The Reverberation Mapping of 3C 273

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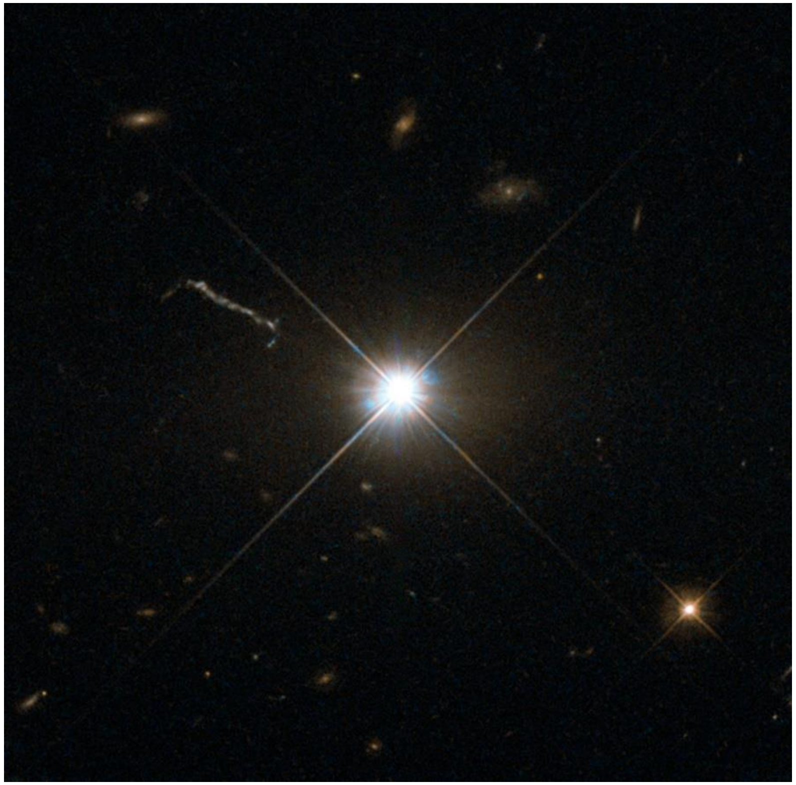
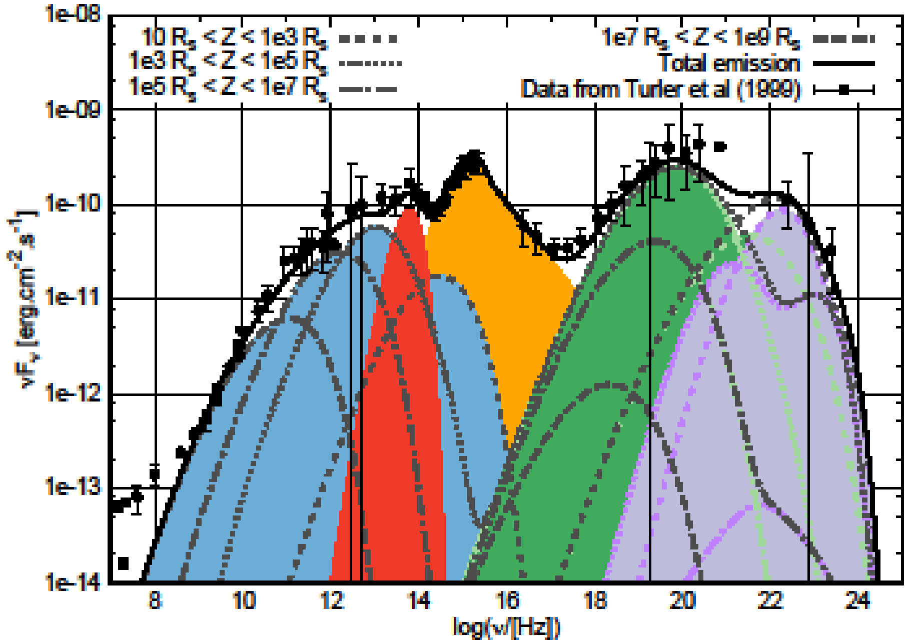
PU DU, PAUL S. SMITH, YULIN ZHAO, CHEN HU, MING XIAO, YAN-RONG LI, YING-KE HUANG, KAI WANG, JIN-MING BAI, LUIS C. HO, JIAN-MIN WANG

Zhang et al. 2019, ApJ, 876, 49

Guilin, 2019.09.19

The image and SED of 3C 273

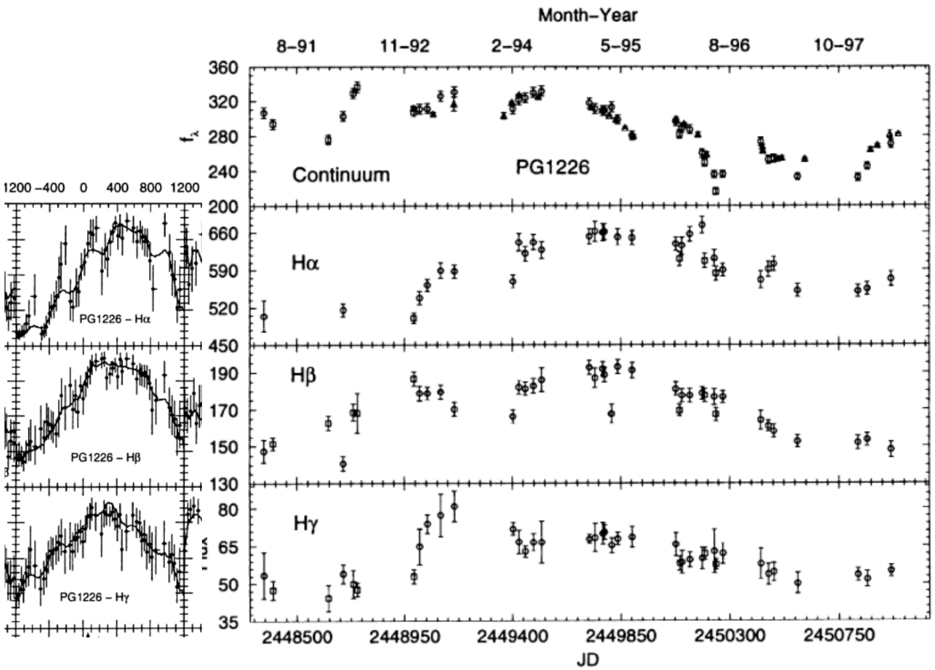




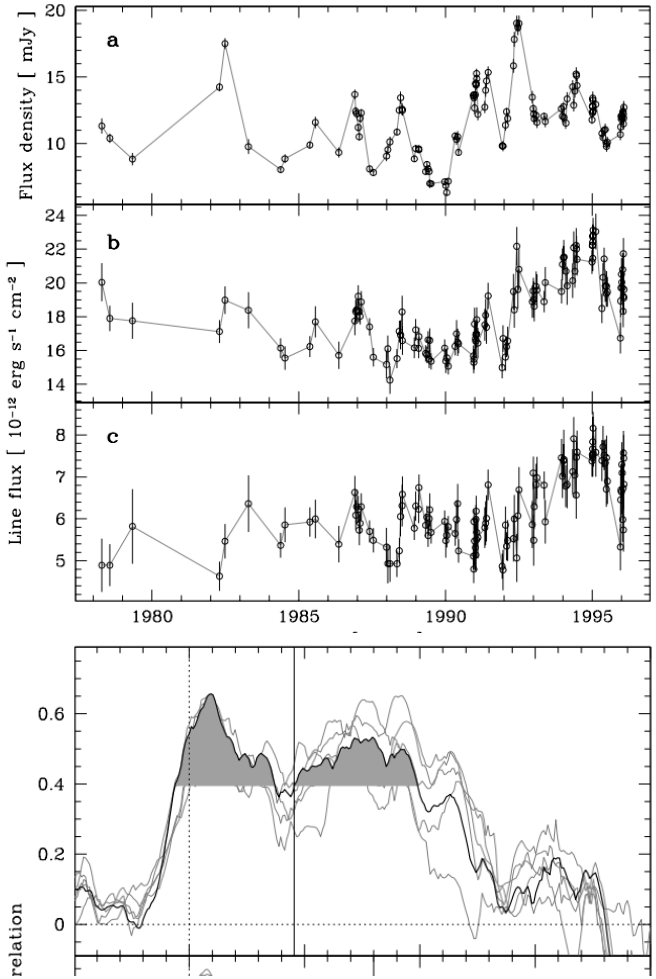
Vuillaume et al. 2018

The previous Reverberation Mapping

- Cadence: 40.3
- Campaign: 7 years
- The time lag measurements have large uncertainties.

