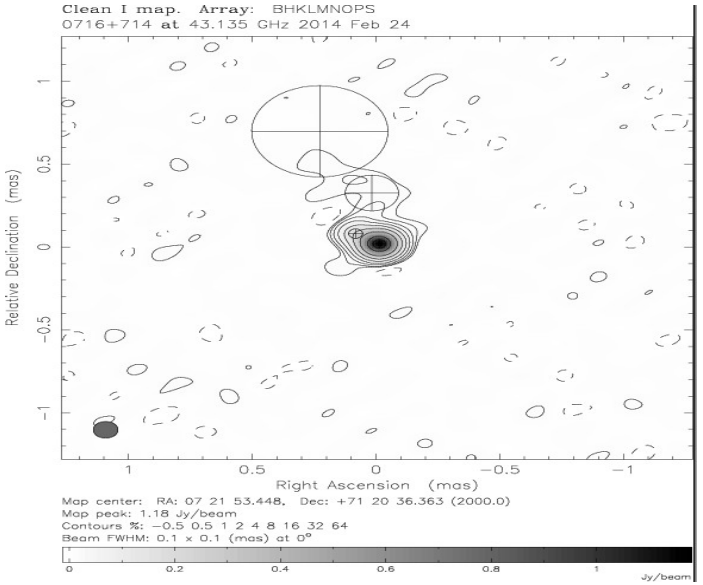
v. Using exceptionally dense sampled optical observations, micro-variability in BL Lac 0716+714 and long-term variability in OJ 287 are studied.

BL Lac S5 0716+714

- **One of the most studied sources by most of the current instruments.**
- **One of the brightest blazars located at z= 0.31 ± 0.01**
- **Bright, and highly variable (nearly 100% DC) in all frequencies (radio to gamma ray) and time scales (minutes to decades)**
- **Classified as 'Intermediate Synchrotron Peaked' IBL**
- **Superluminal radio features ejected with apparent speeds up to 37c**

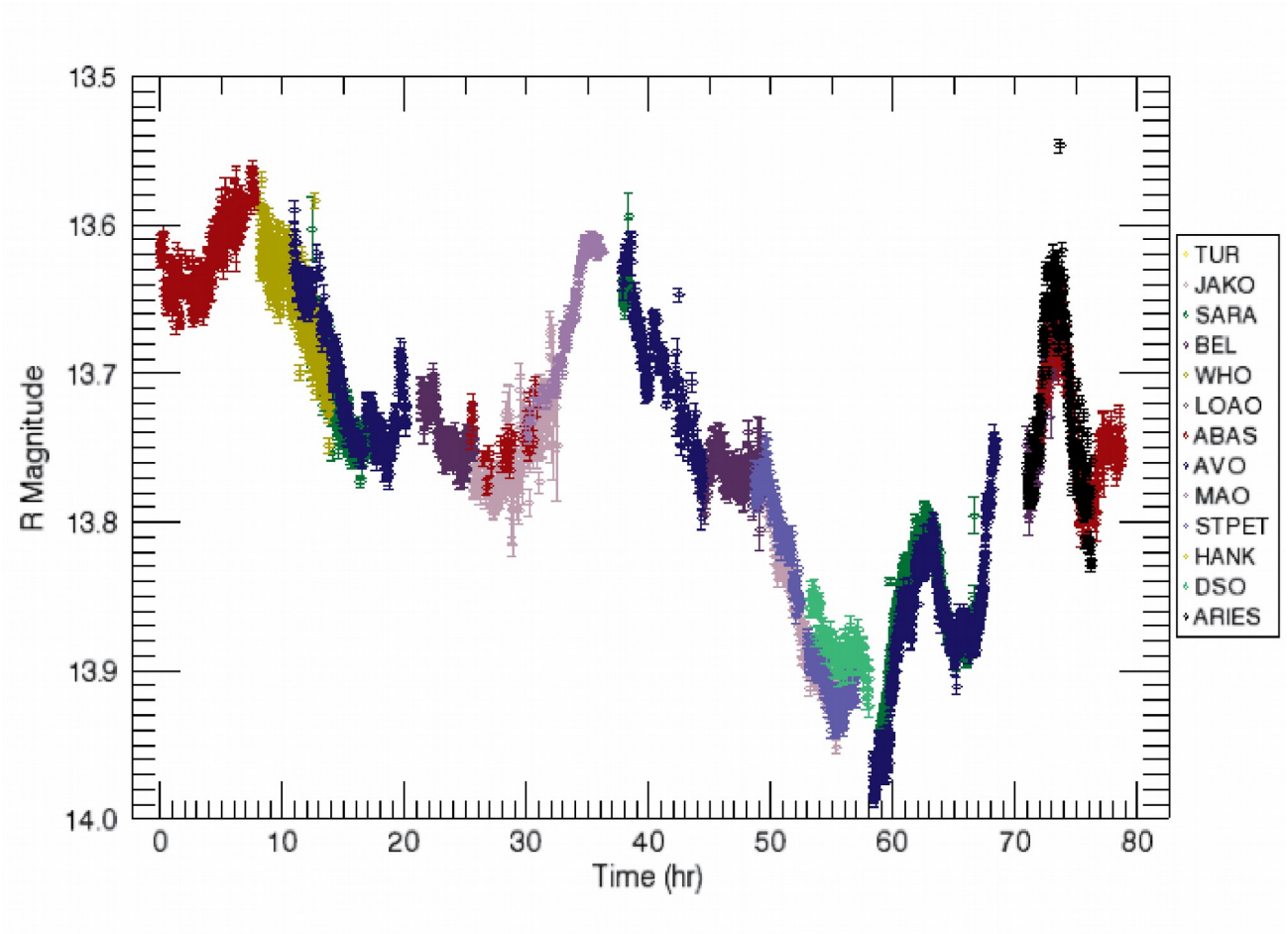


Optical CCD Image



Radio Image at 43.135 GHz on February 2014 (BU blazar group)

2009: Multi-site WEBT Campaign in the Optical



Statistics

Length of Campaign...7. hrs.

