MULTI-FREQUENCY BLAZAR MICRO-VARIABILITY AS A TOOL TO INVESTIGATE RELATIVISTIC JETS

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ABSTRACT

- We have observed micro-variability in a sample of 15 Blazars during 164 nights over 12 years.
- The intermittency, the stochastic nature, and the similar profile shapes seen in micro-variations at different times and in different objects have led us to a possible model to explain the observed behavior.
- The model is based on a strong shock propagating down a relativistic jet and encountering turbulence.
- By fitting these “pulses” to micro-variability observations, we obtain excellent fits to actual micro-variations and are looking for spectral index changes as a function of pulse duration predicted by the model.

THE FLORIDA INTERNATIONAL UNIVERSITY BLAZAR GROUP

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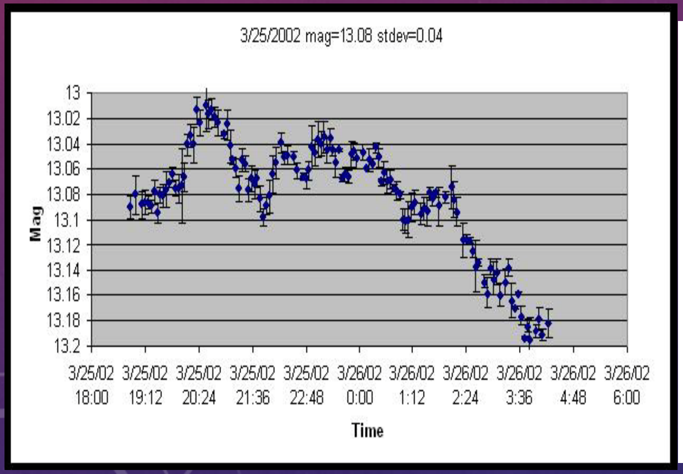
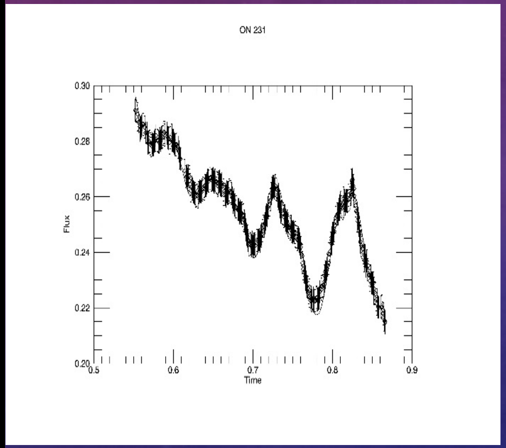
DEFINITION OF MICRO-VARIABILITY

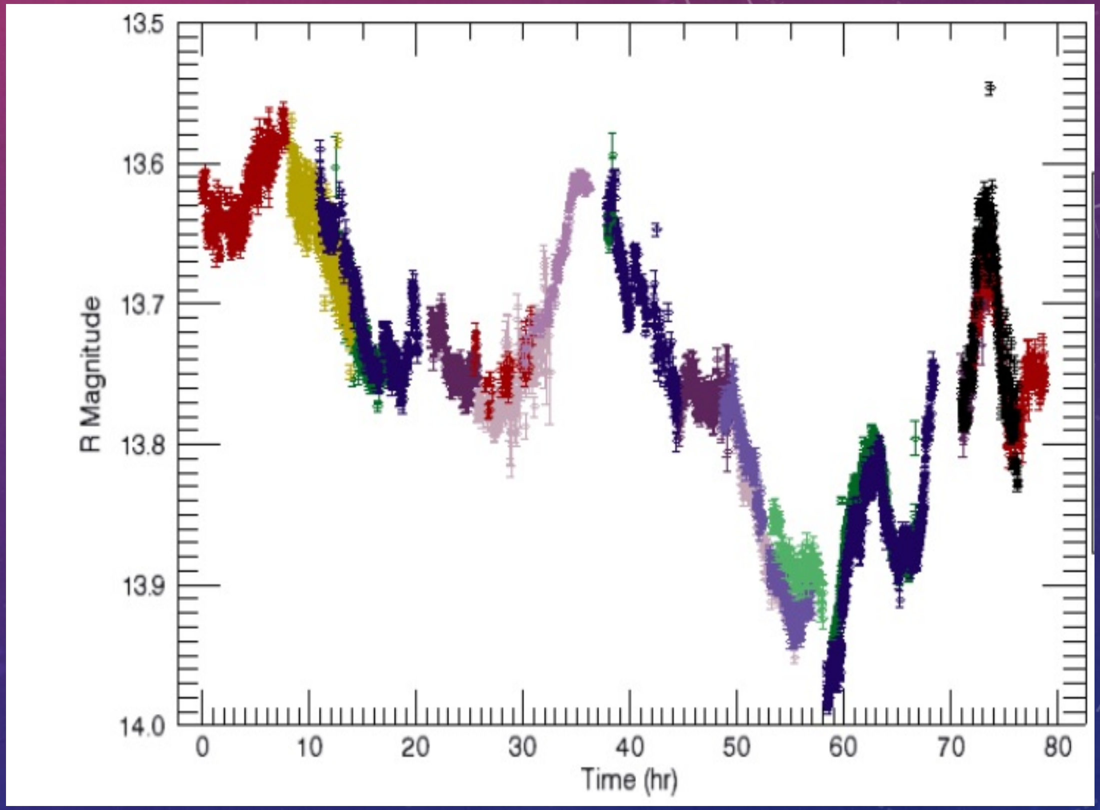
- Rapid, low amplitude ***non-linear*** variations in optical fluctuations in a single night.
- Timescales: a few minutes < Dt < hours
- Amplitudes: 0.01 < Dm < .1 magnitudes



Montagni et al., 2006, A&Ap, 451, 435.



Pollock private communication



Bhatta et al., 2013, A&Ap, 558, A92.

POSSIBLE EXPLANATIONS OF MICRO-VARIABILITY

Extrinsic:

- Interstellar scintillation?
  No: timescale too rapid & two telescopes should see different waveforms. (Habibi et al. A & Ap 552, 2013)

Detector effects:

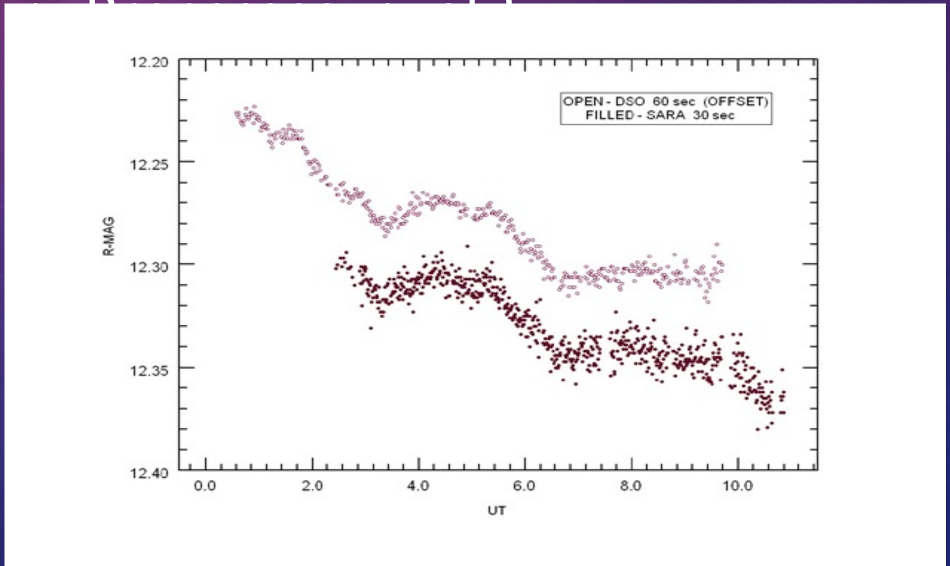
- Two telescopes should see different micro-variations.

