Estimating Central BH mass in AGN using reverberation mapping

By Kartik Singh

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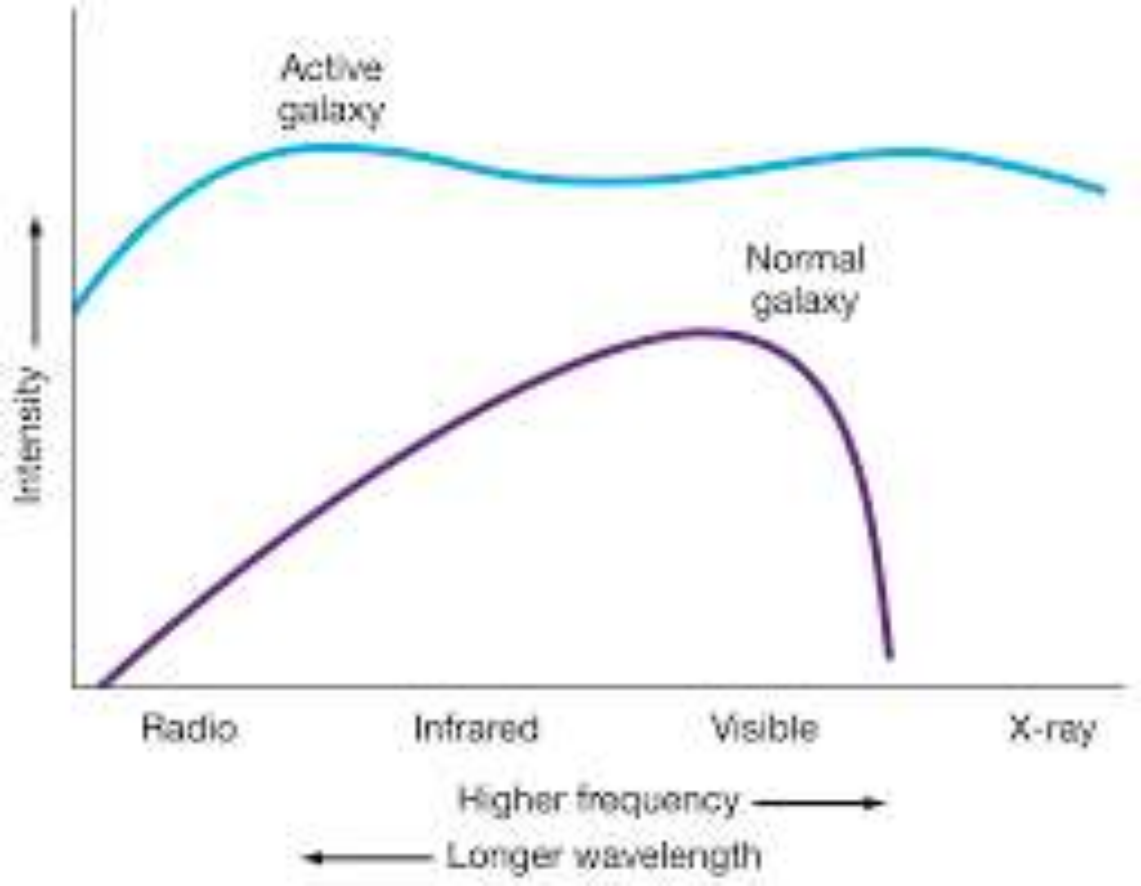
- What is an AGN? And its spectra
- The unified AGN model
- Cloud model
- Reverberation mapping
  - Issues
  - Different approaches
  - Results