Mean Magnitude (R).....13.75

Faint Magnitude (R).....13.96

Bright Magnitude (R).....13.57

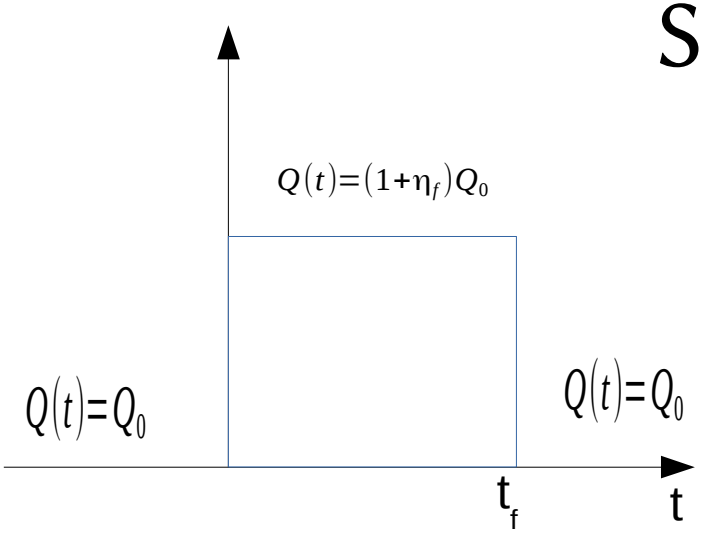
Amplitude (mag).....0.31

Standard Deviation 0.09

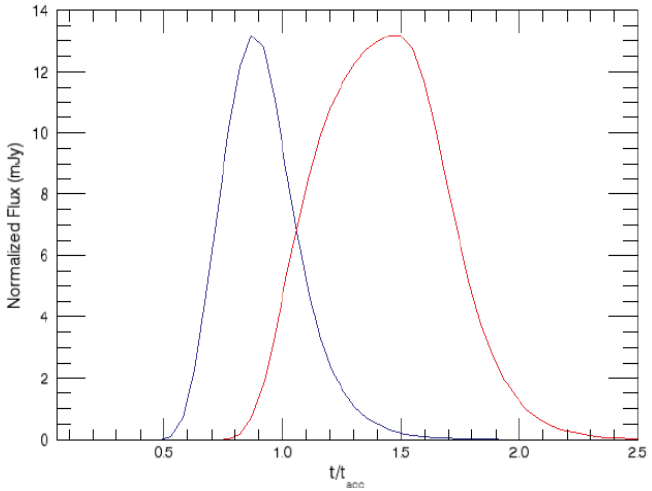
Standard Deviation (NV)....0.017

Bhatta et al. 2013 A&A, 55A, 92B

Modeling the Light Curve as a Convolved Synchrotron Pulses

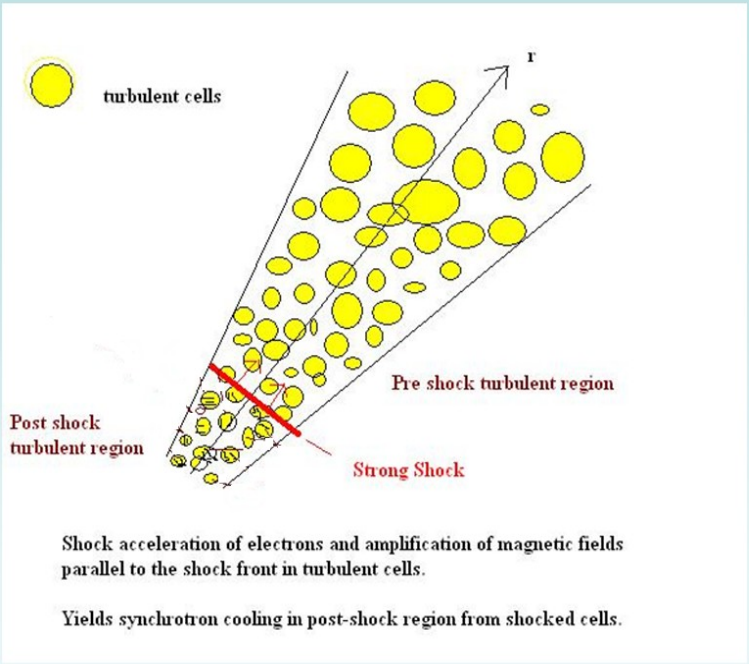


Shot-noise type particle injection



The resulting pulse shapes for frequencies $4.3X10^{16}$ (blue) and $4.3X10^{17}$ Hz (red)

Turbulent Synchrotron Sources Energized by a Plane Shock



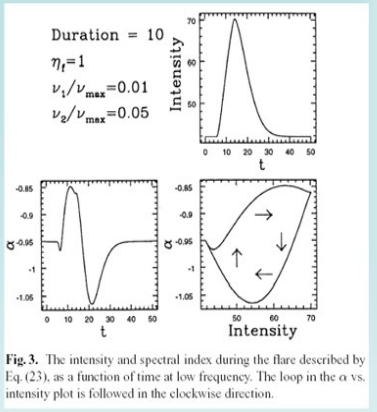
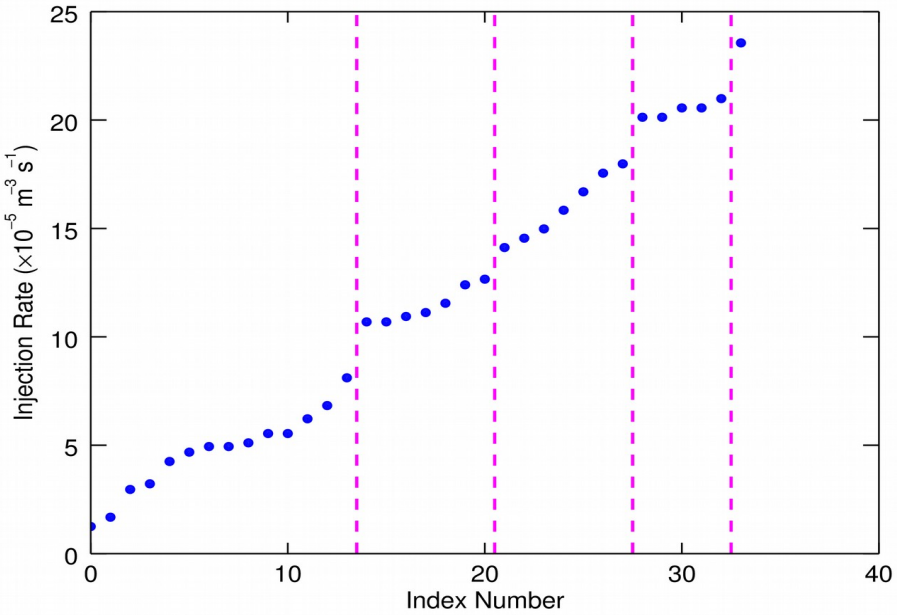
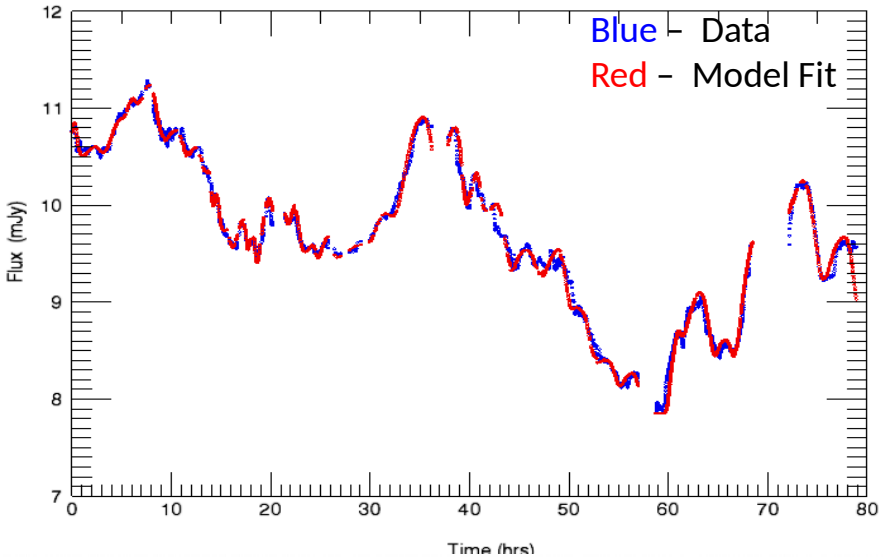


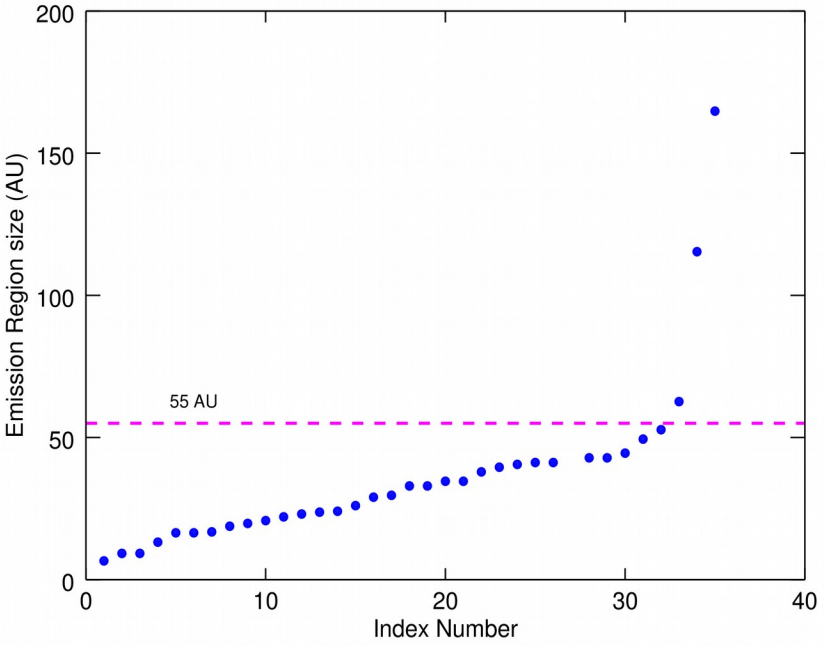
Fig. 3. The intensity and spectral index during the flare described by Eq. (23), as a function of time at low frequency. The loop in the α vs. intensity plot is followed in the clockwise direction.

Figure 3 **above is taken from *Kirk et al. (1998)*. This top right panel shows the time dependence of the intensity of a cylindrical source.**