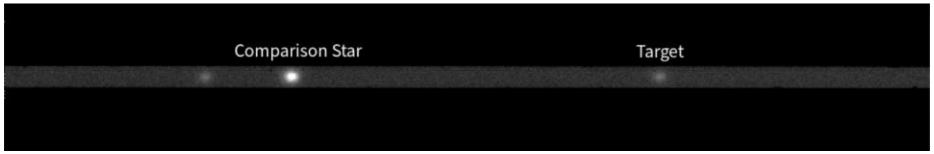


Kaspi et al. 2000



Paltani et al. 2005

Observation



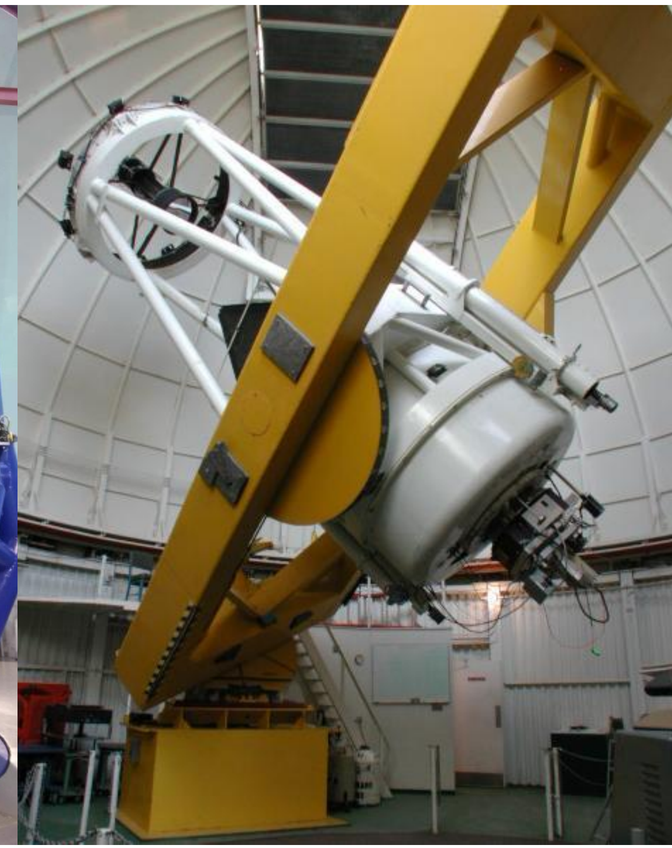
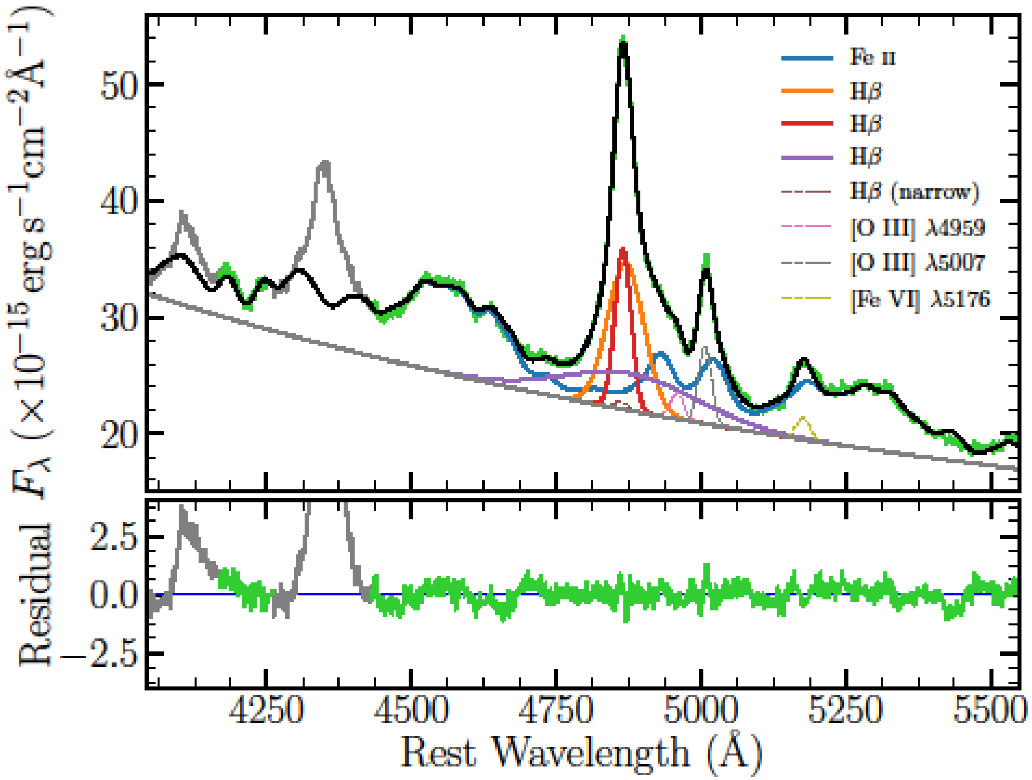


Table 5. Comparison of the RM-campaigns

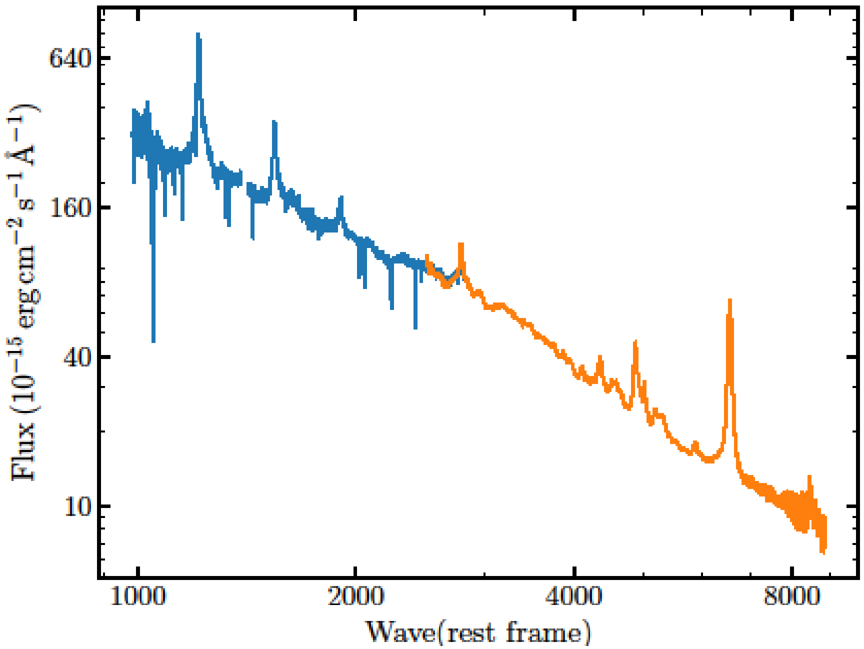
	Cadence		Length	$N_{\rm spec}$
	Obs. season (days)	Entire (days)	(start–end yr) (days)	
Kaspi et al. (2000)	40.3	66.8	2606 (1991-98)	39
This campaign	7.4	12.5	3400 (2008-18)	296