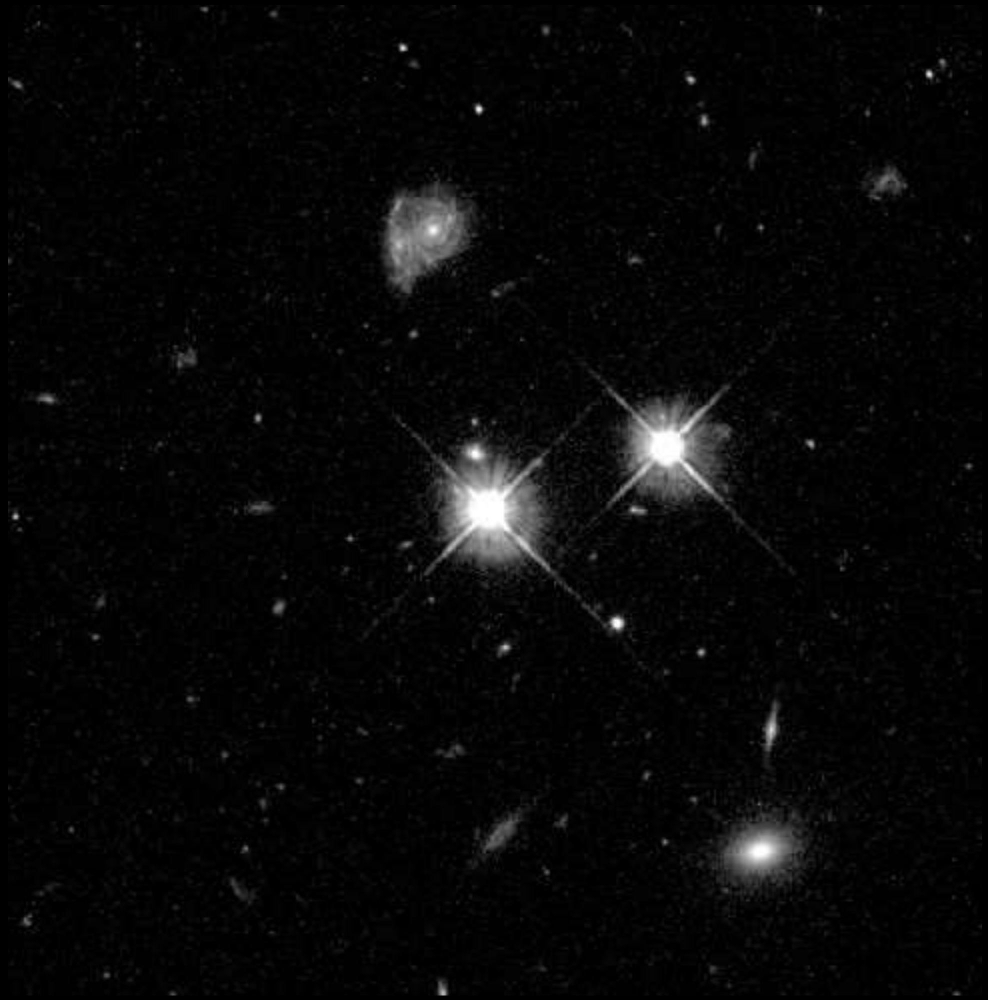
Main idea

- Use virial theorem
  - The radius of satellite orbit
  - The speed of the satellite
- We don’t require the mass of satellite!
- How do we get the radius and velocity?
  - Ans: reverberation mapping

$$M \sim \frac{r\langle v^2 \rangle}{G}$$

What is an AGN





AGN spectra

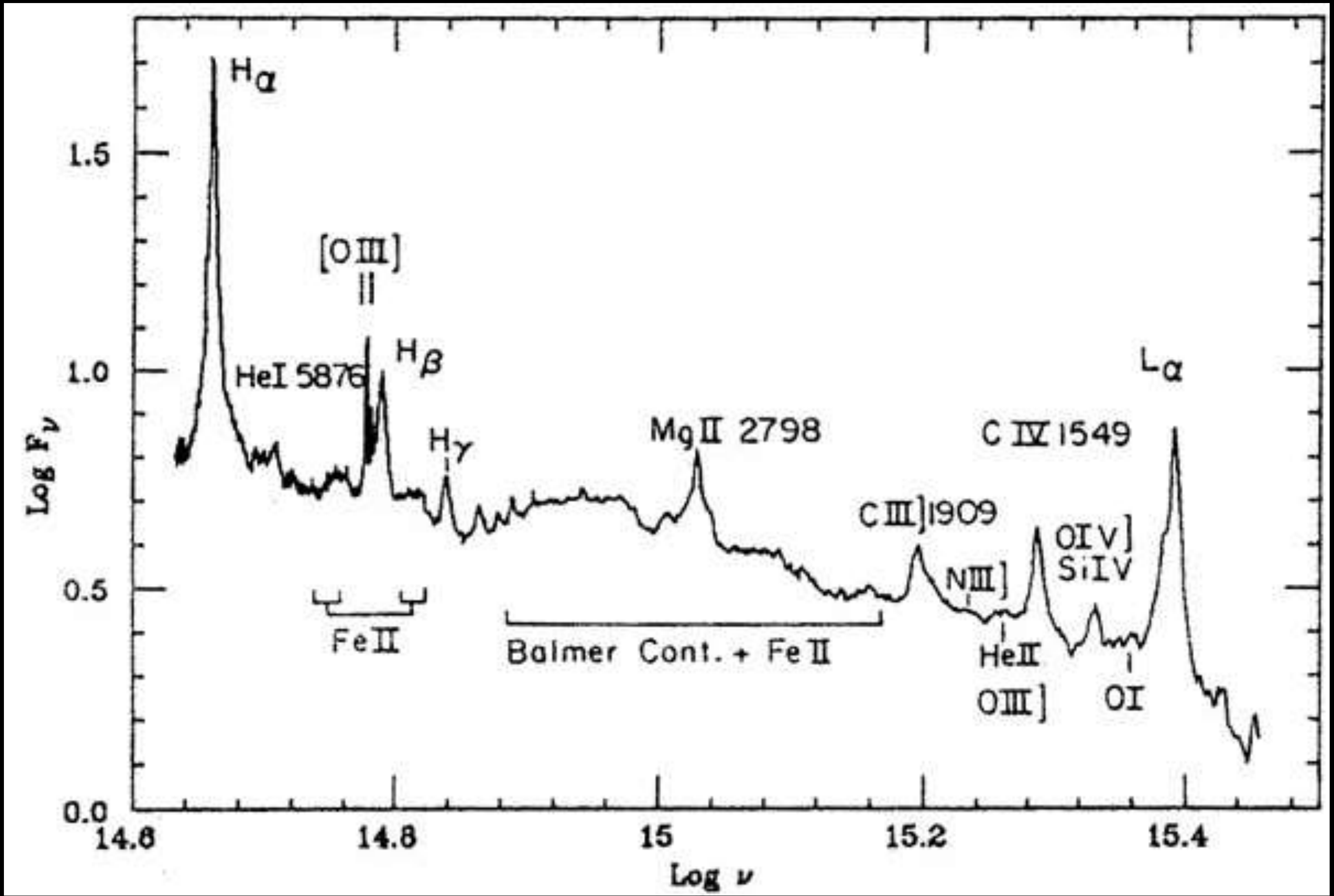
A continuous emission and a line emission.