Results:Particle Injection Rate and Emission Region Distribution



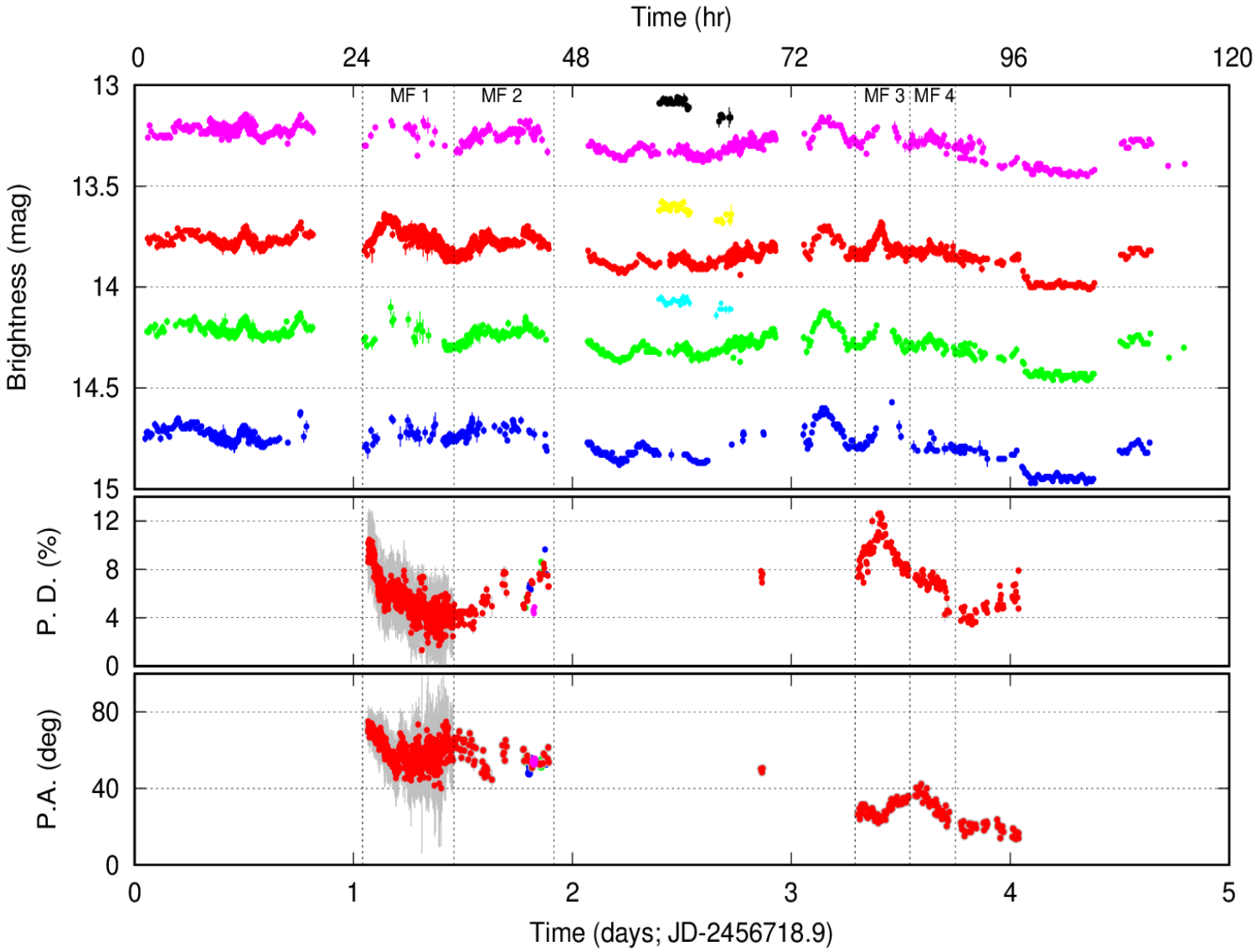




Possibly discrete injection rates in the particle acceleration ?

Turbulent regions of smaller size dominate the emission site in the jet

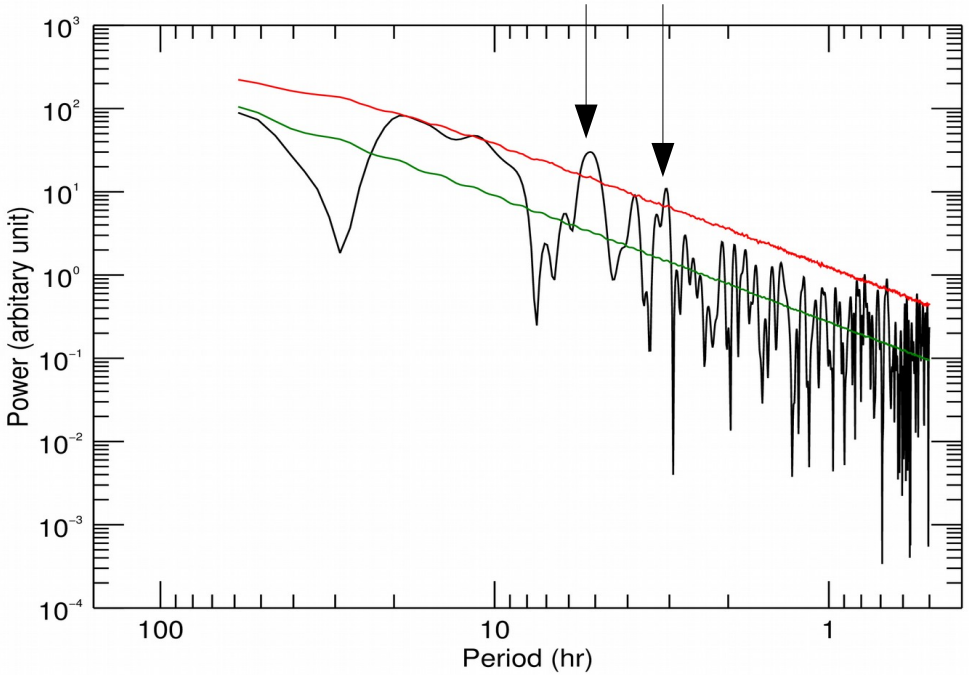
2014: 5-day Multi-frequency photo-polarimetric WEBT Campaign



Bhatta et al. 2016 ApJ

Periodicity search and red-noise PSD

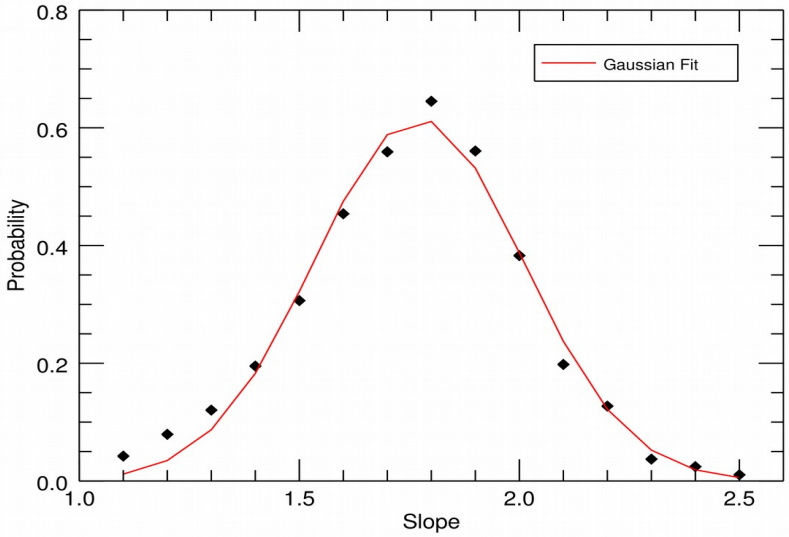
5 h 3 h



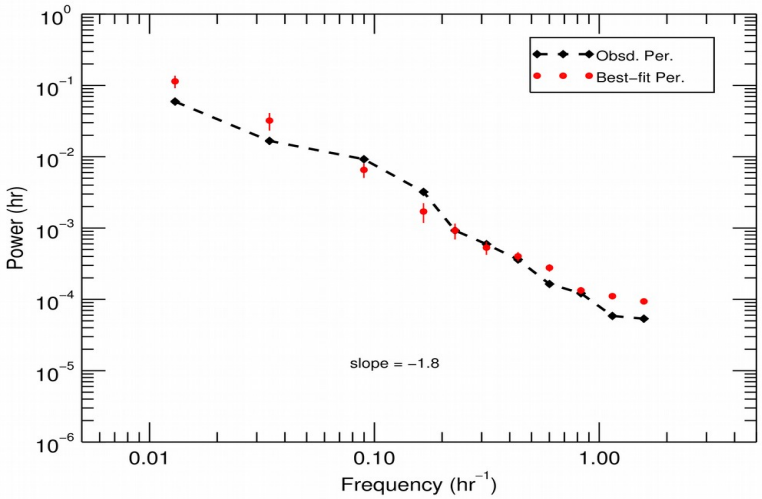
Lomb-Scargle periodogram (black), mean simulate periodogram (green) and 99% confidence contour from the simulations (red)

Hints for the presence of quasi- periodic oscillations at timescales of 3 h and 5 h were seen.