Two telescopes see the same micro-variations: Pollock, Webb and Azarnia

Intrinsic

- Disk Processes? – Looking at Blazars where jet luminosity dominates so concentrate on jet processes.

- Processes in jet?



Ref: Pollock, Webb, Azarnia, 2007, AJ, 133, 487.

THE SOUT
RESEARC

1 meter with ARC CCD
filters (KPNO)

Lowell 2
CCD + fi

24-inch ACE reflector
w/FLI Max Cam CCD
and complete filter
set. (FIU MMC)

JKT 1 meter with ANDOR
CCD + filters (ORM)

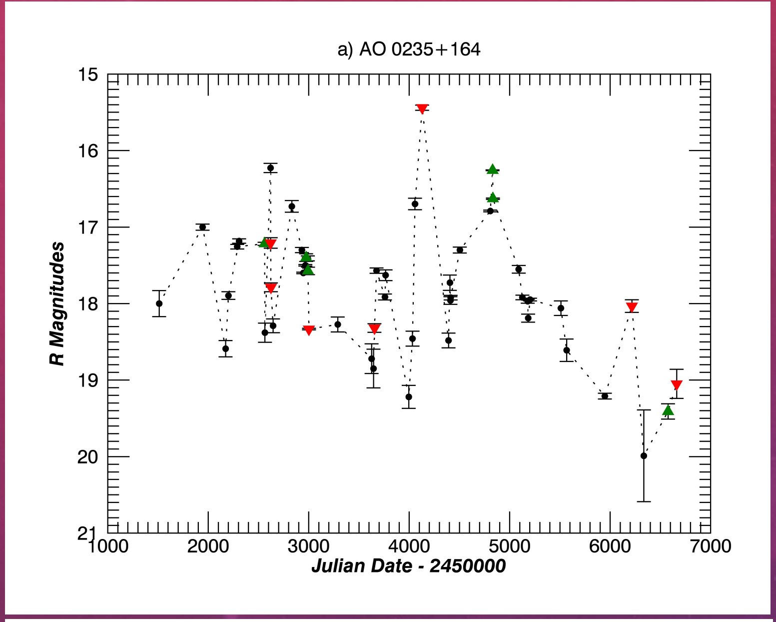
OBSERVATIONS

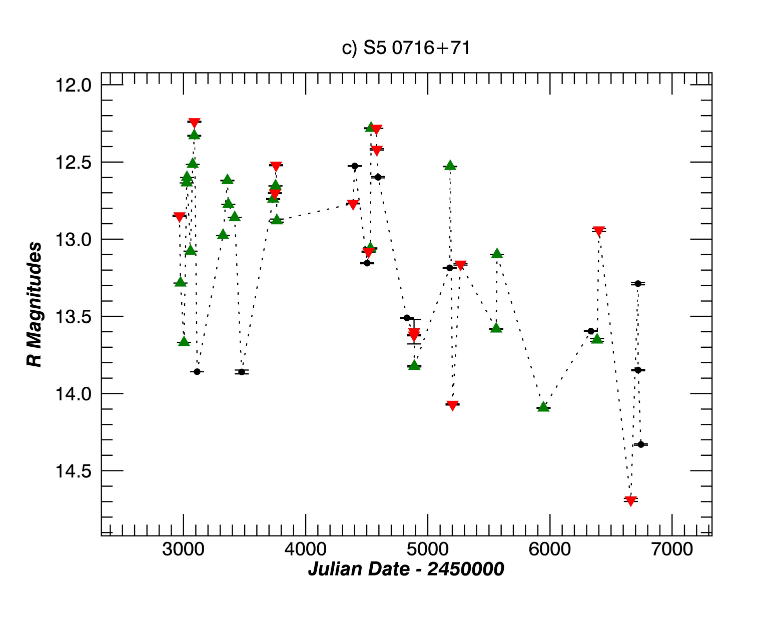
Object	Type	Redshift	Nights Observed	Micro Runs	Duty Cycle
AO 0235+164	Bllac	0.940	59	14	54.66
PKS 0420-01	OVV	0.916	31	10	15.97
S5 0716+71	Bllac	0.300	47	36	85.93
0735+017	Bllac	0.424	15	2	00.00
0736+017	OVV	0.189	4	3	11.29
OJ 287	Bllac	0.306	28	17	49.00
PKS 1156+295	OVV	0.725	16	6	50.99
3C 273	QSO	0.158	5	2	25.28
3C 279	OVV	0.536	28	9	61.07
1510-1	OVV	0.360	13	8	64.70
3C 345	OVV	0.593	31	12	33.83
ON 231	Bllac	0.102	4	3	29.87
3C 454.3	OVV	0.859	9	7	56.54
BL Lac	Bllac	0.068	77	31	54.73
3C 446	OVV	1.404	20	4	42.86