The continuous emission closely follows a power law, for a wide range of frequencies

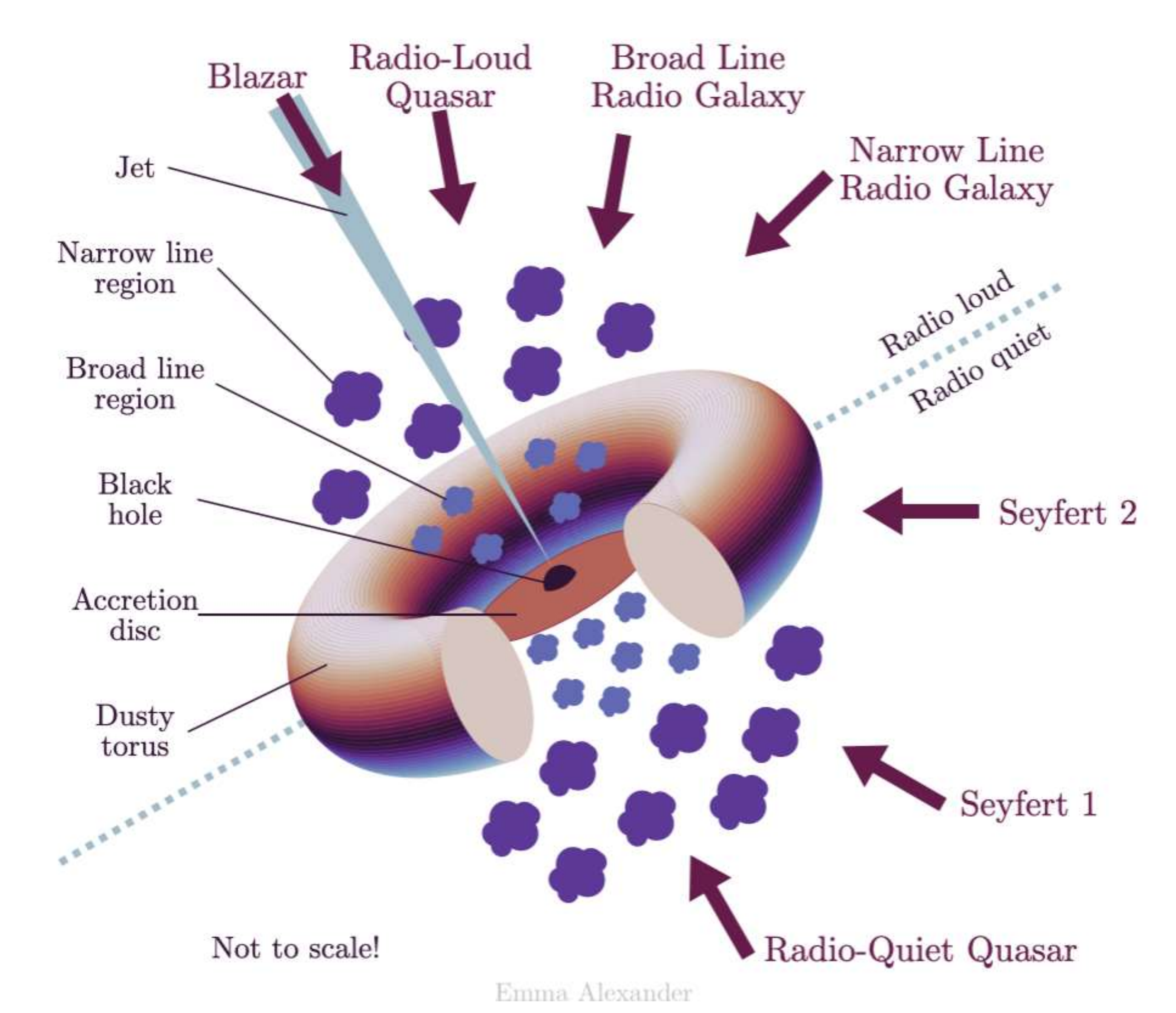
There are two types of line emissions depending on the width: broad and narrow.

This already hints that this is a superposition of light from multiple sources.

How do you explain this spectra?

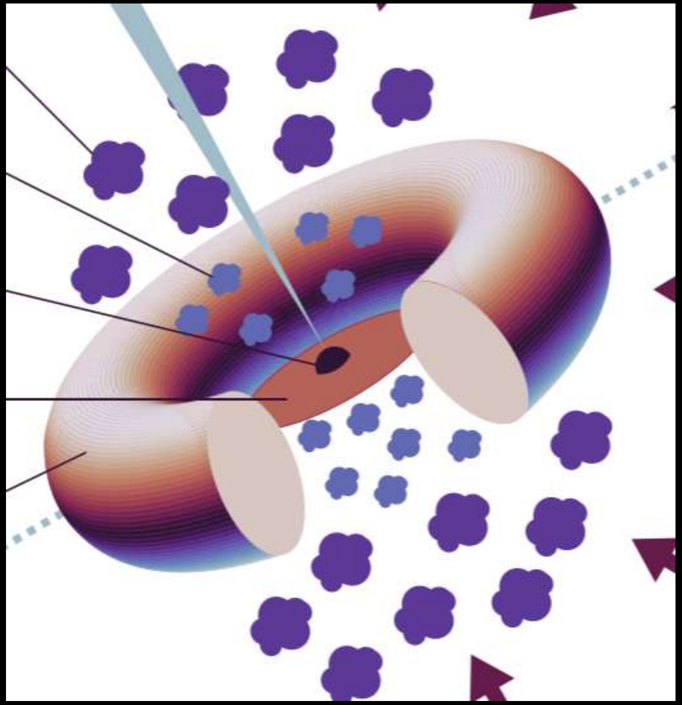


Unified AGN model



Cloud model

- How are the Broad emission lines generated
  - BLR clouds produce broad lines **by photoionization and recombination**
  - Radiation pressure pushes the BLR away from the center. The **width is due to Doppler broadening**.
- The structure of BLR
  - The **BLR is radially stratified**, majority flux comes from a narrow range
  - The BLR consists of numerous discrete gas nebula clouds (aka BLR clouds).