PSRESP: Uttley et al.(2002)

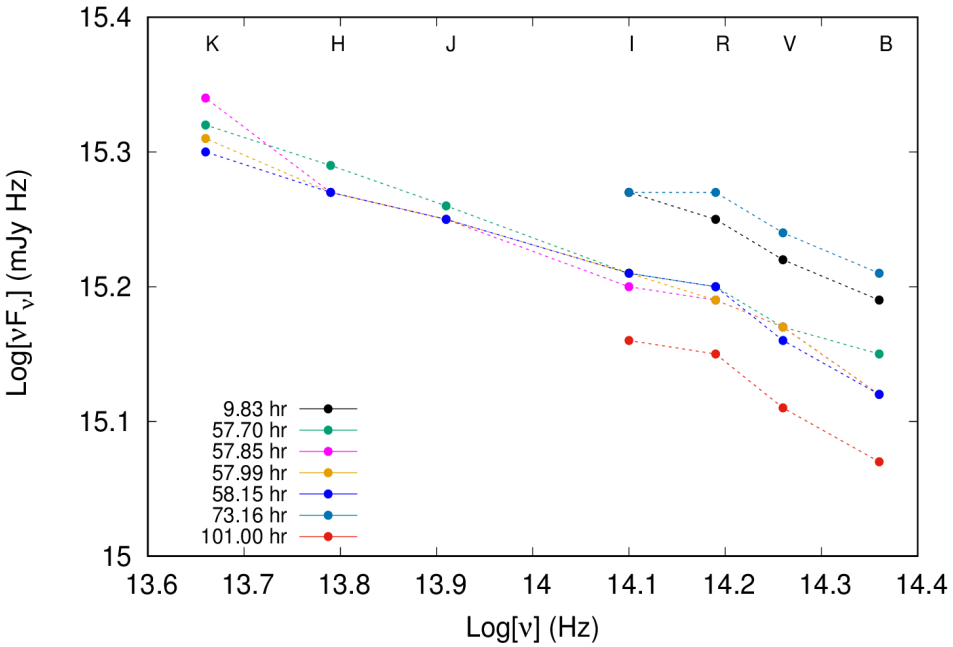


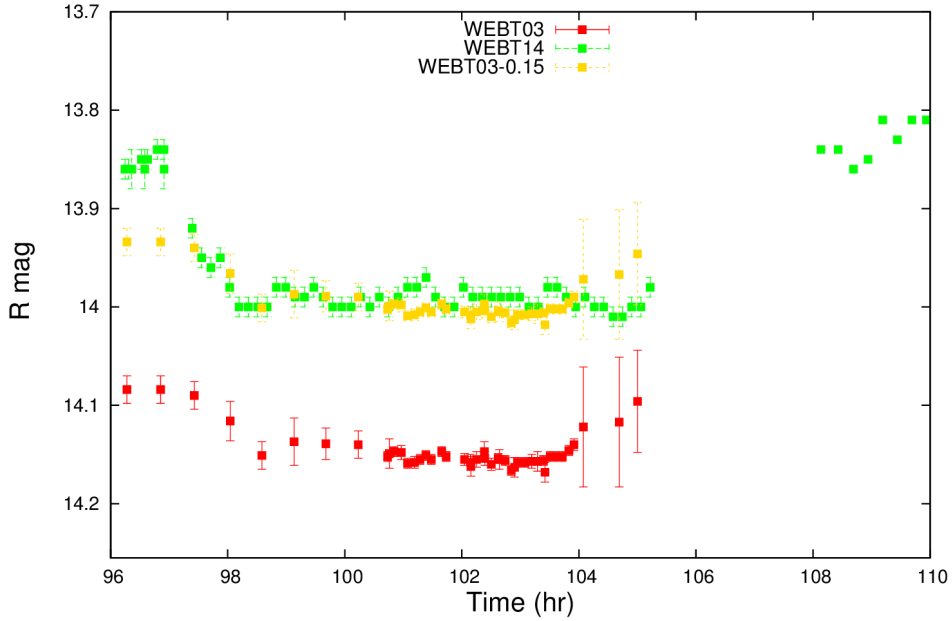
Probability that the power-law slope is acceptable



Binned PSD and the best-fit model

The Plateau - Jet Activity Choked ?





The optical spectra during the campaign.

Keplerian Period around the ISCO

$$\tau_K = \tau_g \left(\frac{r_{isco}}{r_g}\right)^{3/2} \simeq 500 \left(\frac{\mathcal{M}}{10^8 M_\odot}\right) \left(\frac{r_{isco}}{r_g}\right)^{3/2} \text{ s}$$

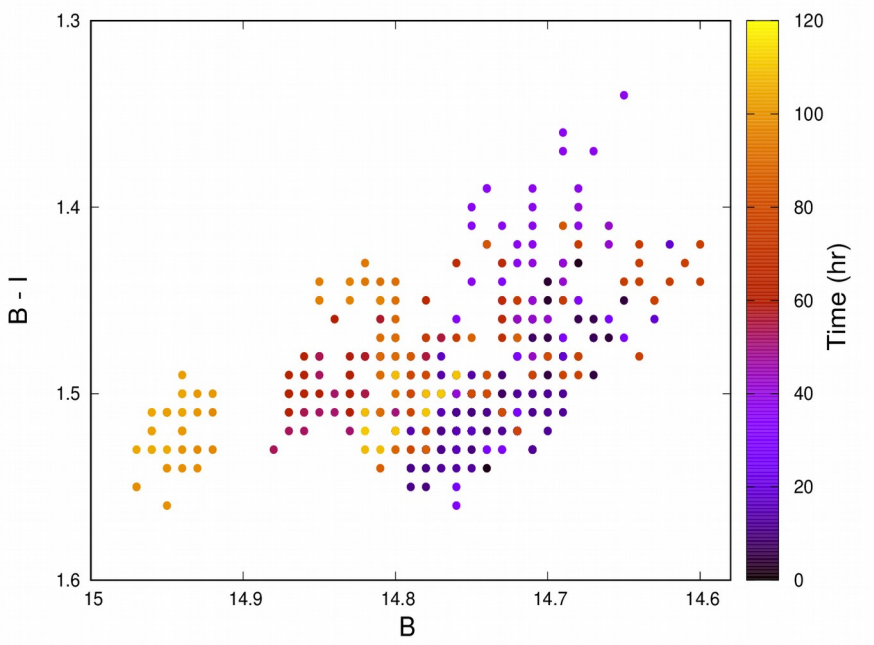
$$\tau_g = r_g/c = G\mathcal{M}/c^3$$

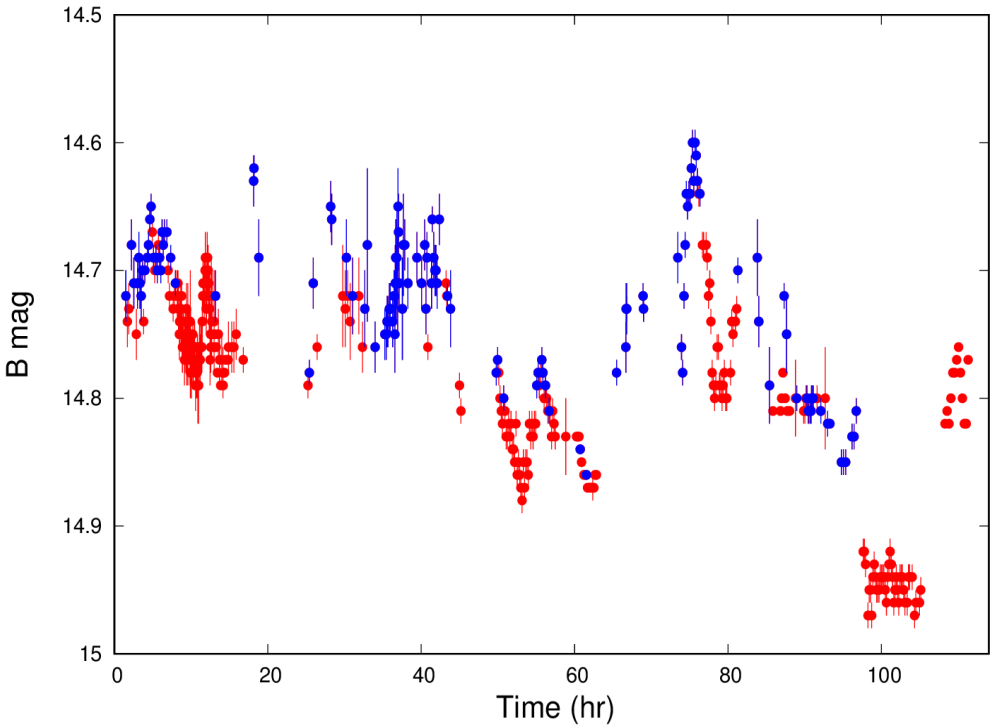
This could be result of temporarily suppressed flow at the jet base !!