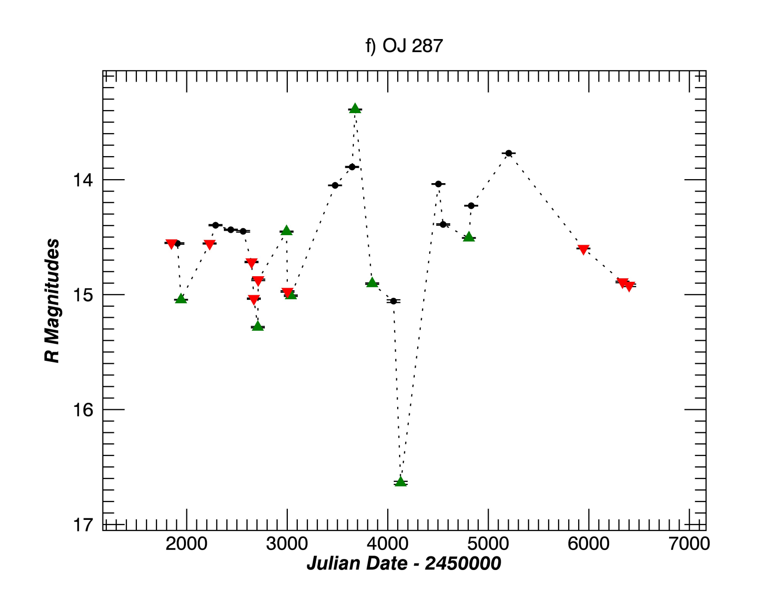
FIU-SARA OBSERVATIONS

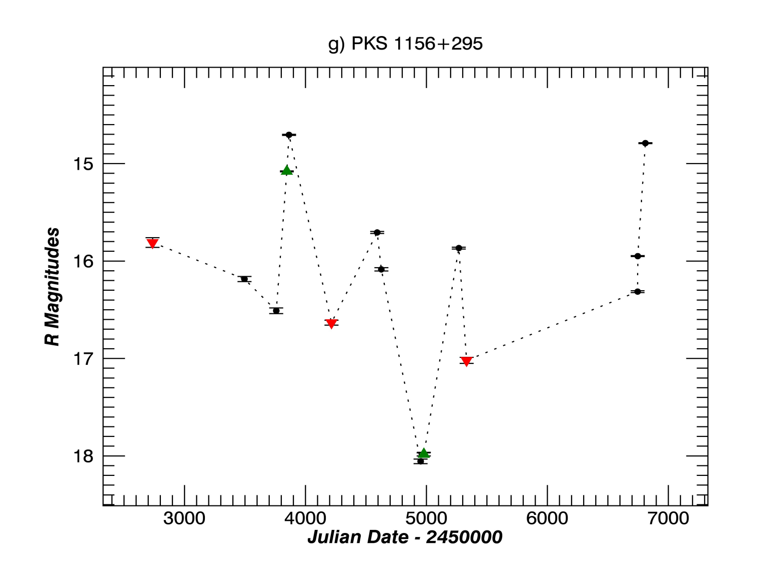
Indicates microvariablity detected that night

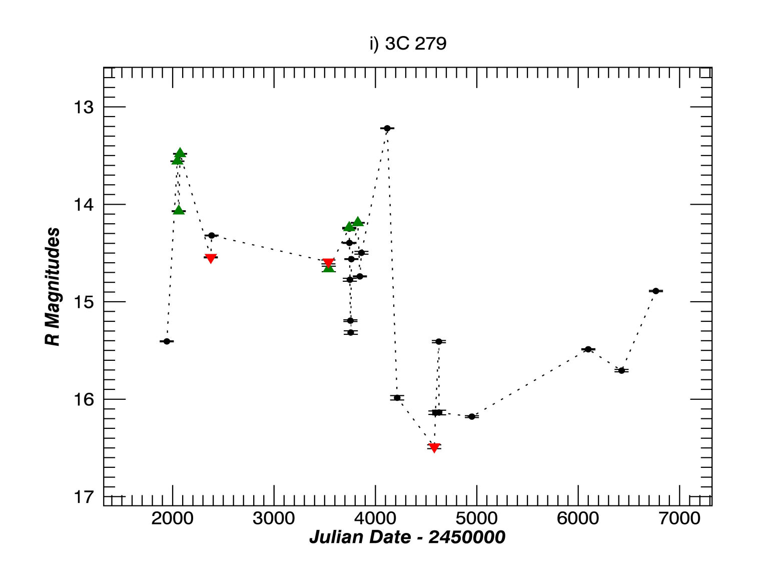
Indicates NO microvariablity detected that night

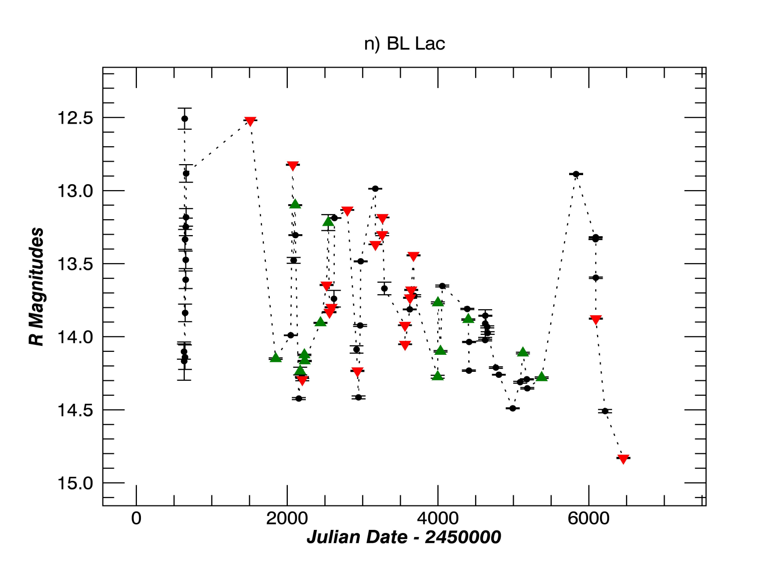












OBSERVATIONAL CHARACTERISTICS OF MICRO-VARIABILITY

- **Micro-variations are intermittent; different objects exhibit a large range of duty cycles (12% to 86%). (Webb in preparation).**

- **The presence of micro-variations does not appear to be correlated with overall brightness (Howard, Webb, Pollock and Stencil 1994, and Webb et al. 2010).**

- **Micro-variations do not show repeatable timescales. (Dhalla, S., Webb, J.R., Bhatta, G. and Pollock, J.T., 2010).**

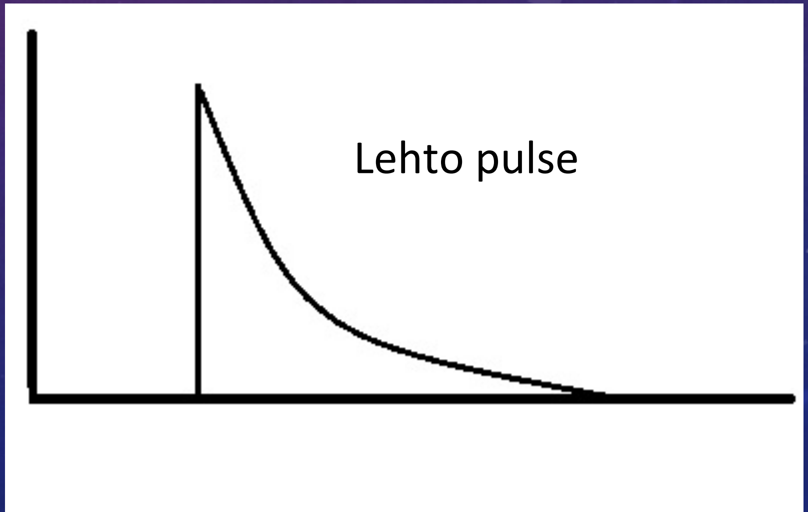
- **Time series analyses of the micro-variability does not show the characteristics of pure noise in the sense that it is unresolved red noise or white noise (Azarnia et al. 2006, Dhalla et al. 2010).**

- **There appears to be resolved individual "events" in the micro-variability curves (Webb 2010, and Bhatta et. al. 2013).**

TURBULENCE IN BLAZAR JETS

- Jones (1988) uses turbulence in jets to explain that lack of polarization from synchrotron emission.
- Marscher, Gear and Travis (1992) use turbulence in radio emission depolarization.
- McHardy (2008) red-noise X-ray PDS in terms of turbulence.
- Marscher and Jorstad (2010). Models a jet with individual “turbulent cells”.