Reverberation mapping

1. The contin. source, much smaller than BLR.
2. BLR clouds themselves occupy a small fraction of the total volume.
3. There is a simple, not necessarily linear, relationship between the observable UV/optical contin. flux and the ionizing contin. flux.
4. The light travel time is much large compared to the cloud response to continuum variations
5. The light travel time is short compared to the time scale over which BLR geometry changes.

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5. The light travel time is short compared to the time scale over which BLR geometry changes.

$$\Delta L(t) = \int \Psi(\tau) \Delta C(t - \tau) d\tau$$

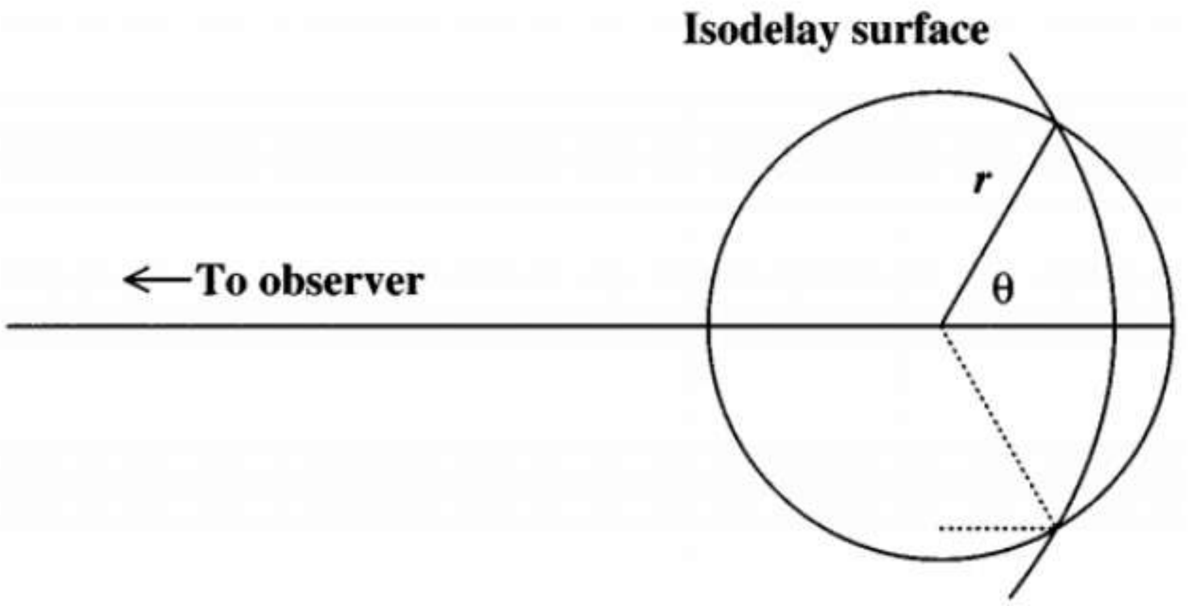

Figure 1: Light from a thin spherical BLR

Basic procedure

- Get data over an extended period of time, probably years*
- Pick a good line,
  - Most of them are too weak
  - CIII line is too sophisticated
  - Mg II is usually the best, because it has low ionization number
  - CIV is also used
- Find time delay with max cross correlation*

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- Compute radius and the mass