Spectral fitting

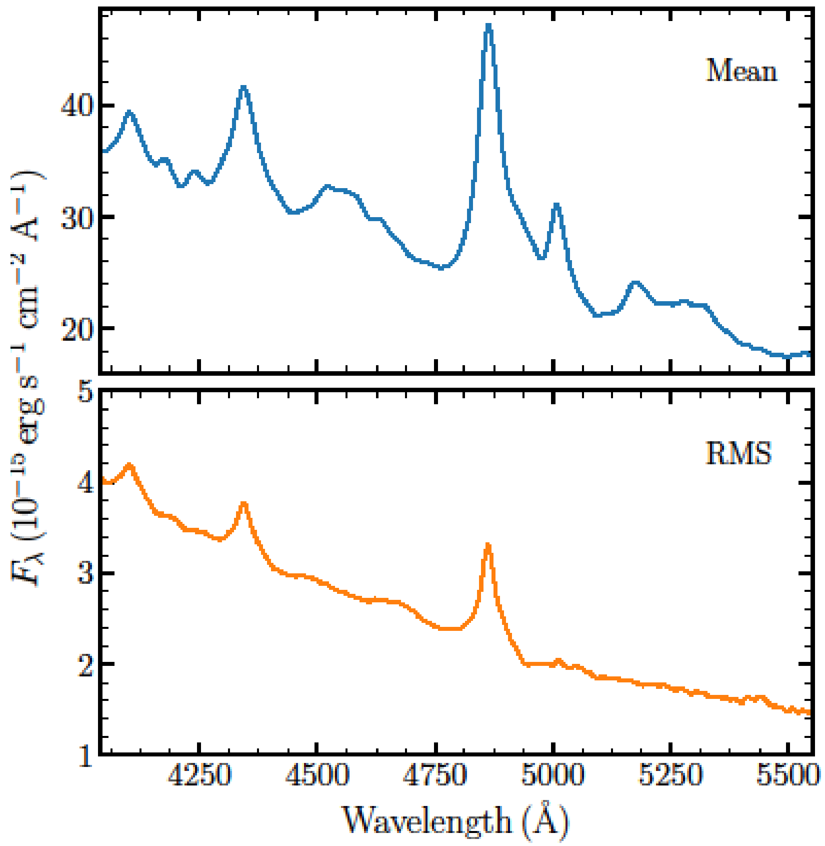
- three Gaussians: the Hβ profile.
- All narrow components are tied to same shift and width.
- The FeII template is from Boroson et al 1992.



Mean and RMS

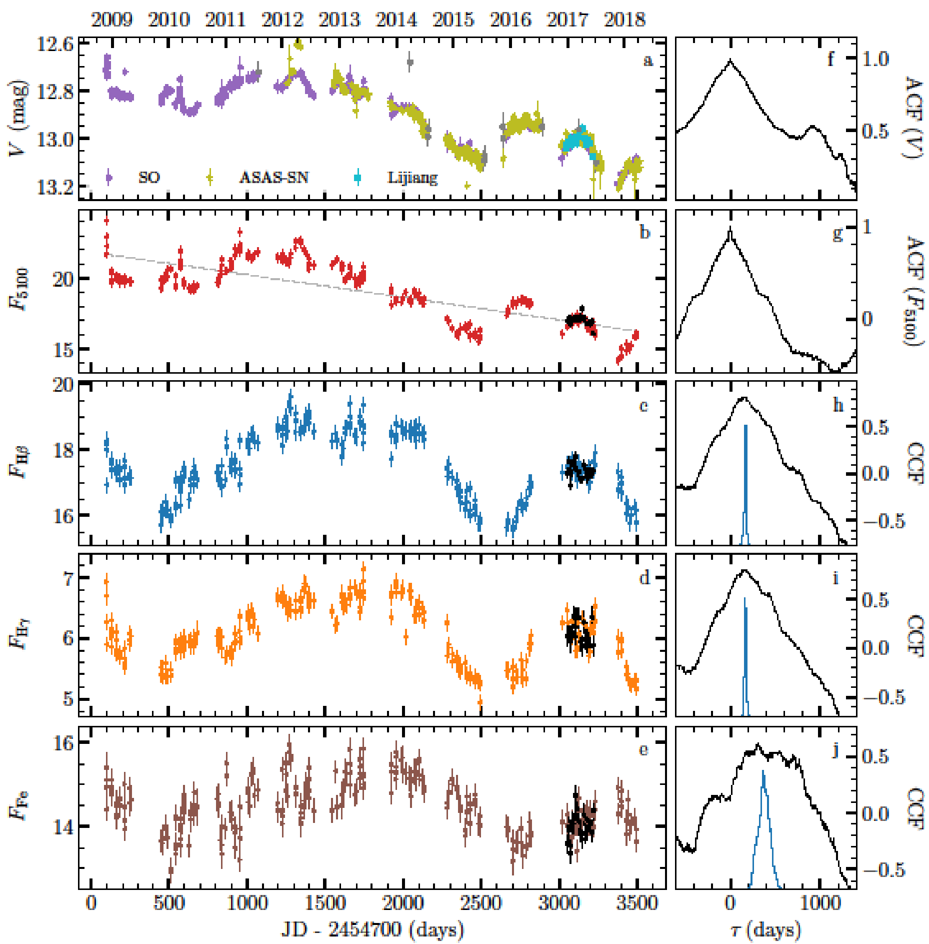


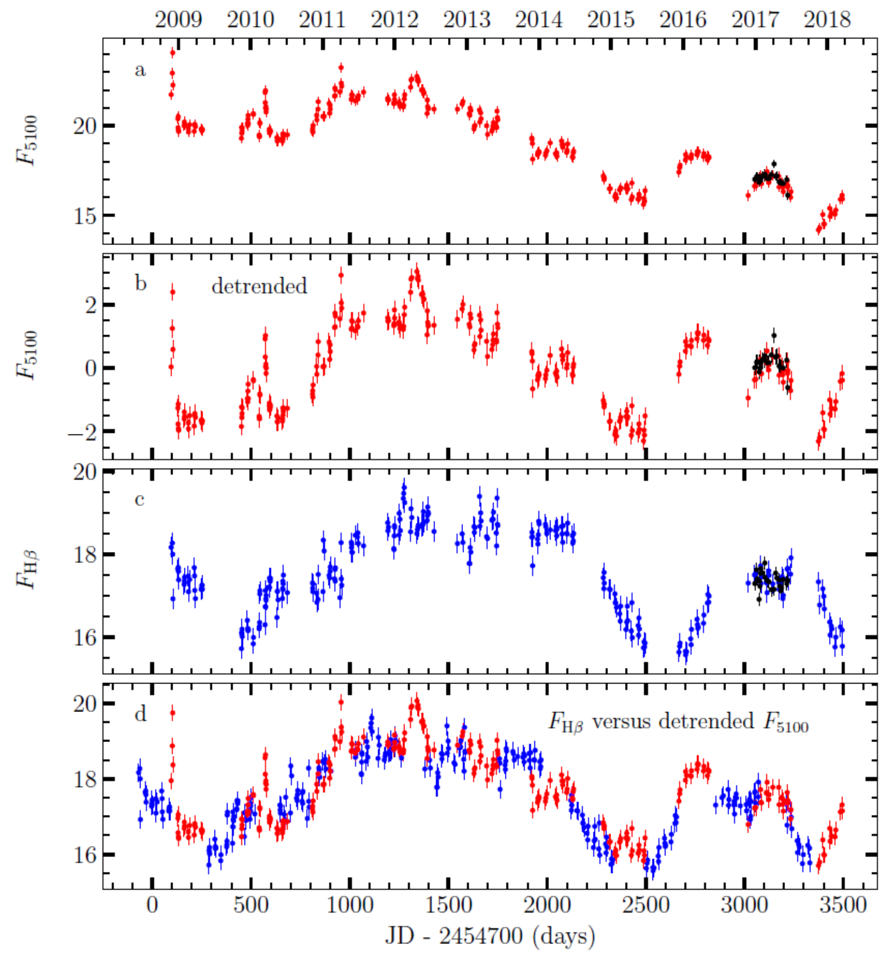
640
160
40
10
1000
2000
4000
8000
Flux $(10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}})$
Wave(rest frame)