Lehto (1989) devised a model of the X-ray variability of blazers assuming a pulse with a step function rise and exponential decline. By superimposing a large number of unresolved pulses with random center times and amplitudes, he was able to show that one can get a light curve that exhibits a 1/f power spectrum.

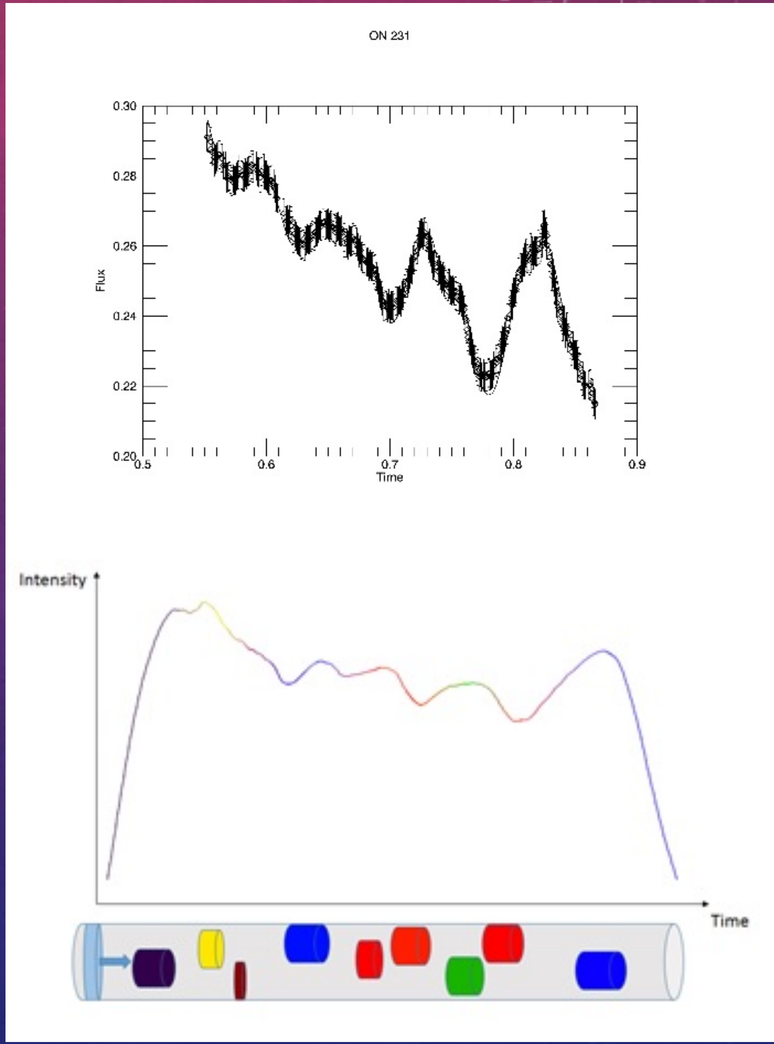


MICRO-VARIATIONS AS PULSES FROM A TURBULENT FLOW

Intermittency of Micro-variations:

1. Turbulent flow in jet + Shock = micro-variability
2. Laminar flow in Jet + Shock = *linear* short term variations (days to weeks), but no micro-variability.

Micro-variability is the superposition of individual synchrotron radiating cells.



KIRK ET AL. (1988): EQUATIONS FOR ACCELERATION AND COOLING PROCESSES OF A SHOCK ENCOUNTERING A CYLINDRICAL DENSITY ENHANCEMENT.

Diffusion equation

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial \gamma}(\beta_{\rm s}\,\gamma^2\,n) \;=\; \frac{N(\gamma,t)}{t_{\rm esc}}\delta(x - x_{\rm s}(t))$$

The source function

$$N(\gamma,t) \;=\; a\,\frac{1}{\gamma^2}\left(\frac{1}{\gamma} - \frac{1}{\gamma_{\rm max}}\right)^{(t_{\rm acc}-t_{\rm esc})/t_{\rm esc}} \times\Theta(\gamma-\gamma_0)\,\Theta(\gamma_1(t)-\gamma)\,,$$

The solution for the diffusion equation

$$n(x,\gamma,t) \;=\; \frac{a}{u_{\rm s}t_{\rm esc}\gamma^2} \left[\frac{1}{\gamma} - \beta_{\rm s}\left(t - \frac{x}{u_{\rm s}}\right) - \frac{1}{\gamma_{\rm max}}\right]^{(t_{\rm acc}-t_{\rm esc})/t_{\rm esc}} \Theta\left[\gamma_1(x/u_{\rm s}) - (1/\gamma - \beta_{\rm s}t + \beta_{\rm s}x/u_{\rm s})^{-1}\right]$$