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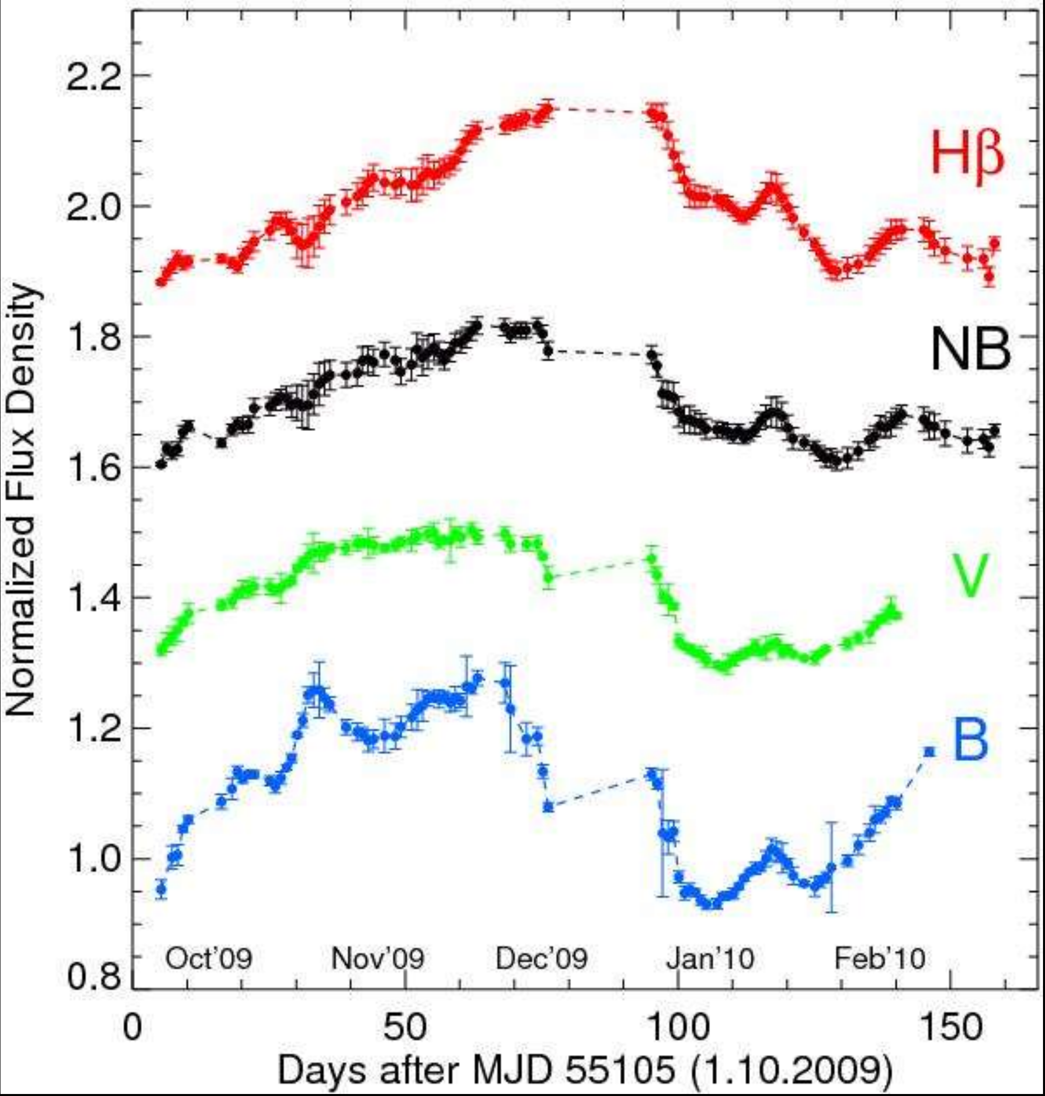
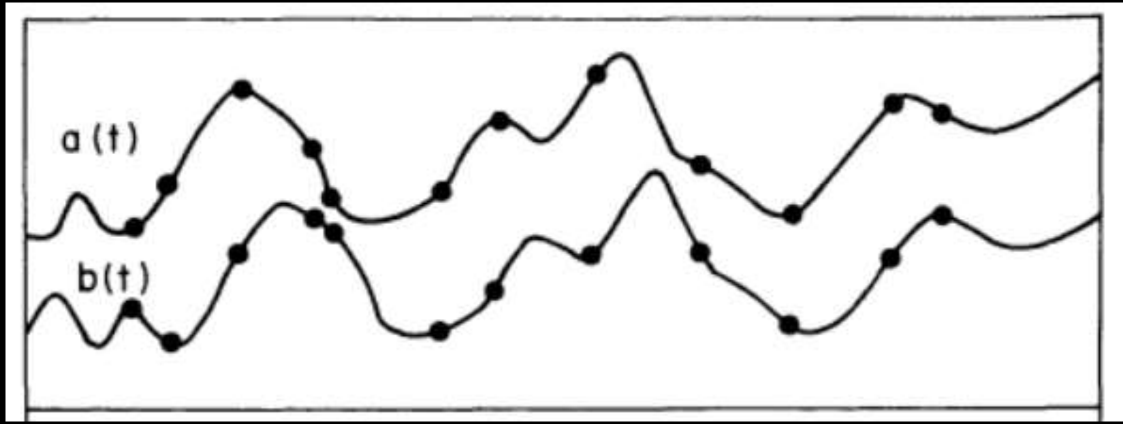
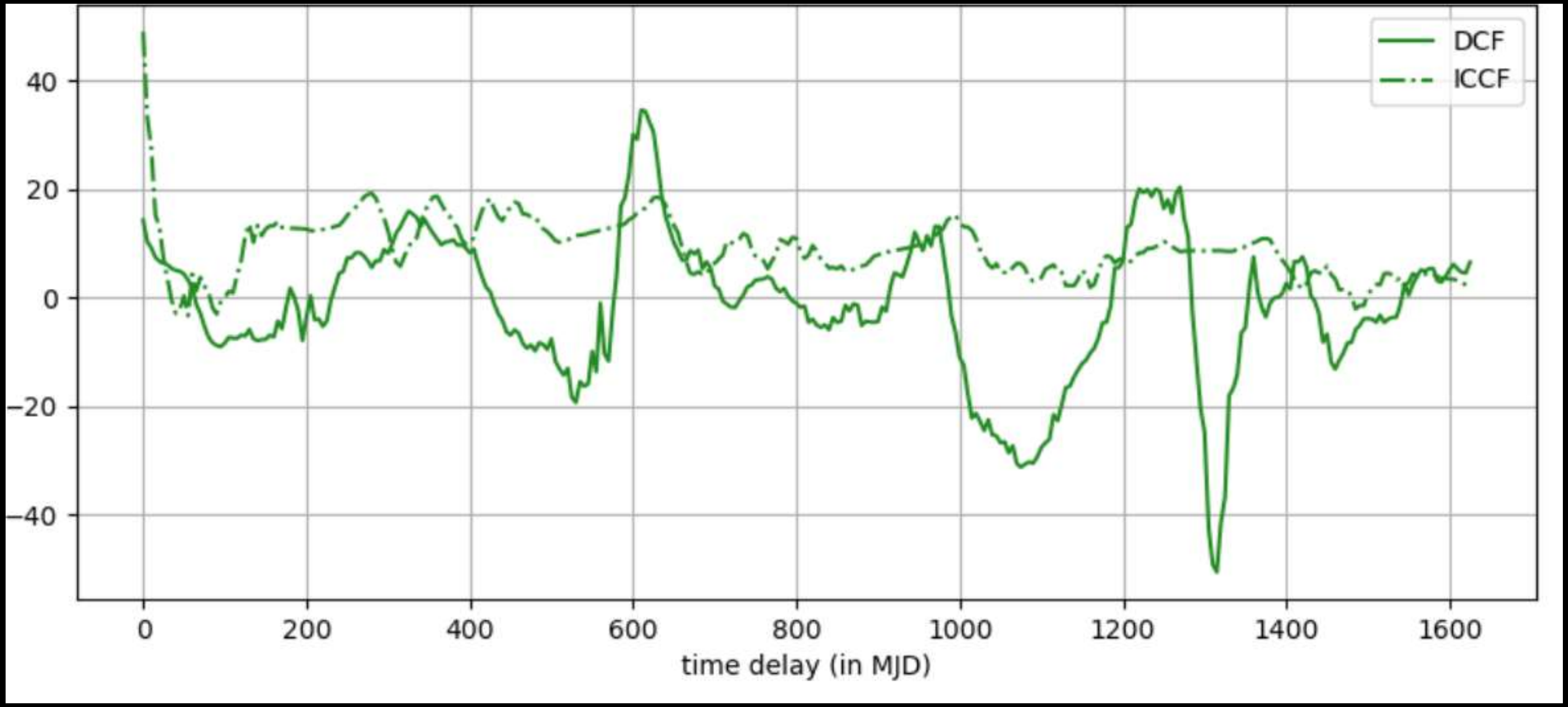
Data is kinda…. bad