$\mathcal{M} \simeq 3 \times 10^8 M_\odot$ assuming very low spin values ($r_{isco} \simeq 6\, r_g$)

Color Variability: Achromatic Behavior

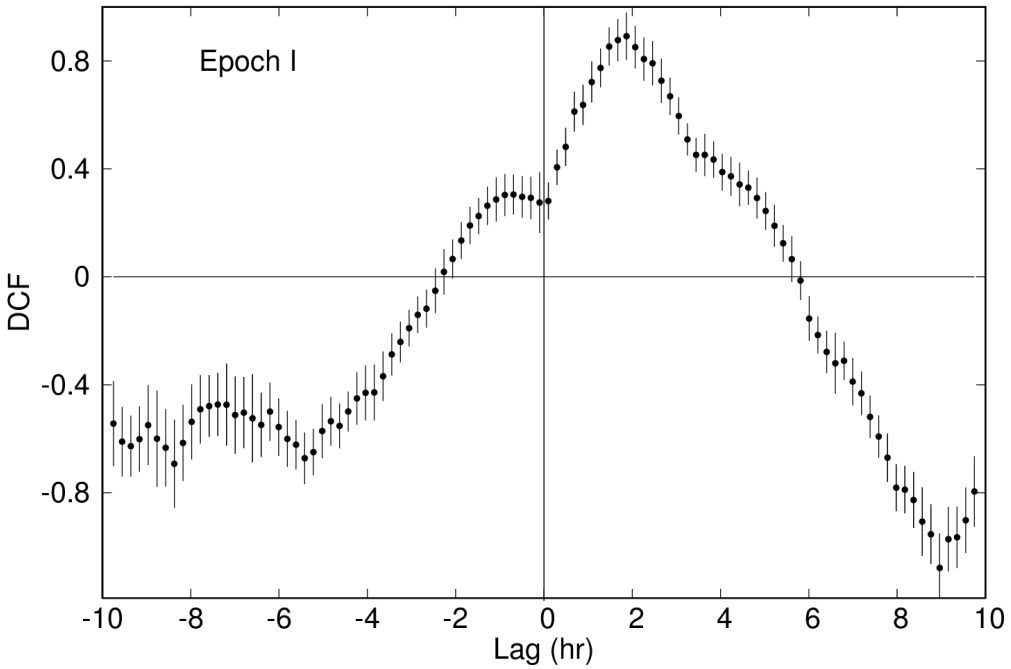
B- and I-band emission are highly correlated at large with a small possible lead of HE emission over LE emission

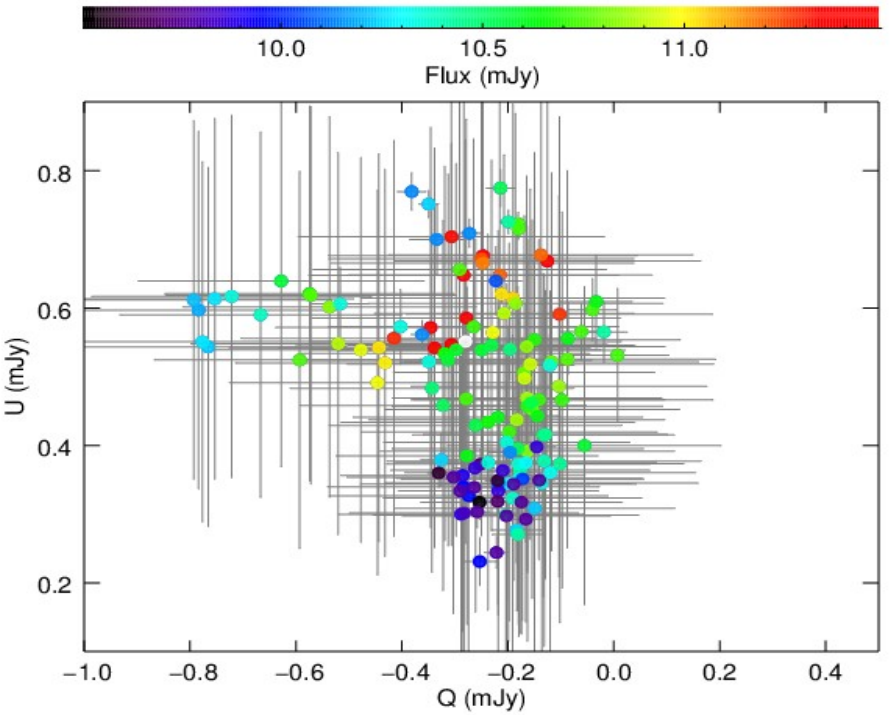




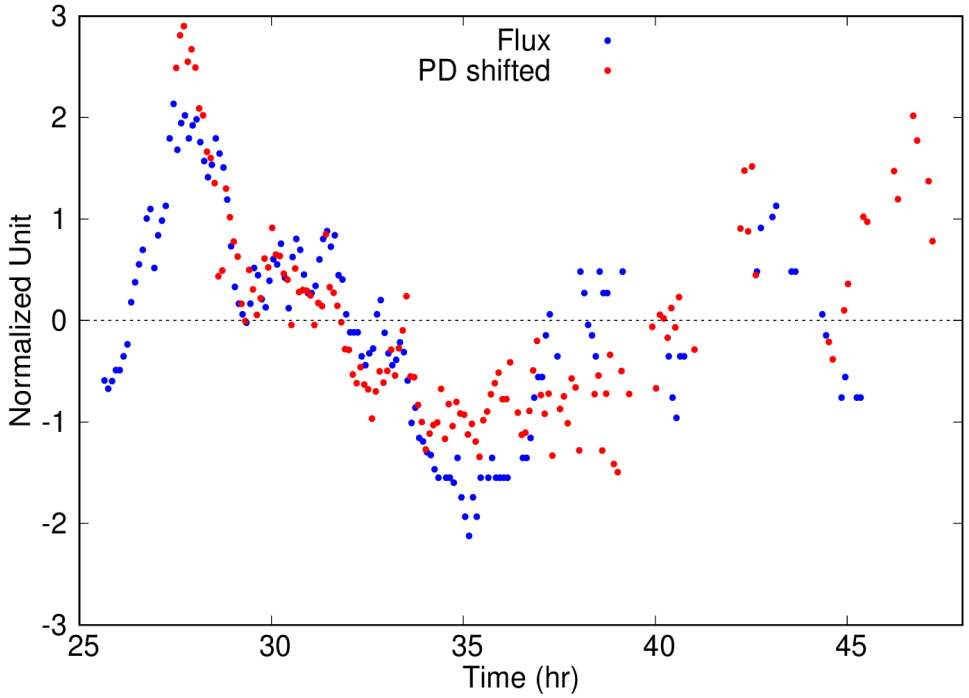
"Bluer-when-brighter" trend was observed in the color-magnitude diagram (lower left) and in the B-band light curve color coded with high (blue) and low (red) color value (above).

Epoch I:Flux-PD-PA Correlation



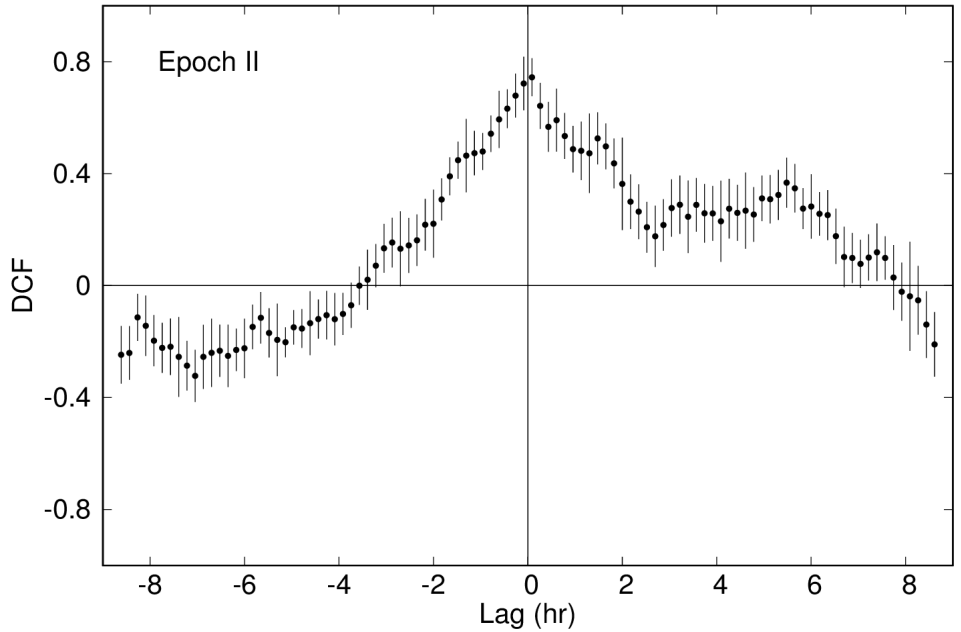


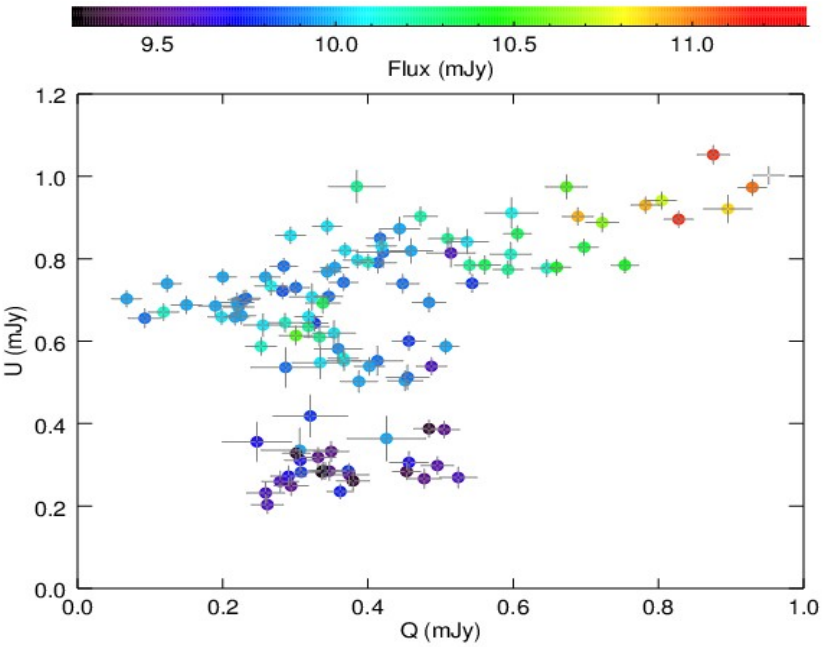
The evolution of Stokes parameters Q and U during Epoch I