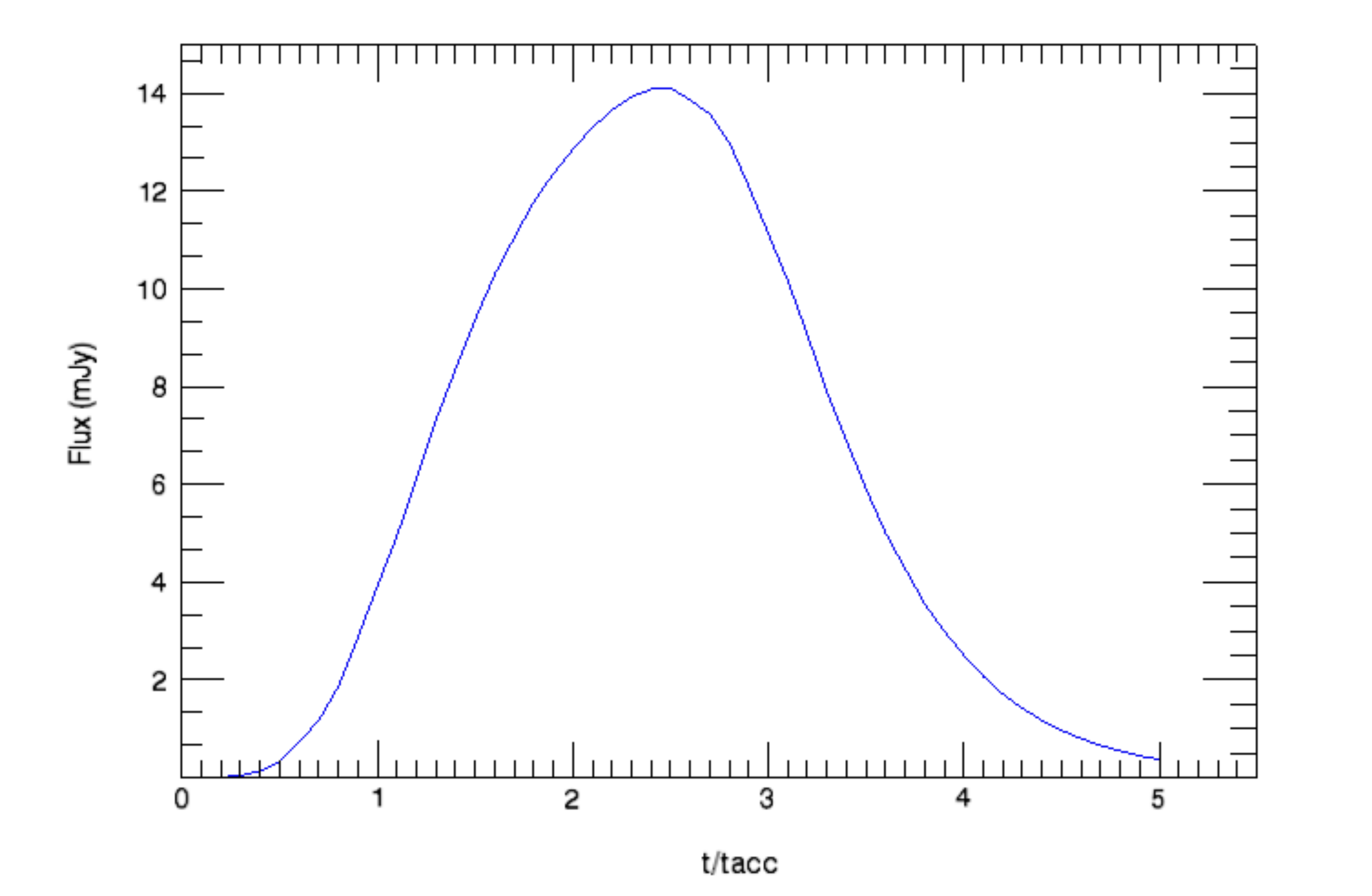
Equation for Emission Process

Intensity of the Emission

$$I_0(\nu, \bar{t}) = \int \mathrm{d}\gamma P(\nu, \gamma) \int \mathrm{d}x\, n(x, \gamma, \bar{t} + x/c)$$

1. Program these equations in IDL for numerical integration.
2. Instead of large density enhancements over entire width of the jet, integrate for small density enhancements expected from individual turbulent cells within the jet.
3. Parameters in model are gleaned from other observations of the Blazar jet.
4. Plot the shape of the synchrotron pulses expected from shock interaction with cells.

RESULTING PULSE SHAPE FOR A PARTICULAR FREQUENCY



B = 2 Gauss

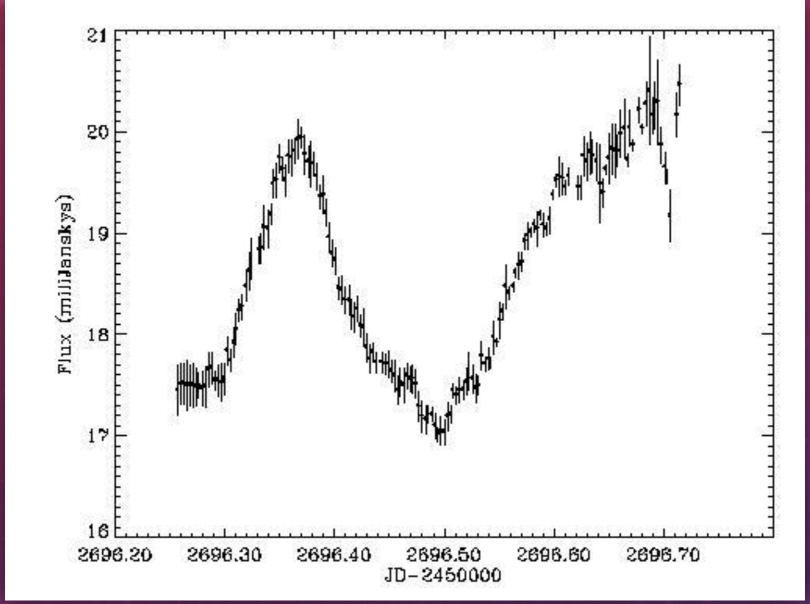
Q = 609.3 m^3s^{-1}

ν = 4.3X10^{14} Hz

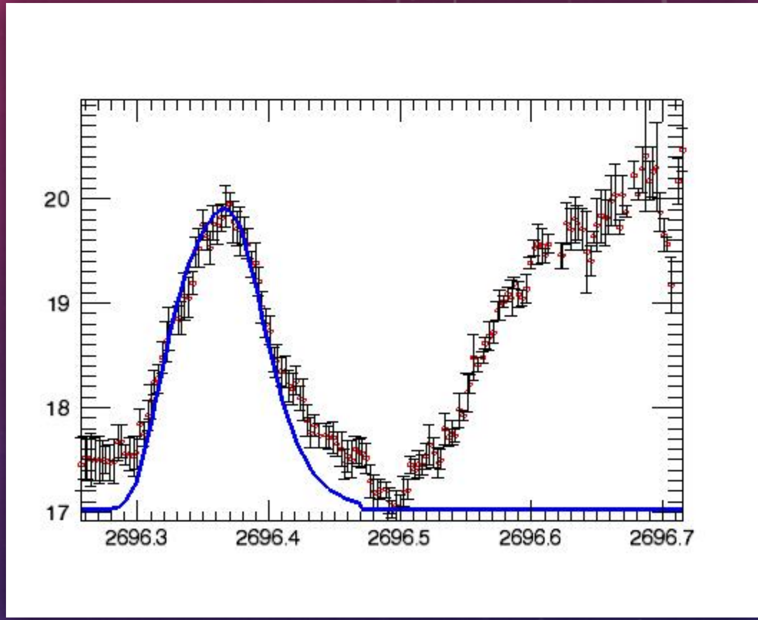
tf = 2.5/tacc

Shock speed = .1c

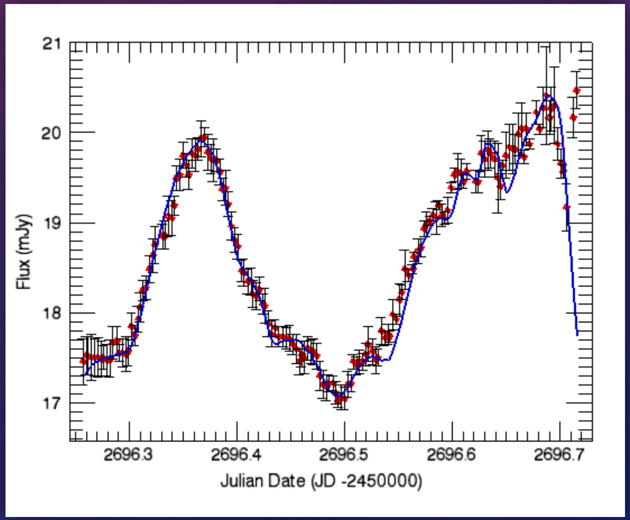
MICROVARIABILITY LIGHT CURVE CONVOLUTION