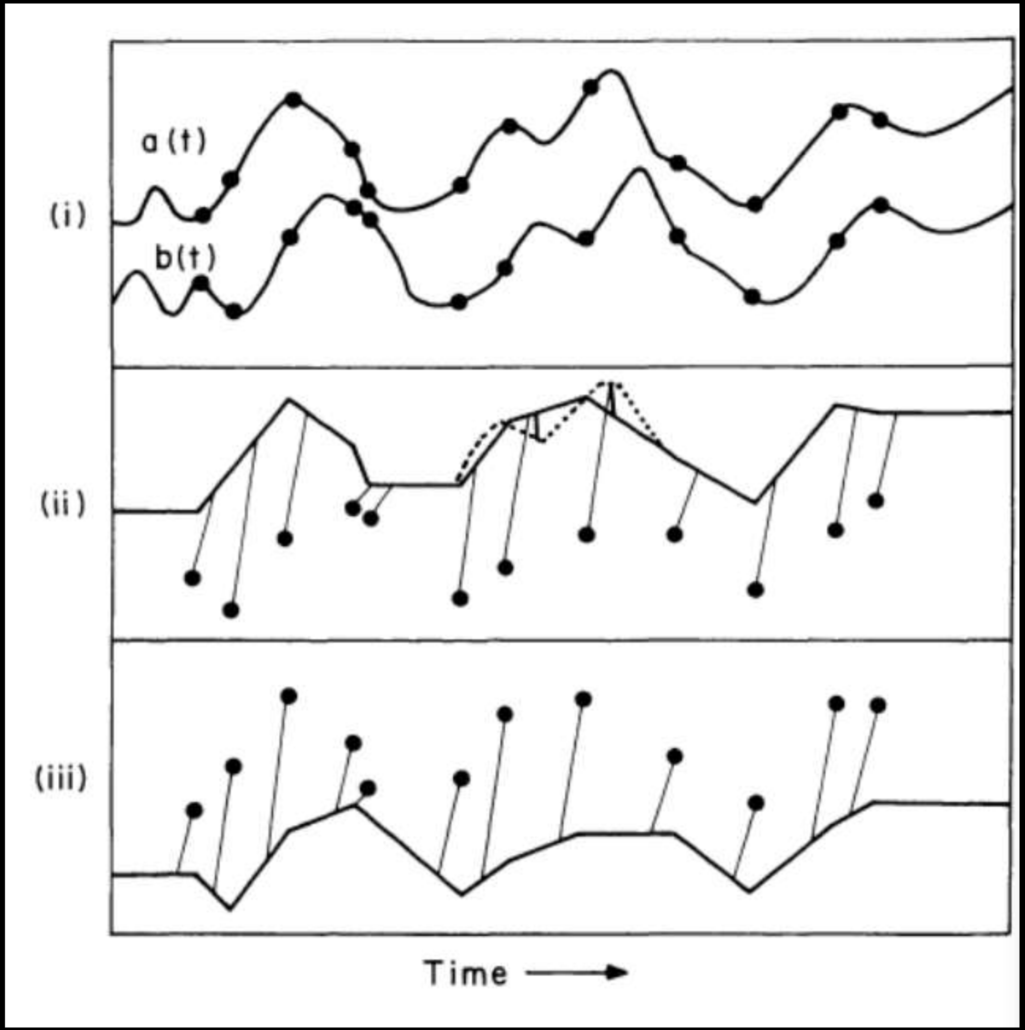
Issues

- Correlated errors in CIV emission line
- Non uniform time interval between data points