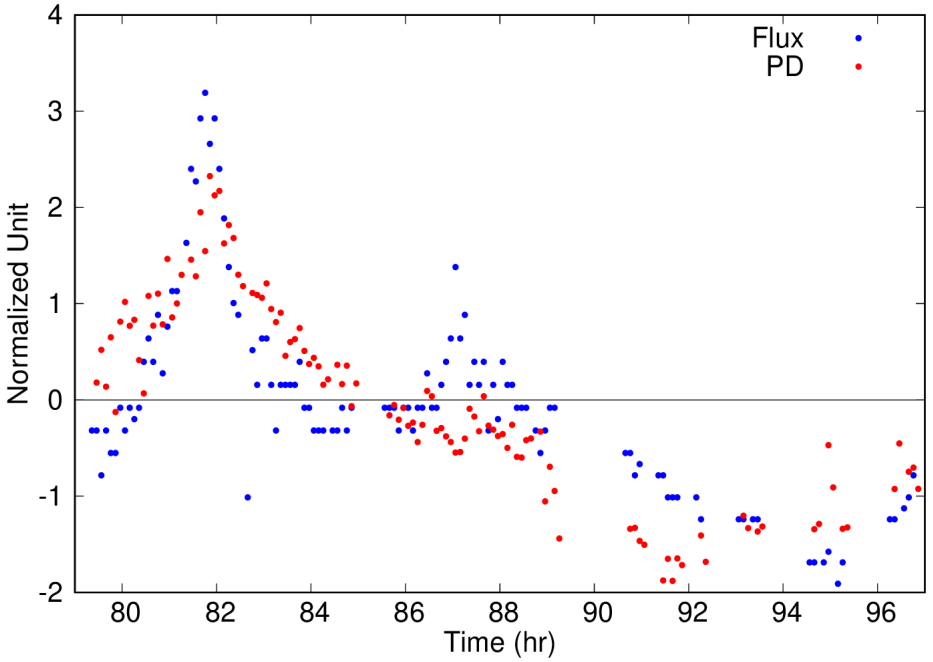
The discrete correlation function between flux and PD shows flux lagging behind PD by 2 hrs (above). It can be also be seen in normalized flux and PD shifted by 2 hrs (below)

Epoch II: Flux-PD-PA Correlation



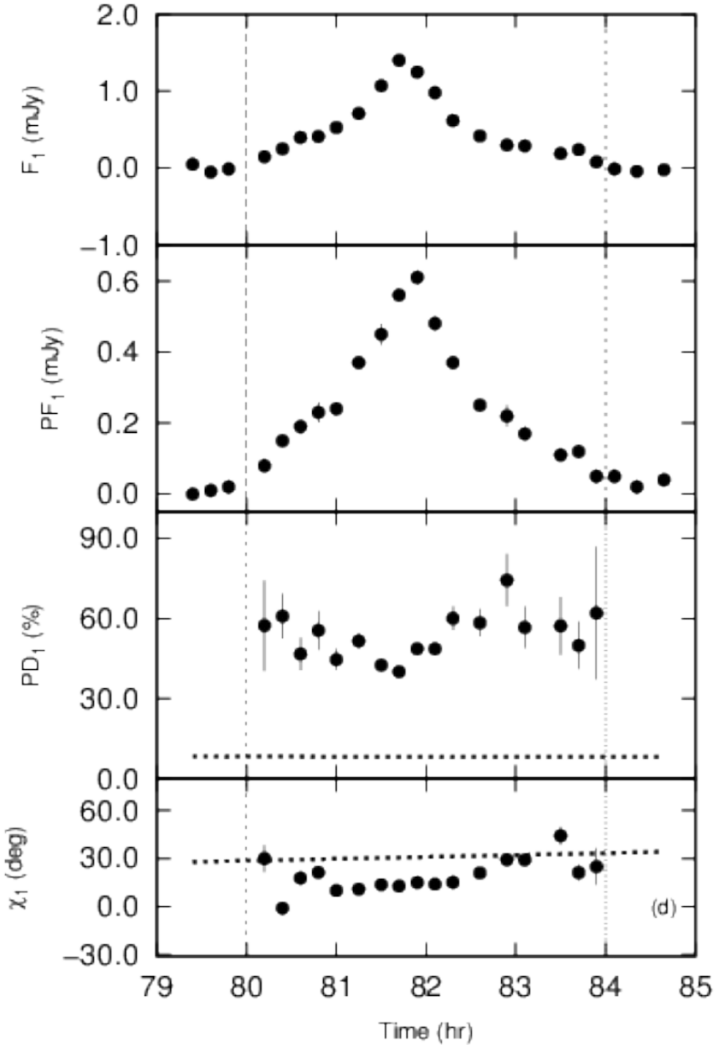


The evolution of Stokes parameters Q and U during Epoch II

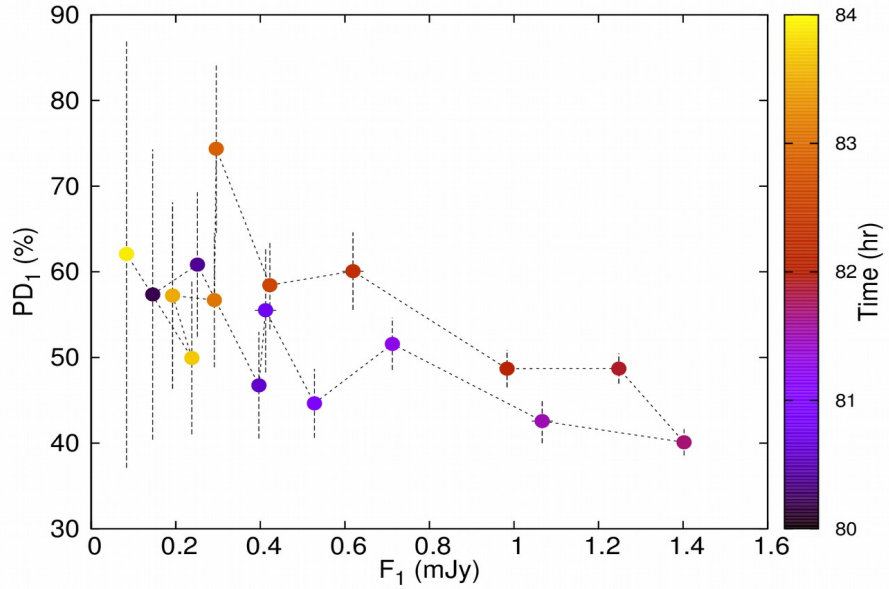


The discrete correlation function between flux and PD showing high correlation (above). It can be also be seen in normalized flux and PD (below).