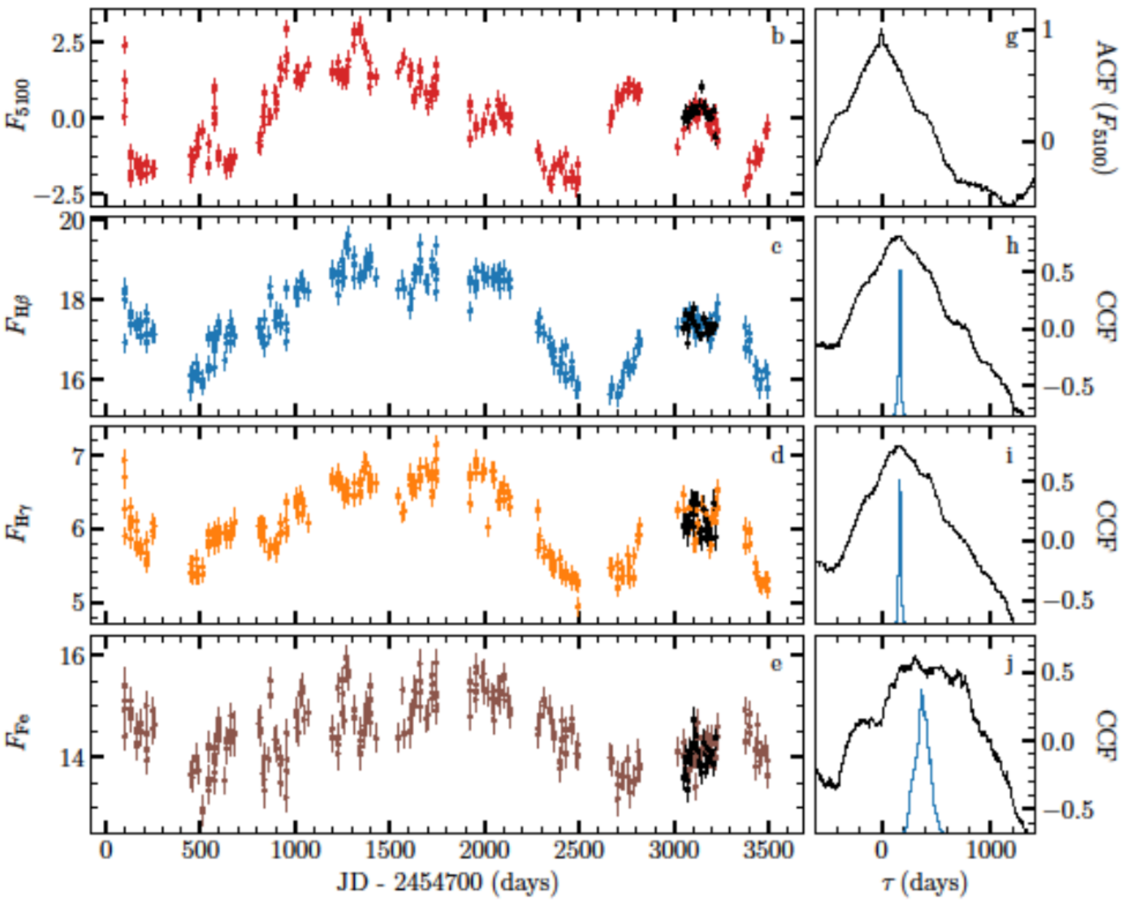
Mean
RMS
40
30
20
5
4
3
2
1
4250
4500
4750
5000
5250
5500
$F_\lambda\ (10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\AA^{-1}})$
Wavelength (Å)