Model First Pulse



Modelled with several pulses

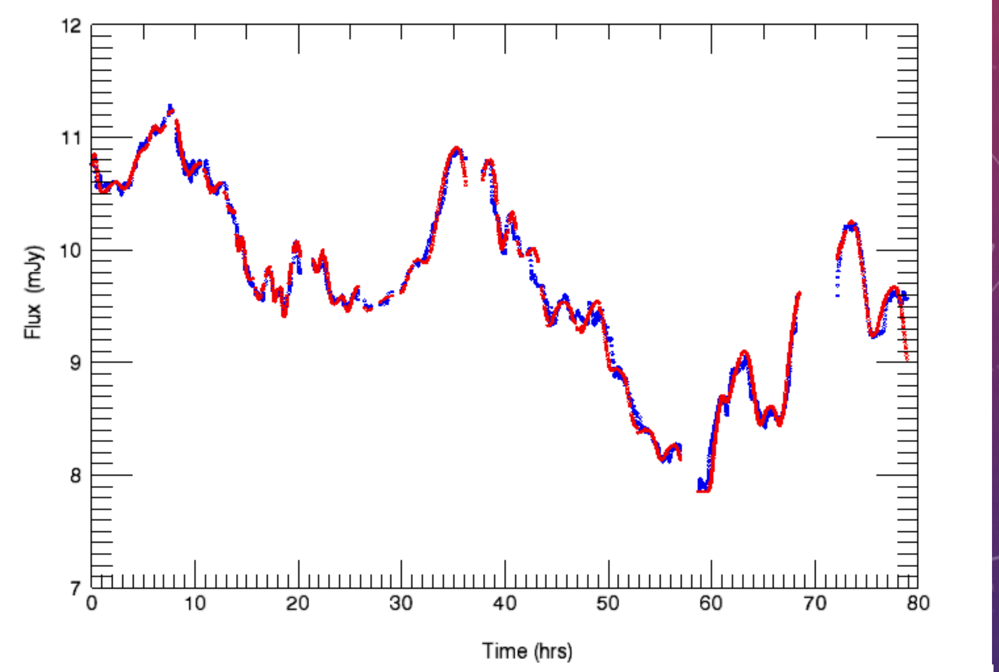


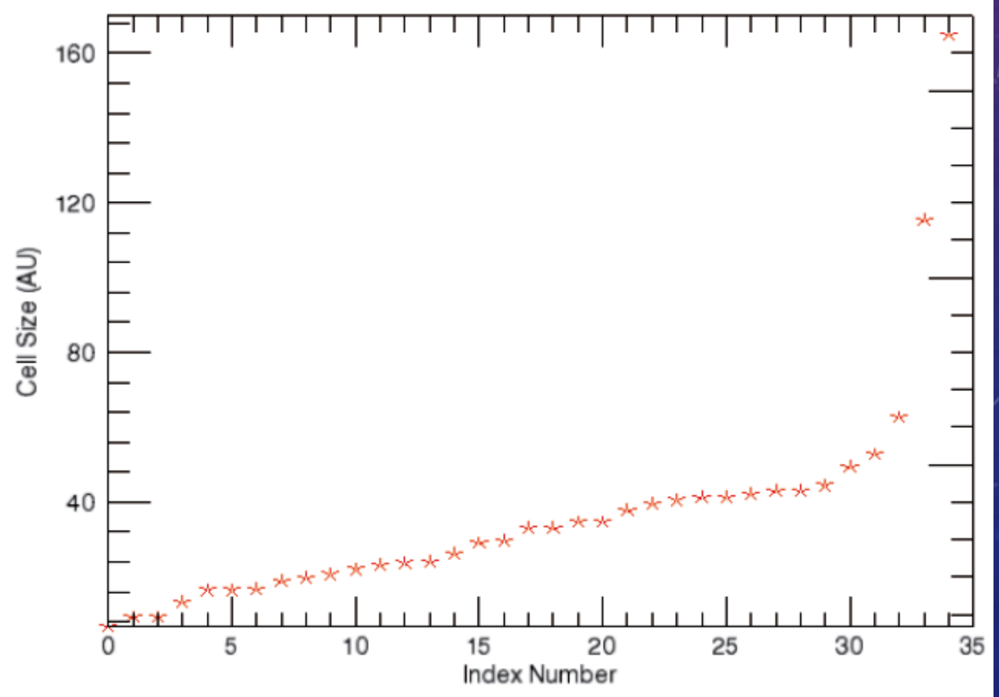
Soon to be automated

WEBT FEBRUARY 2009 CAMPAIGN

- Gathered continuous data for 78 hours on 0716+714
- Fit 35 pulses to the curve with a correlation coefficient of 0.97
- Cell Sizes:
  - Min = 9 AU
  - Max = 165 AU
  - Average = 33.26 AU
  - Cell sizes are a continuum up to about 60 AU.

(G Bhatta et al. (2012))

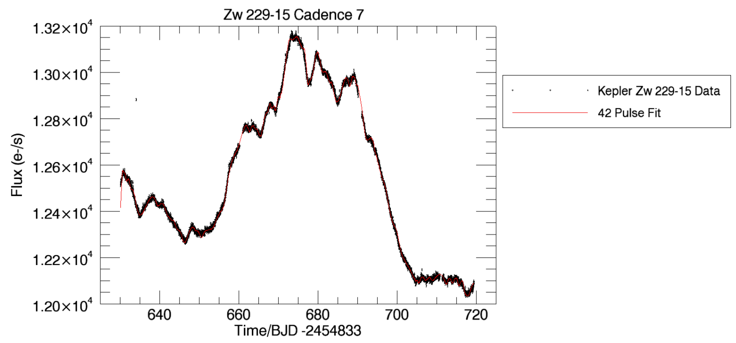


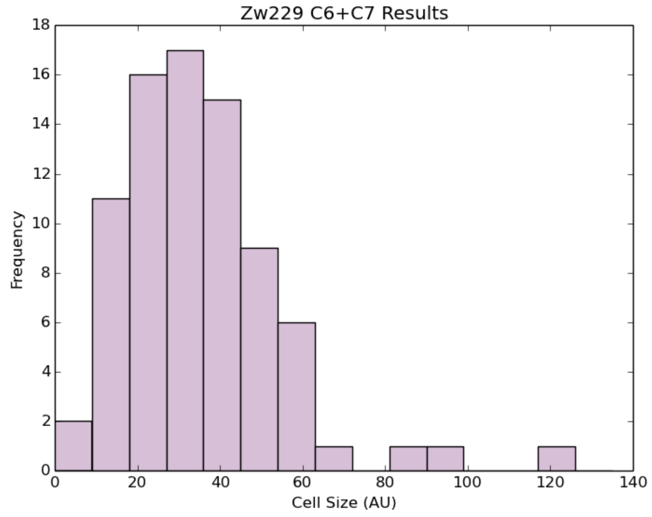


RESULTS FROM MICRO-VARIABILITY FITS TO KEPLER DATA

DHALLA MS THESIS FIU (2013)