Interpolated Cross Correlation Function

- Uses linearly interpolate to fill the gaps
- Apply on each series, take avg

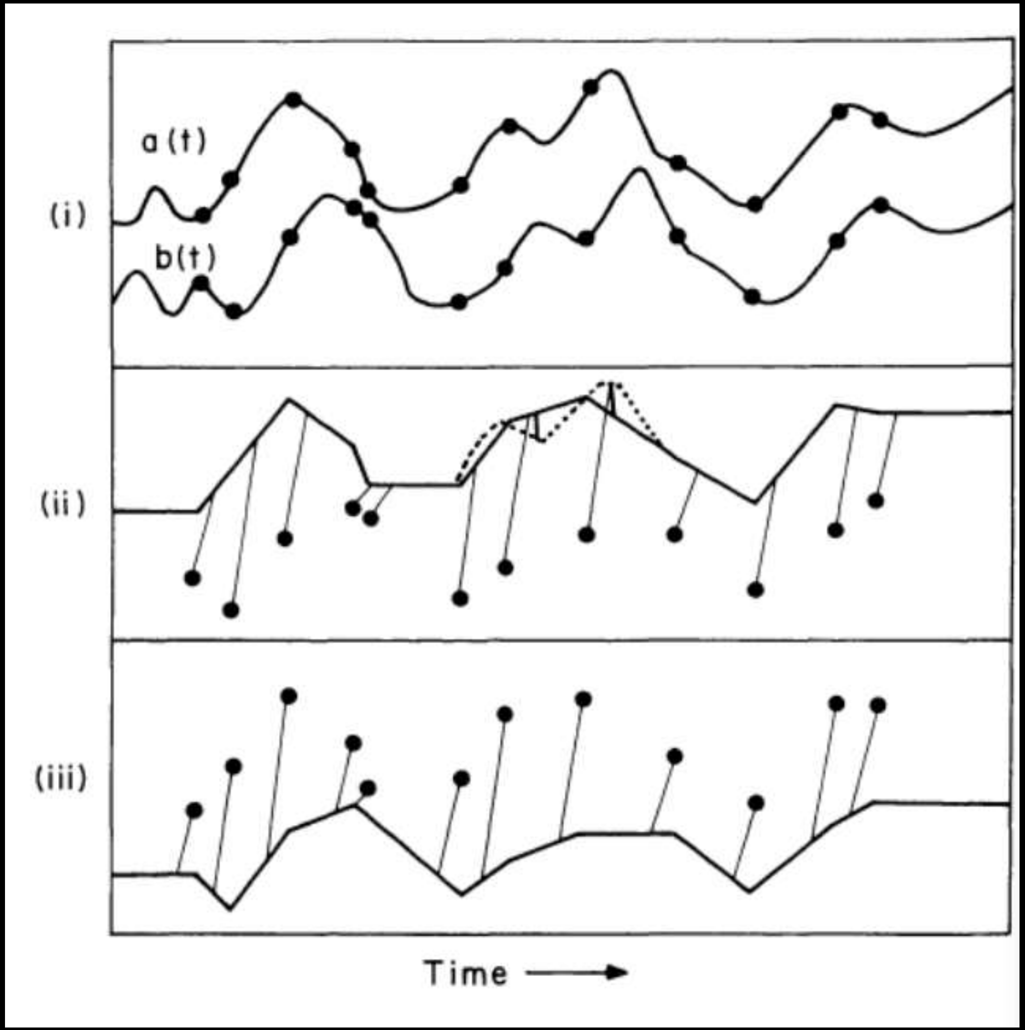


Interpolated Cross Correlation Function

- Uses linearly interpolate to fill the gaps
- Apply on each series, take avg

Drawbacks

- Validity of interpolation for non-uniform time intervals
- Peak at zero time delay
- Hard to quantify error



Discrete Correlation function

- Creates bins for each time lag, with some tolerance
- Takes the average of all data points that are within each bin

$$\mathrm{UDCF}_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{(\sigma_a^2 - e_a^2)(\sigma_b^2 - e_b^2)}} ,$$

pairwise lag $\Delta t_{ij} = t_j - t_i$.

DCF(τ) to be measured. Averaging over the M pairs for which $\tau - \Delta\tau/2 \leq \Delta t_{ij} < \tau + \Delta\tau/2$,

$$\mathrm{DCF}(\tau) = \frac{1}{M} \mathrm{UDCF}_{ij} . \tag{4}$$

Discrete Correlation function

- Creates bins for each time lag, with some tolerance
- Takes the average of all data points that are within each bin

Drawbacks

- Its worse in general, (lol)

$$\mathrm{UDCF}_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{(\sigma_a^2 - e_a^2)(\sigma_b^2 - e_b^2)}} ,$$

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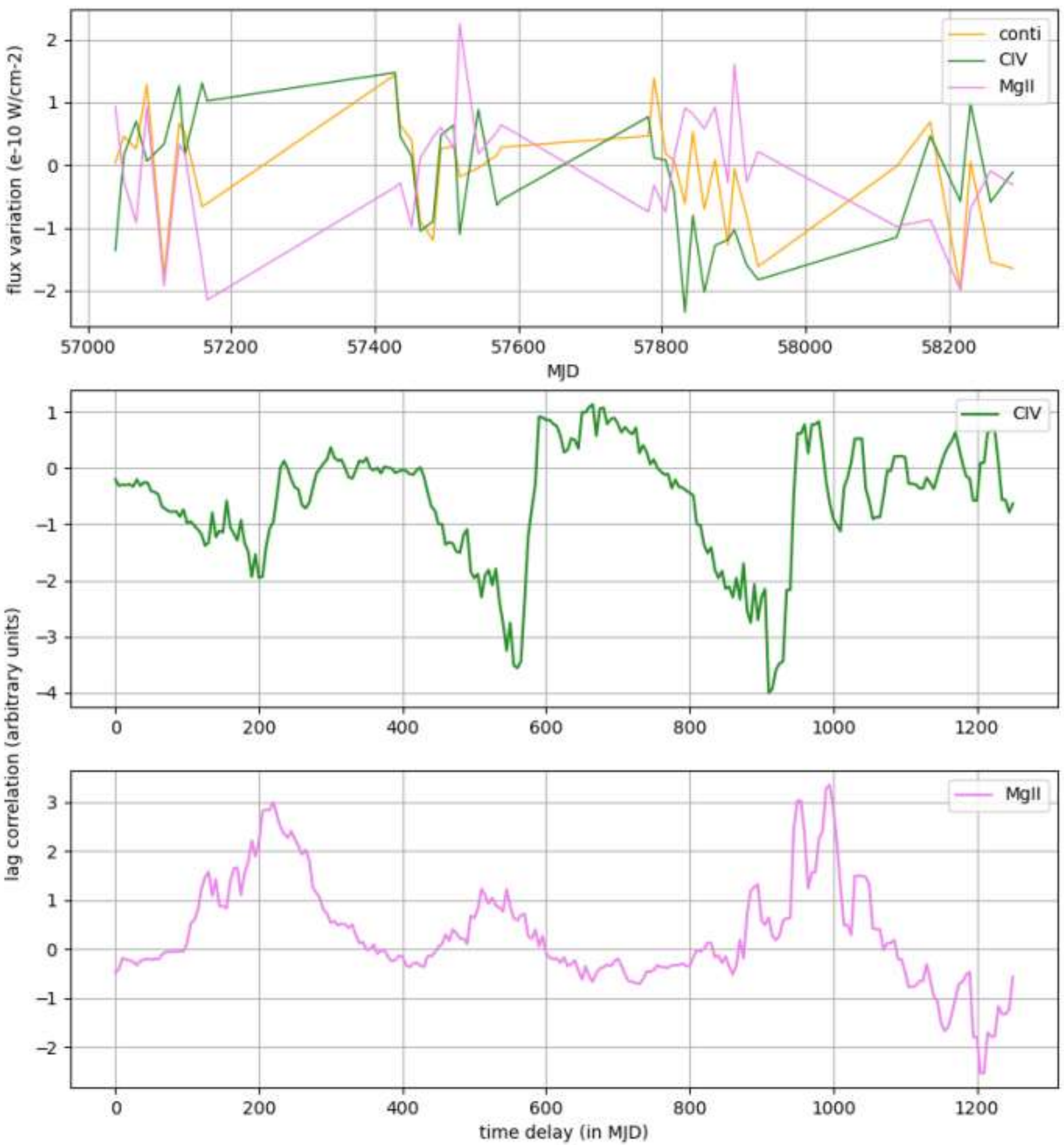
TABLE 1