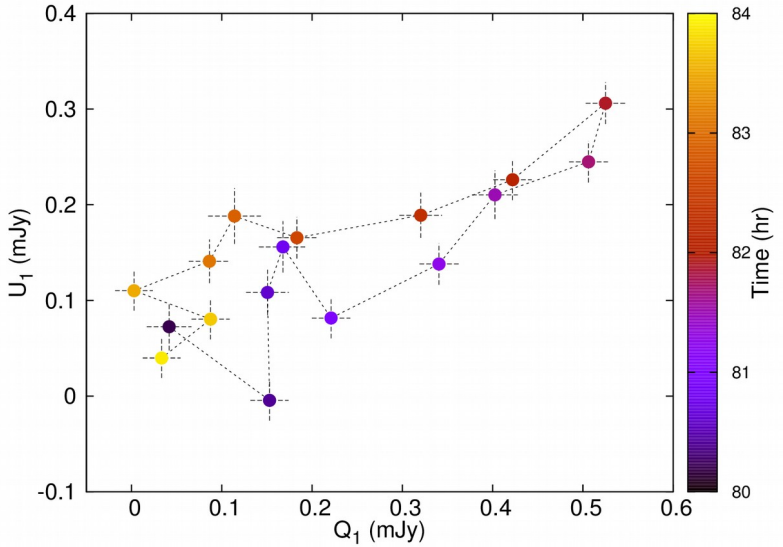
Modeling of Individual Microflares



The modeling shows presence of highly polarized microflares during the campaign



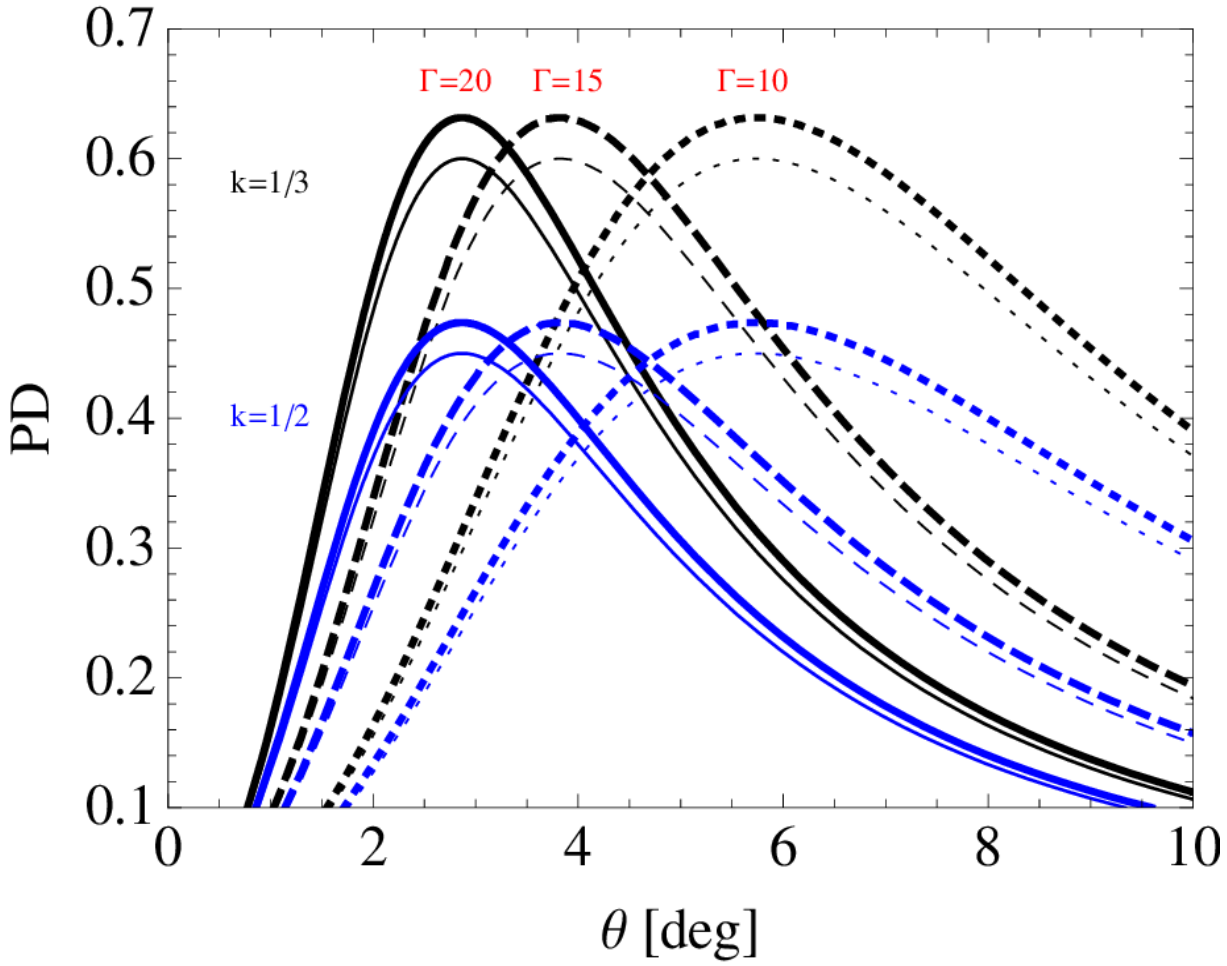
The modeled flux and PD for the flaring component appear in anti-correlation



The flaring component exhibits loop-like behavior in the Q-U plane

Bhatta et al. 2015, ApJL, 09, L27

Could it be shocks ?



$$PD = \frac{3+3\alpha}{5+3\alpha} \frac{\delta^2\left(1-k^2\right)\sin^2\theta}{2-\delta^2\left(1-k^2\right)\sin^2\theta}$$

Highly polarized microflares showing anti-correlation between flux and PD, could be explained as the result due to variation in the angle with the line of sight.

0716+714 Summary

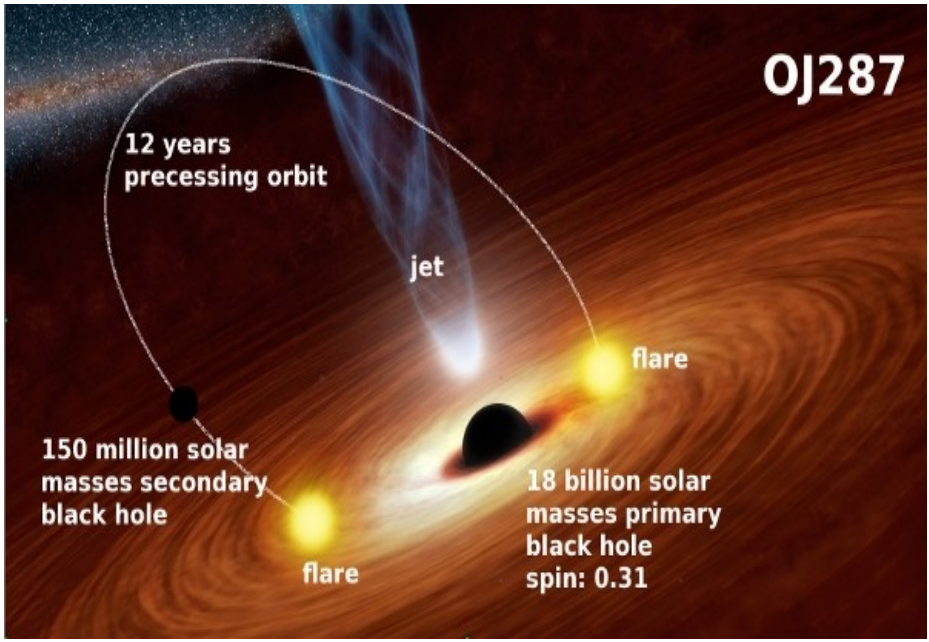
I. The overall variability of 0716+714 is of the red noise type (consistent with a random-walk process).

II. In 0716+714, hints for quasi-periodic oscillations at timescales of ~3h and ~5h were found as well, though there are indications that they do not represent highly significant departures from a pure red-noise power spectrum. Whereas in OJ 287 a quasi-periodic oscillation with a period of ~400 days was found.

III. The observed optical flux is produced in compact emission sites within the outflow, with range of sizes and range of distances from the core;
- only sometimes polarization properties reveal any coherence in the magnetic field evolution (e.g. PD leading the total flux changes, hysteresis in the PD-F plane, large PA swings, etc.).

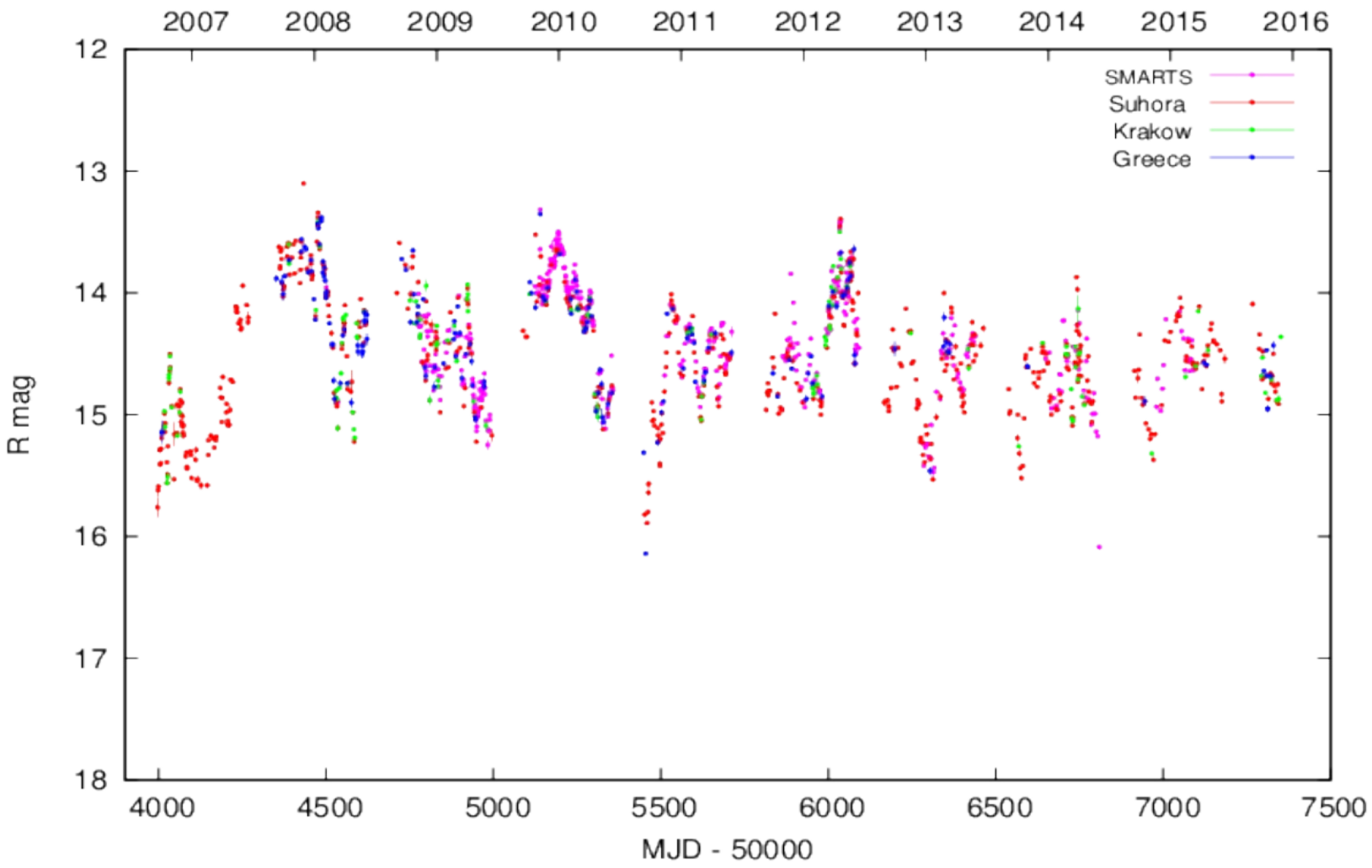
IV. Compact emission sites in 0716+714 jets may be identified with either turbulent cells, merging magnetic island related to magnetic reconnection, or small-scale internal shocks.
- only a further systematic investigation of flaring polarization properties and statistics (duty cycle, sell size distribution, etc.) may help to distinguish between the above mentioned possibilities