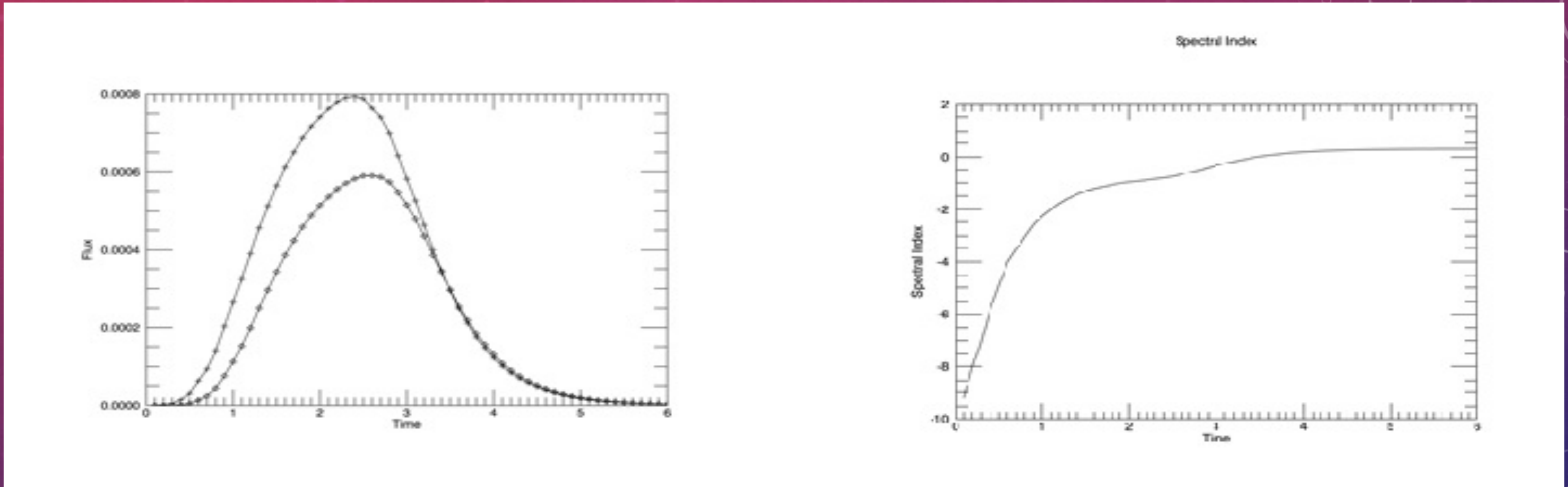
Source Name	Cadence Number	Number of points	Number of pulses/Cells	Average Cell Size (AU)	Correlation coefficient	Degrees of Freedom
Zw 229-15	6 7	4276 4227	38 42	35.83 34.65	0.98 0.99	4161 4100
1925+50	6 7	4277 4226	55 52	36.70 40.34	0.99 0.99	4111 4069
1858+48	6 7	4277 4226	46 37	31.34 28.51	0.99 0.99	4138 4115
1904+37	7	4227	26	54.70	0.99	4148





Cell sizes ranged from 10 to 140 AU.

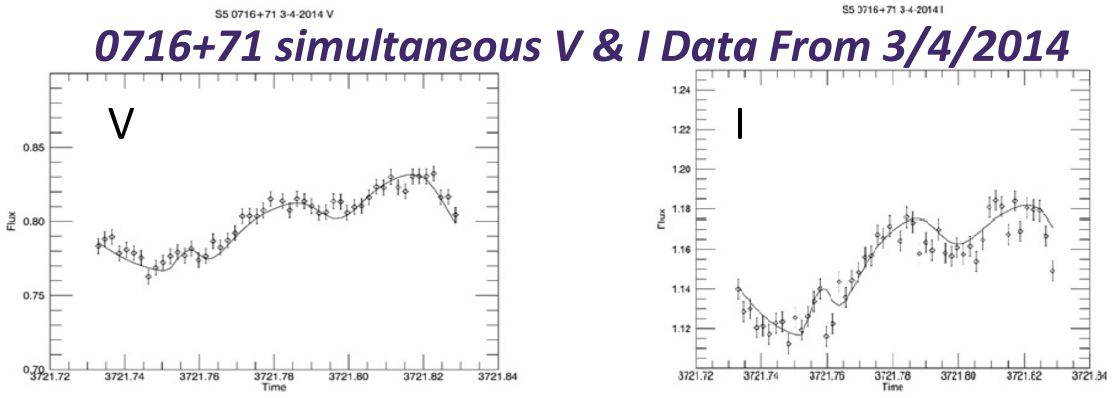
TESTING THE MODEL: MULTI-COLOR MICROVARIABILITY



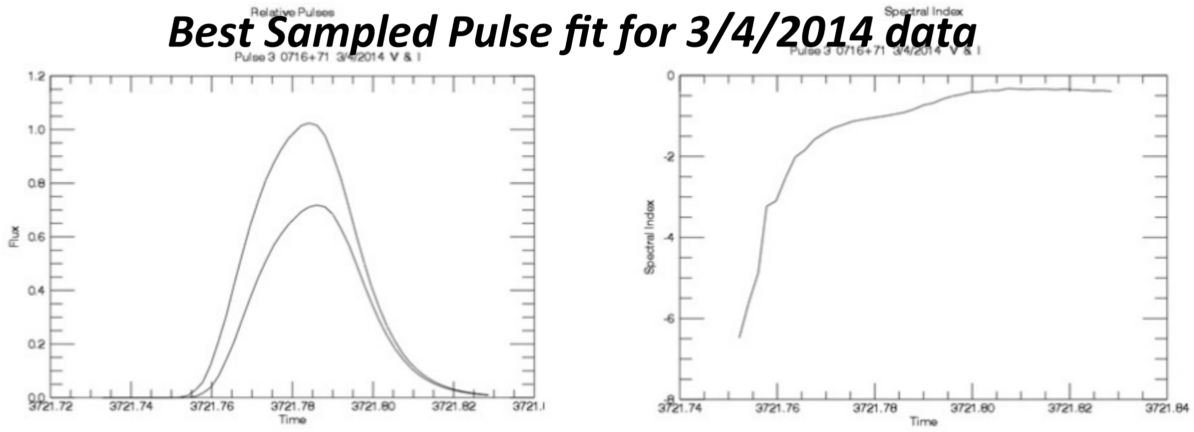
Generic V and I pulses from integrating the KRM kinetic equations. The brightness evolution (left) and the spectral Index evolution (right panel).