The light curves





Time lags

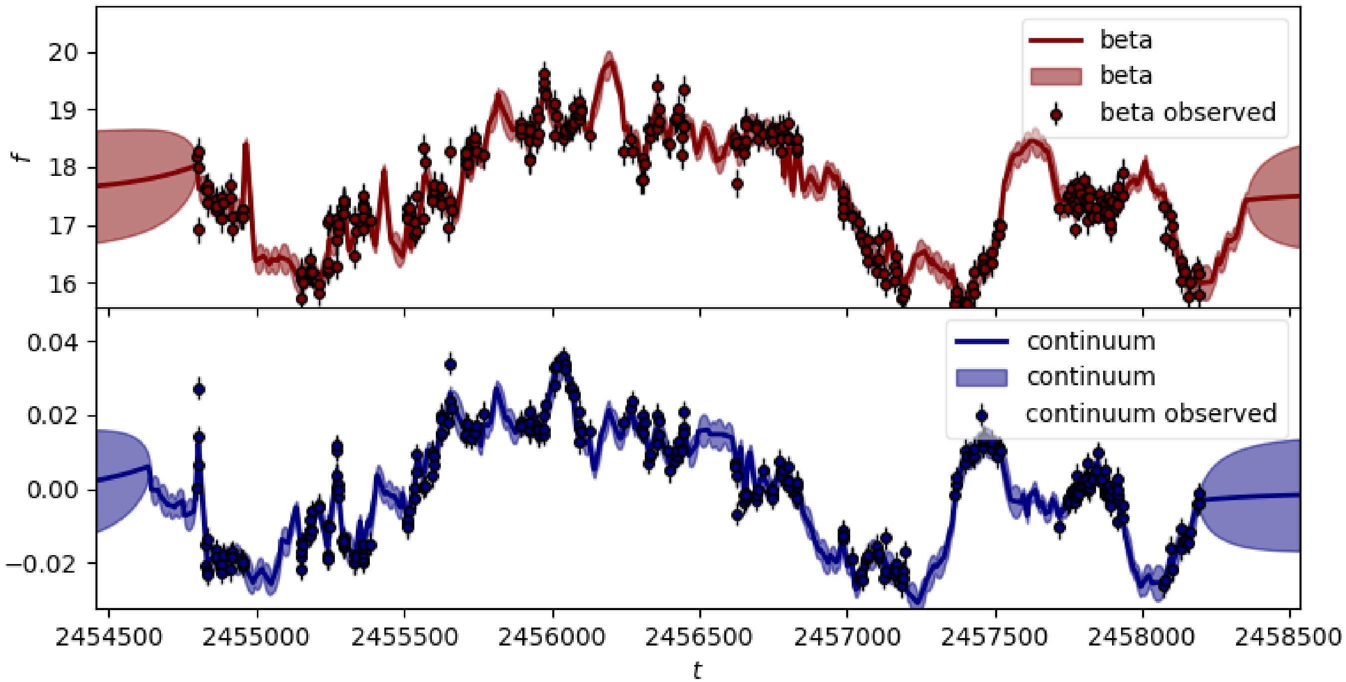


$$\tau_{\mathrm{H\beta}} = 146.8^{+8.3}_{-12.1}$$

$$\tau_{\mathrm{H\gamma}} = 146.5^{+8.8}_{-9.7}$$

$$\tau_{\mathrm{Fe\,II}} = 322.0^{+55.5}_{-57.9}$$

JAVELIN result



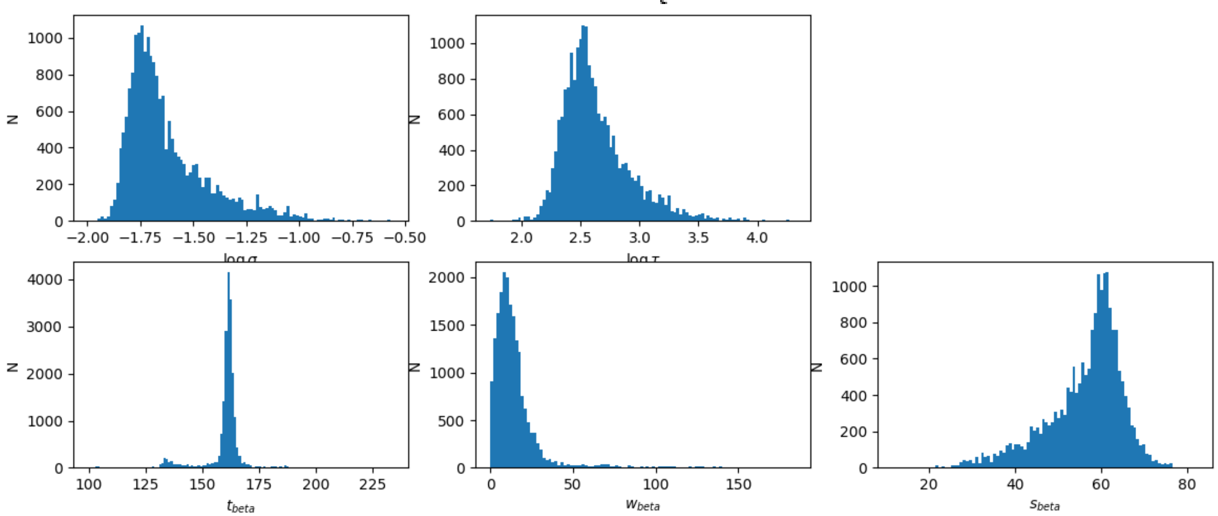


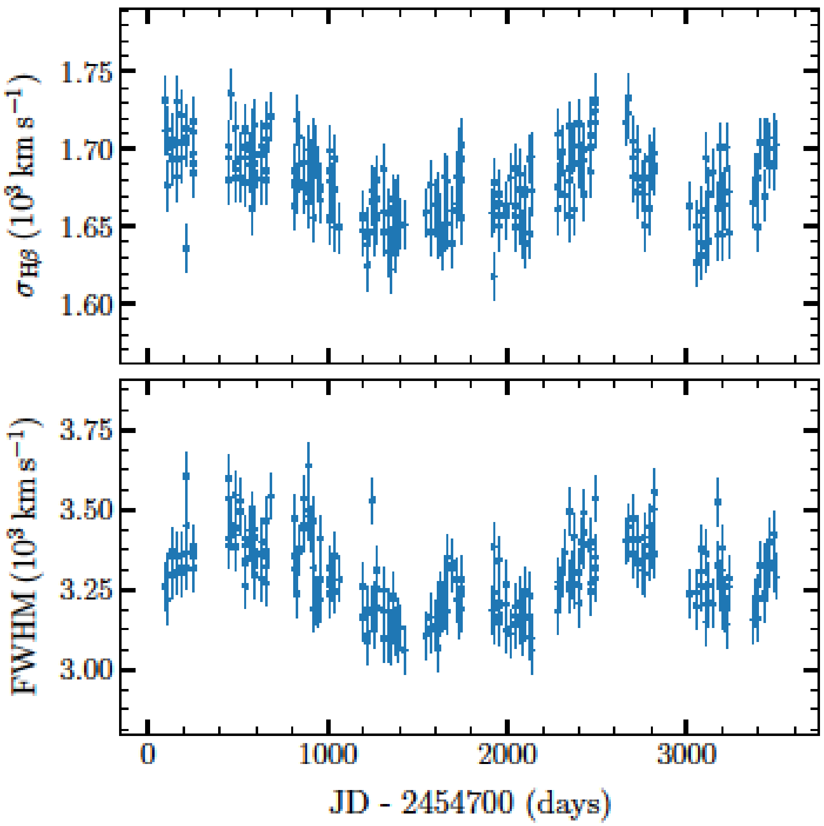
Table 3. Emission-line Time Lags

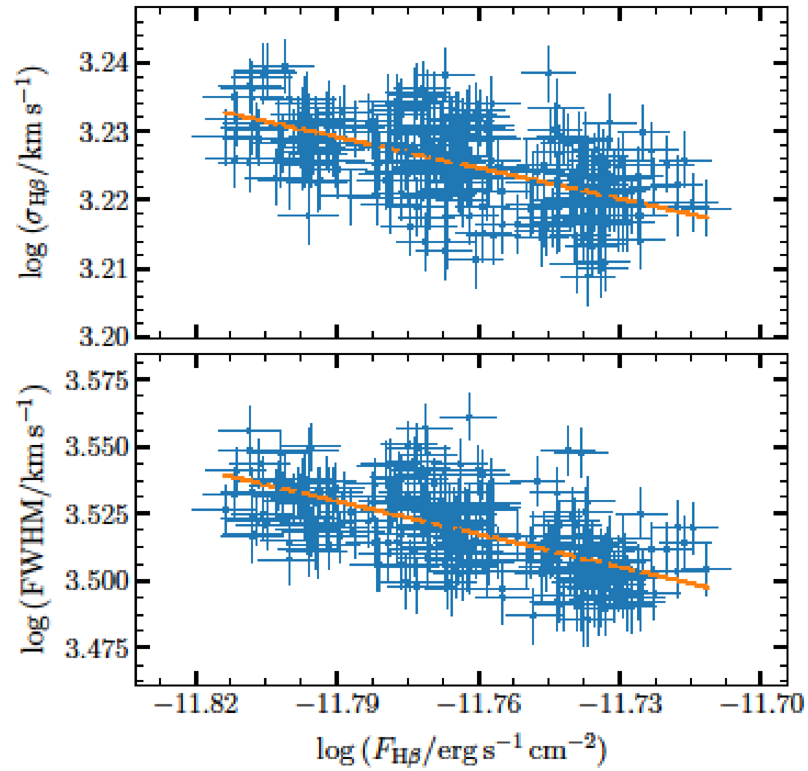
Lines	$r_{\max}$	lags (days)	
		observed frame	rest frame
Hβ	0.81	$170.0^{+9.6}_{-14.0}$	$146.8^{+8.3}_{-12.1}$
Hγ	0.79	$169.7^{+10.2}_{-11.2}$	$146.5^{+8.8}_{-9.7}$
Fe II	0.63	$373.0^{+64.3}_{-67.1}$	$322.0^{+55.5}_{-57.9}$

Table 4. Emission-line Widths

	Lines	Line width (mean)		Line width (RMS)	
		FWHM ($\mathrm{km\,s^{-1}}$)	$\sigma_{\rm line}$ ($\mathrm{km\,s^{-1}}$)	FWHM ($\mathrm{km\,s^{-1}}$)	$\sigma_{\rm line}$ ($\mathrm{km\,s^{-1}}$)
Steward	Hβ	3314.1 ± 59.3	1698.8 ± 25.1	1941.4 ± 69.5	1098.9 ± 39.9
	Hγ	3313.8 ± 59.2	1667.7 ± 25.2	2439.1 ± 82.5	1444.5 ± 46.4
	Fe II	2142.4 ± 116.1	...	...	...
Lijiang	Hβ	3196.9 ± 39.2	1702.9 ± 16.5	3305.2 ± 420.1	1081.0 ± 238.8
	Hγ	3139.0 ± 40.5	1535.9 ± 19.6	4079.7 ± 509.2	1176.9 ± 260.8
	Fe II	2039.3 ± 70.6	...	...	...