OJ 287



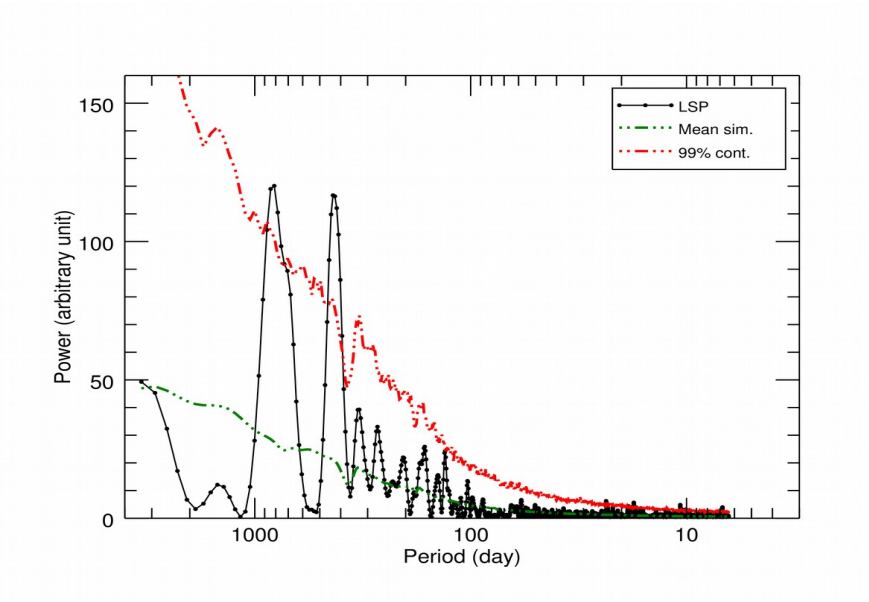
- **One of the brightest blazars located at z= 0.306**
- **Exhibits double-peaked optical outbursts repeating every ~ 12 yr .**
- **The only blazar modeled as a binary black hole system**
- **A number of the quasi-periods of similar timescales have been claimed in radio, NIR and gamma-rays previously.**
-
- **Besides, 65 years, 12 years, 50 days quasi-period are claimed for the source**

OJ 287 ~9 Yrs Light Optical Curve

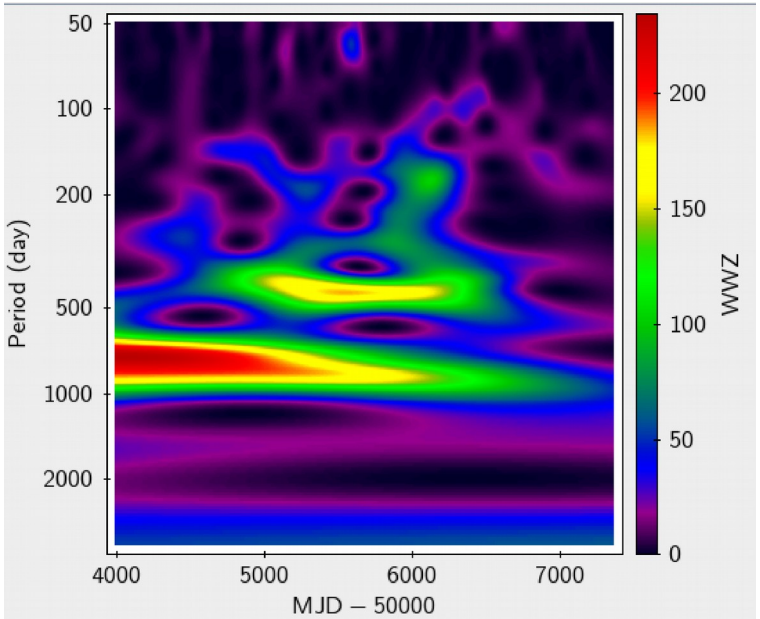


Bhatta et al. 2016 ApJ

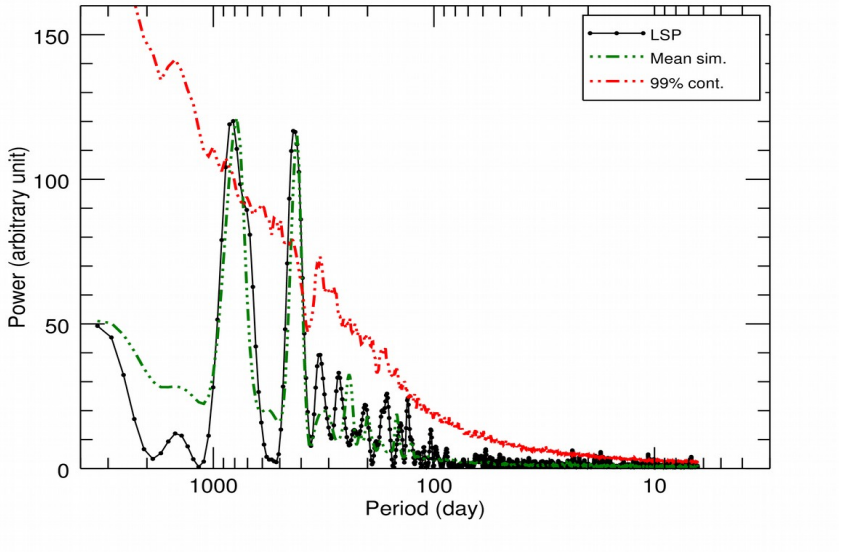
LSP and WWZ Revealed 400 day QPO



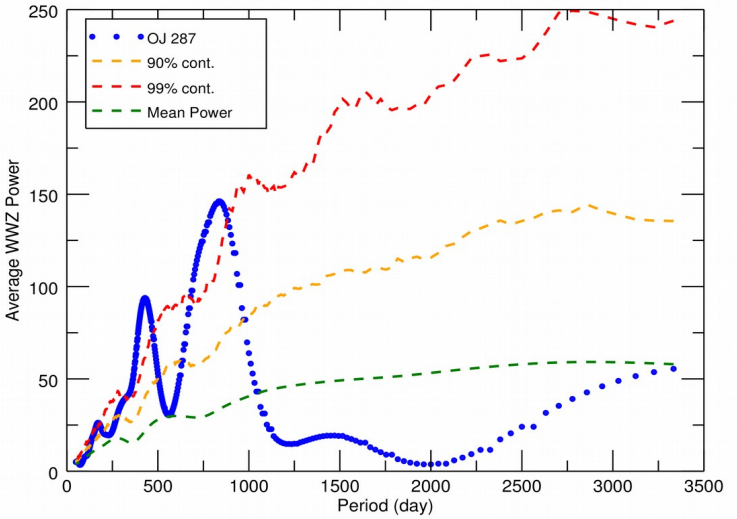
Source LC Lomb-Scargle Periodogram



Z-transformed weighted wavelet



Simulated LC Lomb-Scargle Periodogram



OJ 287 Summary

I. A study of ~9 yrs exceptionally dense observations carried out.

II. Lomb-Scargle periodogram and weighted wavelet transform methods revealed a ~400 day quasi-period with possible harmonics of ~800 days

III. A number of likely scenarios trying to explain quasi-period are discussed in the literature, e.g. binary black hole, jet precession, wobbling jet, Lense-Thirring precession of the innermost parts of accretion disks etc.

IV. Jet modulation by the innermost parts of the accretion disk could also be the likely scenario.


धन्यवाद
Thank You