INITIAL TESTS USING V AND I MICROVARIABILITY

0716+71 simultaneous V & I Data From 3/4/2014

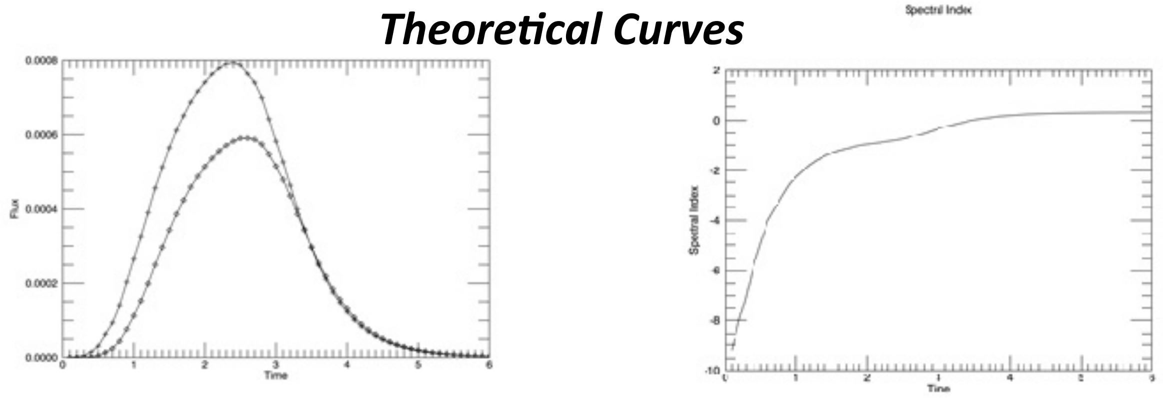


Best Sampled Pulse fit for 3/4/2014 data



The model fit for pulse 3 for 0716+71. The right panel shows the evolution of the spectral index obtained by calculating the spectral index over time from the V and I light curves for pulse 3. Compare them to the theoretical predictions shown to the lower right.

Theoretical Curves



FUTURE TESTS AND OBSERVATIONS

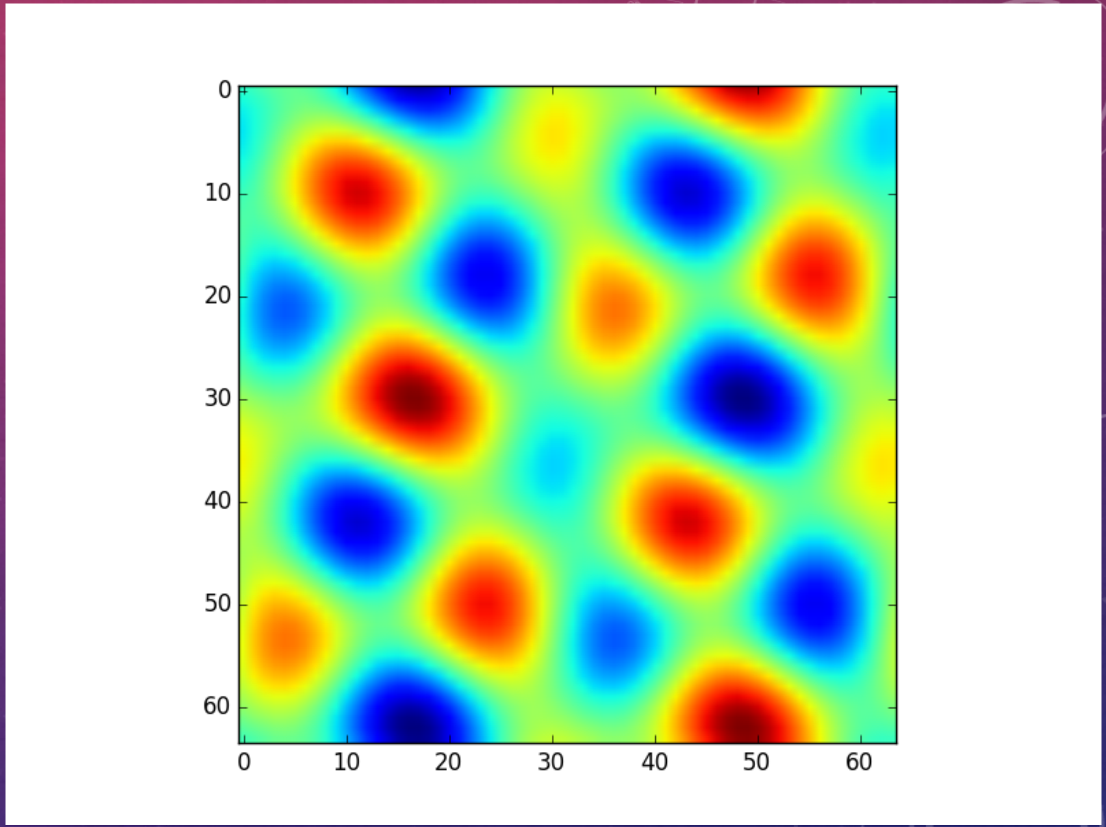
- Multi-frequency micro-variability observations with 2-meter class or larger telescopes.

- The GCT 10.4 meter is equipped with the CIRCE (Canarias InfraRed Camera Experiment) instrument. These observations would include polarization as well as multi-frequency.
    - CIRCE can measure the polarizations and fluxes in the J, H and K, bands. It can do imaging polarimetry using a Wedged Double Wollaston prism which allows full Stokes measurements in a single exposure

- The follow-up instrument to the CIRCE will be the MIRADAS instrument. We are Co-I's on a funded proposal for a detector arm for MIRADAS.

SIMULATED TURBULENCE

- Collaboration with theorist Jonathon Zrake:
  - Take a chunk of simulated relativistic turbulence from his code.
  - Create an IDL routine to read the turbulence “data” and determine cell centers, Densities and magnetic field characteristics.
  - Use our code to determine light curve if we pass a shock through the data.
  - Study the statistical properties of resulting light curve



Piece of simulated relativistic turbulence.
Private communication: J. Zrake.

CONCLUSIONS

- Evidence mounting for nature of microvariability:
  - Intermittent turbulence in blazar jet flow.
- Continuing observations of multifrequecy microvaribility using three 1-meter class telescopes at major observatories: CTIO, KPNO and ORM La Palma:
  - Start out at ORM, pick object up at KPNO thus observing continuously over 18 hours with overlap.
  - Observe same object simultaneously at two different observatories either in same filter or different filters.
  - Propose for 2+ meter telescopes and eventually (better S/N shorter exposures).
- Observations of micro-variability + polarization with GTC 10.4-m and CIRCE
- Continuing theoretical development:
  - Automating fitting routines.
  - Analyzing numerical relativistic turbulence.

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