Hβ emission line widths VS. its flux





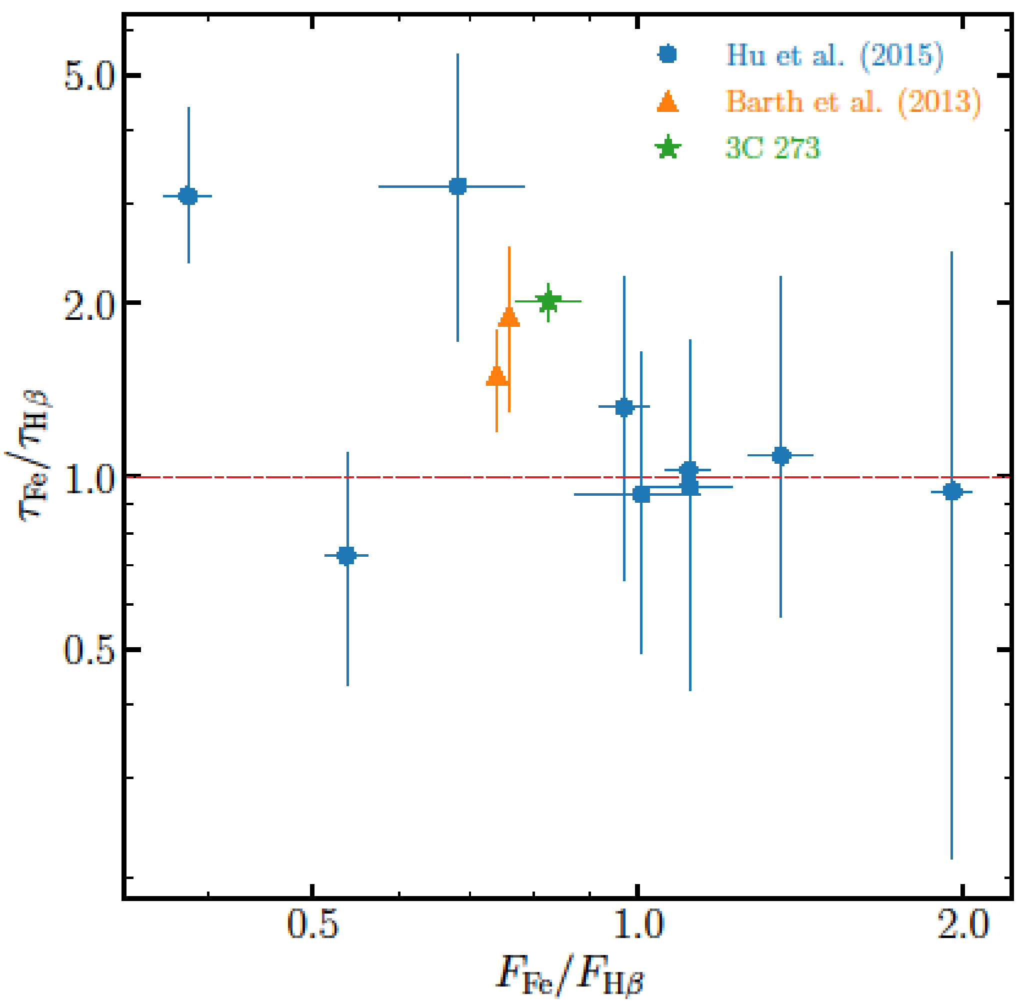
$\log \mathrm{V}_{\mathrm{H\beta}} = \alpha + \beta \log F_{\mathrm{H\beta}}$