Monte Carlo Simulation Results for $1/f^{2.5}$ Power Spectrum

Model Parameters			Sampling		Interpolation Method					DCF Method			
R (light days) (1)	A (2)	$\tau_{expected}$ (days) (3)	Number of Epochs N (4)	Mean Interval $\overline{\Delta t}$ (days) (5)	$\langle\tau_{peak}\rangle$ (days) (6)	Median (days) (7)	$\Delta\tau_{67}$ (days) (8)	$\Delta\tau_{90}$ (days) (9)	$\Delta\tau_{GP}$ (days) (10)	Mode (days) (11)	P_{mode} (12)	P_{lower} (13)	P_{upper} (14)
20	0	20.0	40	5.10	18.59	20	+3/−4	+5/−8	3.13 ± 2.12	20	0.37	0.31	0.32
			30	6.86	18.92	19	+4/−3	+8/−7	3.69 ± 2.38	18	0.35	0.20	0.45
			24	8.65	19.91	20	+3/−4	+7/−8	4.26 ± 2.56	24	0.38	0.46	0.16
			20	10.47	18.96	19	+5/−4	+11/−8	4.36 ± 2.98	20	0.47	0.21	0.32
			16	13.27	18.81	19	+5/−5	+11/−9	4.74 ± 3.04	26	0.38	0.43	0.19
			13	16.58	17.90	19	+6/−6	+16/−13	5.54 ± 3.52	16	0.46	0.16	0.37
			10	22.11	16.24	19	+8/−9	+19/−37	5.85 ± 4.34	22	0.44	0.25	0.31
			8	28.43	17.07	18	+10/−9	+50/−75	6.89 ± 4.70	28	0.42	0.30	0.28
			6	39.80	20.42	18	+26/−17	+78/−68	7.34 ± 5.54	39	0.37	0.43	0.20
20	1	26.7	40	5.10	27.99	28	+3/−2	+5/−4	3.03 ± 1.95	30	0.47	0.42	0.11
			30	6.86	27.04	28	+3/−3	+5/−6	3.26 ± 2.23	30	0.52	0.32	0.16
			24	8.65	27.03	28	+3/−4	+6/−7	3.80 ± 2.58	32	0.48	0.44	0.09
			20	10.47	25.81	28	+3/−4	+6/−9	4.14 ± 2.91	30	0.59	0.23	0.18
			16	13.27	27.03	28	+4/−5	+8/−11	4.73 ± 3.17	26	0.56	0.17	0.27
			13	16.58	24.46	27	+5/−6	+14/−23	5.22 ± 3.53	32	0.48	0.31	0.21
			10	22.11	24.61	27	+10/−9	+48/−94	5.08 ± 3.96	22	0.40	0.18	0.41
			8	28.43	24.76	27	+12/−12	+57/−79	6.27 ± 4.55	28	0.46	0.23	0.31
			6	39.80	24.64	26	+33/−22	+71/−98	6.28 ± 5.44	39	0.45	0.35	0.20
10	0	10.0	40	5.10	9.94	10	+1/−2	+3/−3	3.18 ± 2.12	10	0.72	0.16	0.12
			30	6.86	9.97	10	+1/−2	+3/−3	3.85 ± 2.48	12	0.63	0.28	0.10
			24	8.65	10.08	10	+2/−2	+3/−4	4.50 ± 2.66	8	0.60	0.06	0.34
			20	10.47	9.96	10	+2/−2	+4/−4	4.51 ± 3.05	10	0.75	0.09	0.16
			16	13.27	9.63	10	+2/−3	+4/−6	5.08 ± 3.21	13	0.63	0.21	0.16
			13	16.58	9.65	10	+3/−4	+8/−7	5.50 ± 3.47	16	0.52	0.32	0.16
			10	22.11	7.76	9	+5/−5	+13/−14	6.14 ± 4.21	0	0.33	0.17	0.50
			8	28.43	7.96	9	+7/−8	+21/−28	6.63 ± 4.77	0	0.38	0.16	0.45


conti
CIV
MgII
flux variation (e-10 W/cm-2)
MJD
CIV
MgII
lag correlation (arbitrary units)
time delay (in MJD)

References

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