FWHM： $(\alpha, \beta) = (-1.28 \pm 0.37, -0.41 \pm 0.03)$

σ_{line}： $(\alpha, \beta) = (1.46 \pm 0.15, -0.15 \pm 0.01)$

$r_{\mathrm{BLR}} \propto L_{5100}^{0.5}$ & virialized motion => $\beta = -0.25$

$\tau_{Fe}/\tau_{H\beta}$ VS. $F_{Fe}/F_{H\beta}$

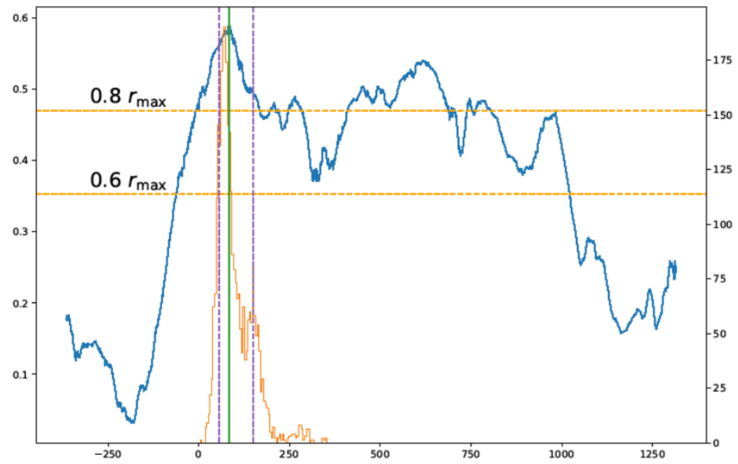


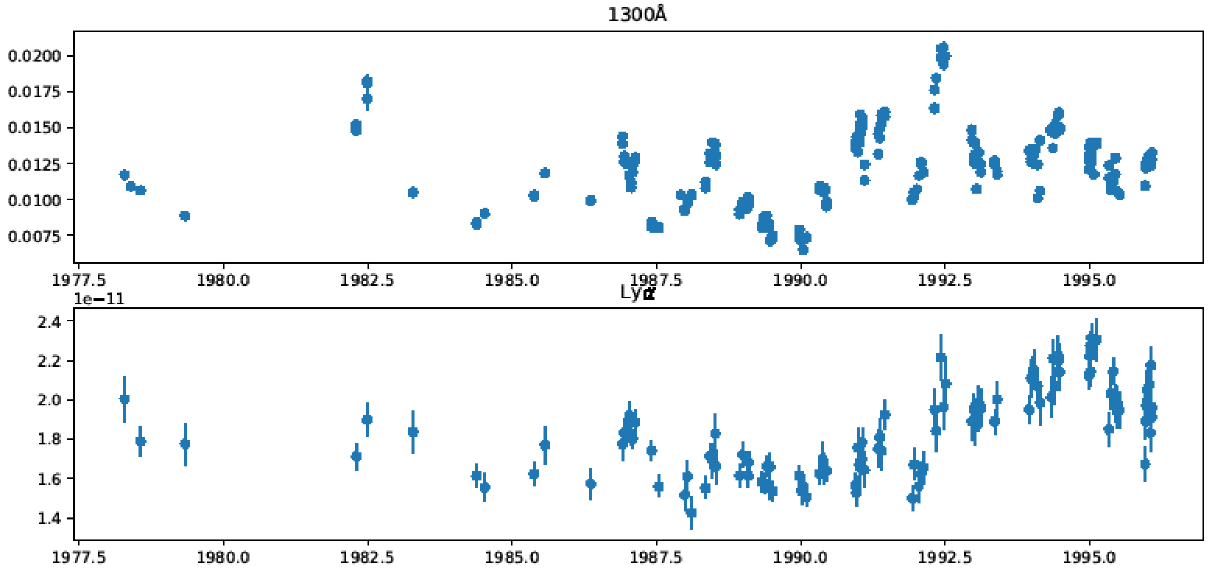
Lyα time lag

Time lag using the 0.8 $r_{\max}$ criterion

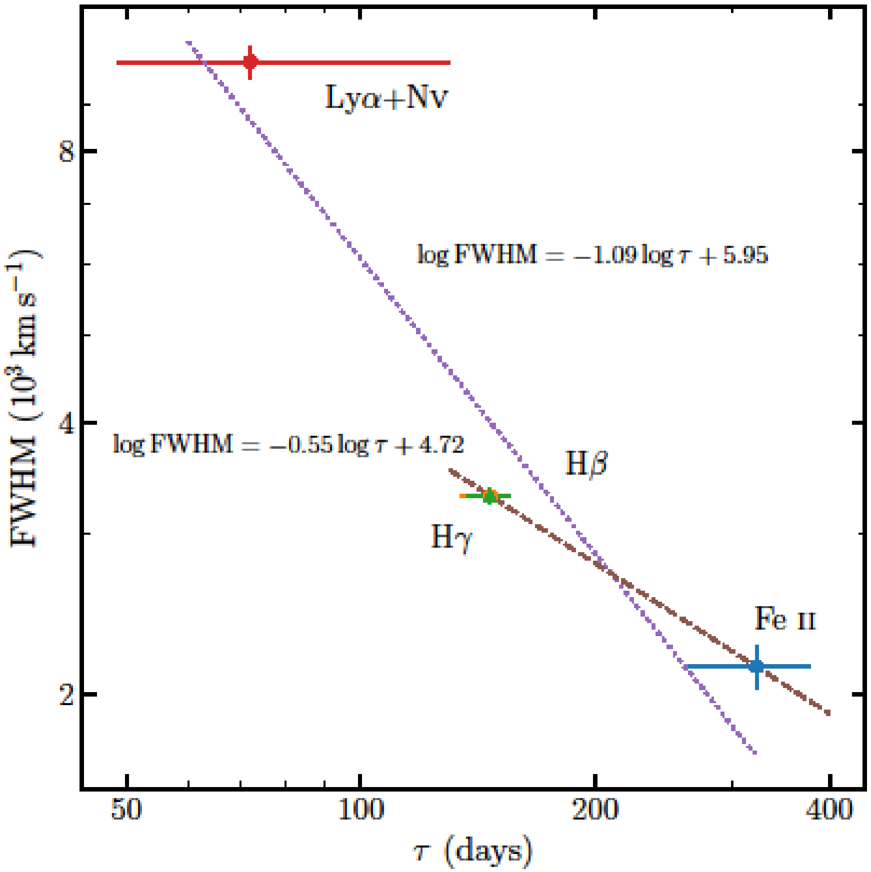
Only integrating the highest peak

$\tau_{\mathrm{Ly}\alpha+\mathrm{Nv}} = 72.2^{+58.1}_{-23.5}$days.

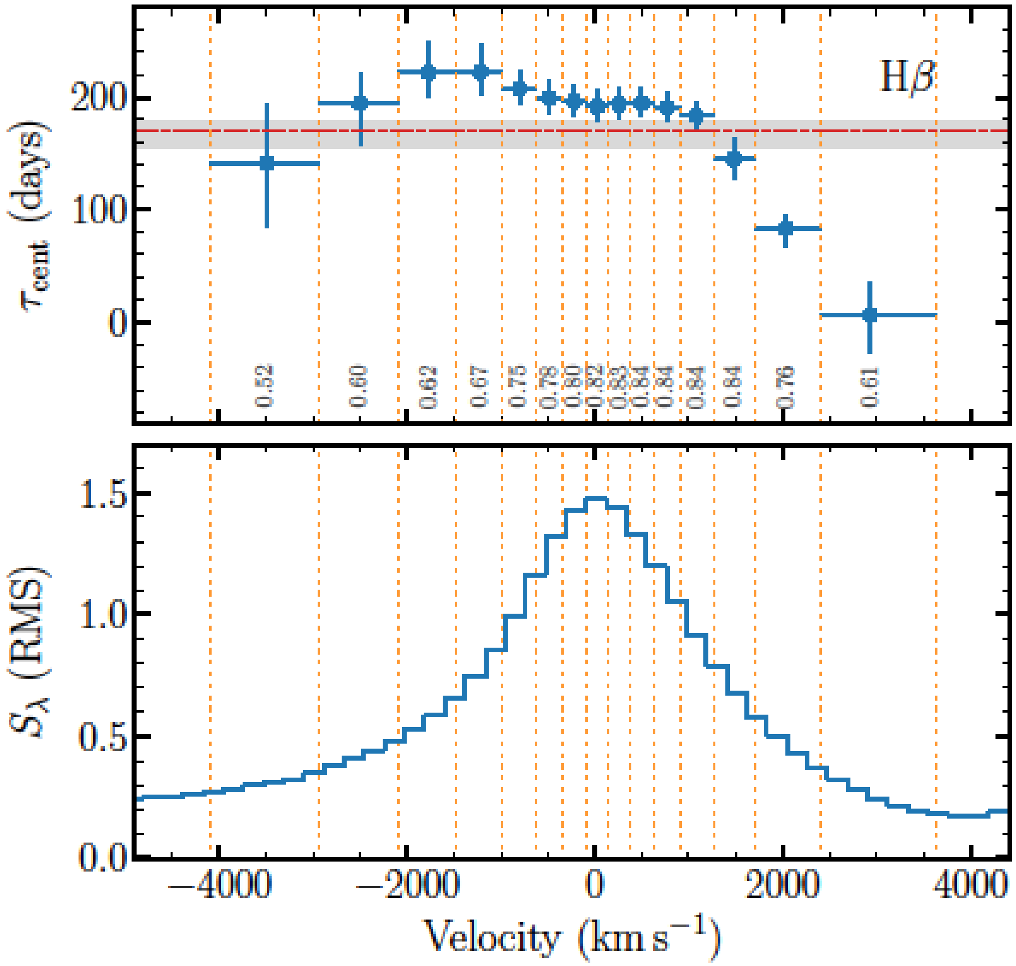




Emission line widths vs. the time lags



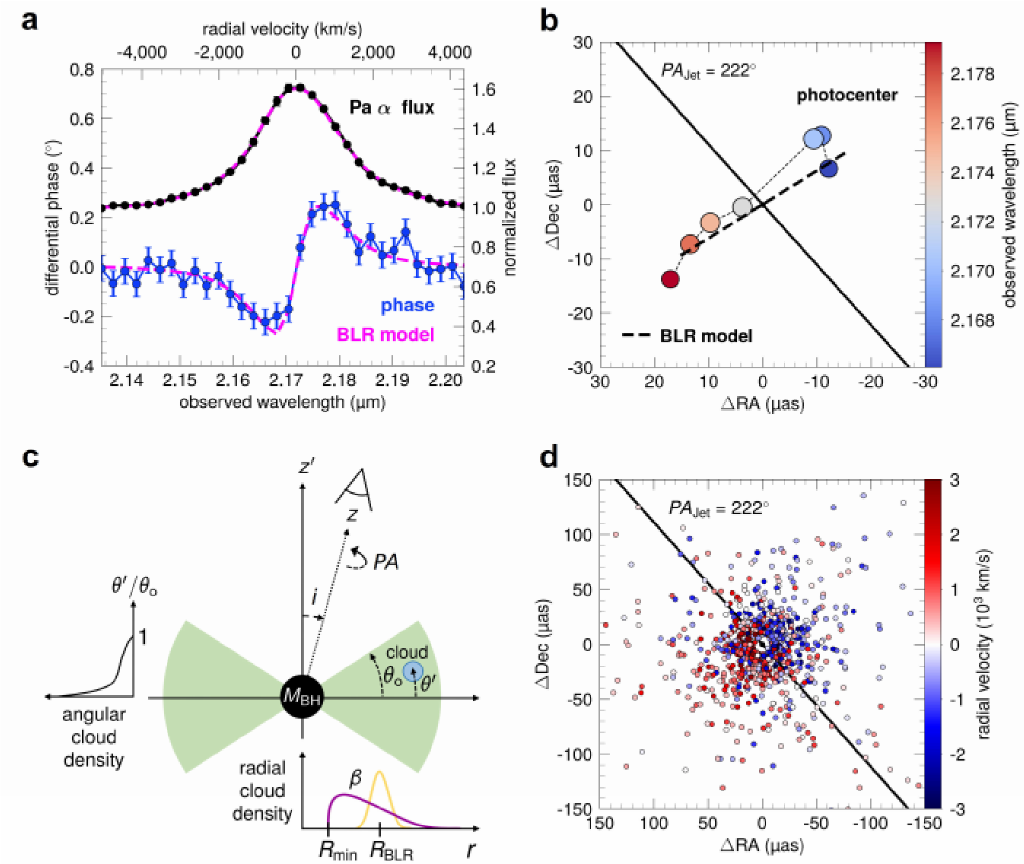
The velocity-resolved time lags



The black hole mass and accretion rate

- $M_{\rm BH} = f_{\rm BLR}\dfrac{c\tau V^2}{G}$， $R_{\rm BLR} = c\tau$
- $f_{\rm BLR} = 1.3$： $M_{\rm BH} = 4.1^{+0.3}_{-0.4} \times 10^8 M_\odot$
- $i = 12^\circ$: $\dot{\mathscr{M}} = 20.1\left(\dfrac{l_{44}}{\cos i}\right)^{3/2} m_7^{-2} \approx 9.6$

Compared with GRAVITY



Gravity Collaboration 2018

$R_{\mathrm{Pa}\alpha} = 145 \pm 35$ lt-days

Disk structure

Incline angle $i = 12 \pm 2^{\circ}$

correlation with torus？

Possible explanation of the detrending: optical emissions of the jet

Untangling Optical Emissions of the Jet and Accretion Disk in the Flat-Spectrum Radio Quasar 3C 273 with Reverberation Mapping Data

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ABSTRACT

3C 273 is an intensively monitored flat-spectrum radio quasar with both a beamed jet and blue bump together with broad emission lines. The coexistence of the comparably prominent jet and accretion disk leads to complicated variability properties. Recent reverberation mapping monitoring for 3C 273 revealed that the optical continuum shows a distinct long-term trend that does not have a corresponding echo in the Hβ fluxes. We compile multi-wavelength monitoring data from the *Swift* archive and other ground-based programs and clearly find two components of emissions at optical wavelength. One component stems from the accretion disk itself and the other component can be ascribed to the jet contribution, which also naturally accounts for the non-echoed trend in reverberation mapping data. We develop an approach to decouple the optical emissions from the jet and accretion disk in 3C 273 with the aid of multi-wavelength monitoring data. The results show that the jet contributes a fraction of $\sim 25\%$ at the minimum and up to $\sim 50\%$ at the maximum to the total optical emissions. This is the first time to provide a physical interpretation to the "detrending" manipulation conventionally adopted in reverberation mapping analysis. Our work also illustrates the importance of appropriately analyzing variability properties in cases of coexisting jets and accretion disks.

Data

Table 1. Monitoring Data of 3C 273.

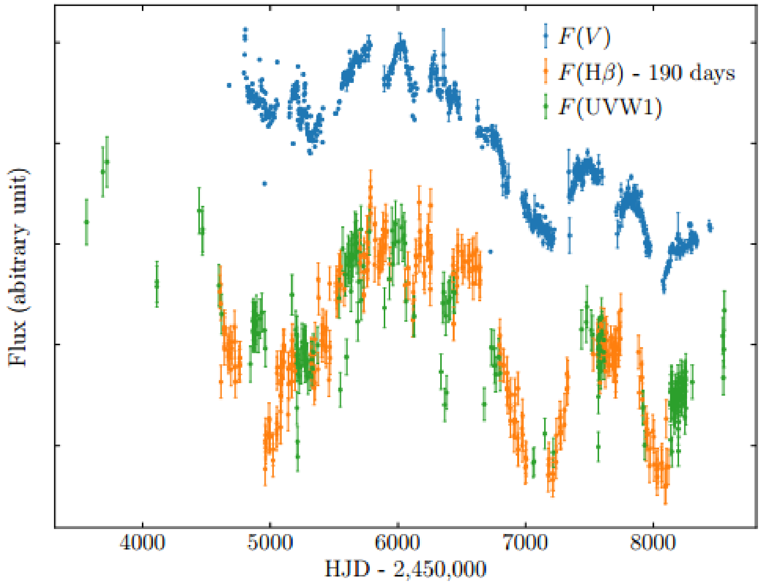
Source	Filter	Wavelength	Observation Period JD-2,450,000	Observation Period Date	$N_{\rm obs}$	$\Delta t_{\rm ave}$ (day)	$\Delta t_{\rm med}$ (day)	Ref
Swift	*UVW2*	1928 Å	3562.152–8553.836	2005 Jul–2019 Mar	246	20.3	2.9	···
Swift	*UVM2*	2246 Å	3562.152–8582.797	2005 Jul–2019 Apr	232	21.6	2.9	···
Swift	*UVW1*	2600 Å	3562.152–8555.820	2005 Jul–2019 Mar	225	22.2	3.1	···
Swift	*U*	3465 Å	3562.086–8580.789	2005 Jul–2019 Apr	194	25.9	1.9	···
Swift	*B Swift*	4392 Å	3562.086–8304.324	2005 Jul–2018 Jul	111	42.7	1.1	···
SMARTS	*B*	4450 Å	4677.497–7856.656	2008 Jul–2017 Apr	363	8.8	2.9	3
RM[a]	···	5100 Å	4795.018–8305.687	2008 Nov–2018 Jul	285	11.4	2.1	4
Swift	*V Swift*	5468 Å	3562.086–8304.324	2005 Jul–2018 Jul	225	21.1	1.9	···
ASAS-SN	*V*	5510 Å	5956.146–8449.136	2012 Jan–2018 Nov	988	2.5	0.002	2
SMARTS	*V*	5510 Å	4677.499–7856.658	2008 Jul–2017 Apr	365	4.7	2.1	3
RM	*V*	5510 Å	4795.020–8305.697	2008 Nov–2018 Jul	306	11.9	2.0	4
SMARTS	*R*	6580 Å	4537.596–7856.660	2008 Jul–2017 Apr	371	8.9	2.9	3
SMARTS	*J*	12200 Å	4501.786–7091.743	2008 Feb–2015 Mar	306	8.5	2.1	3
OVRO	···	200 μm	4473.983–8477.155	2008 Jan–2018 Dec	697	5.8	3.0	5

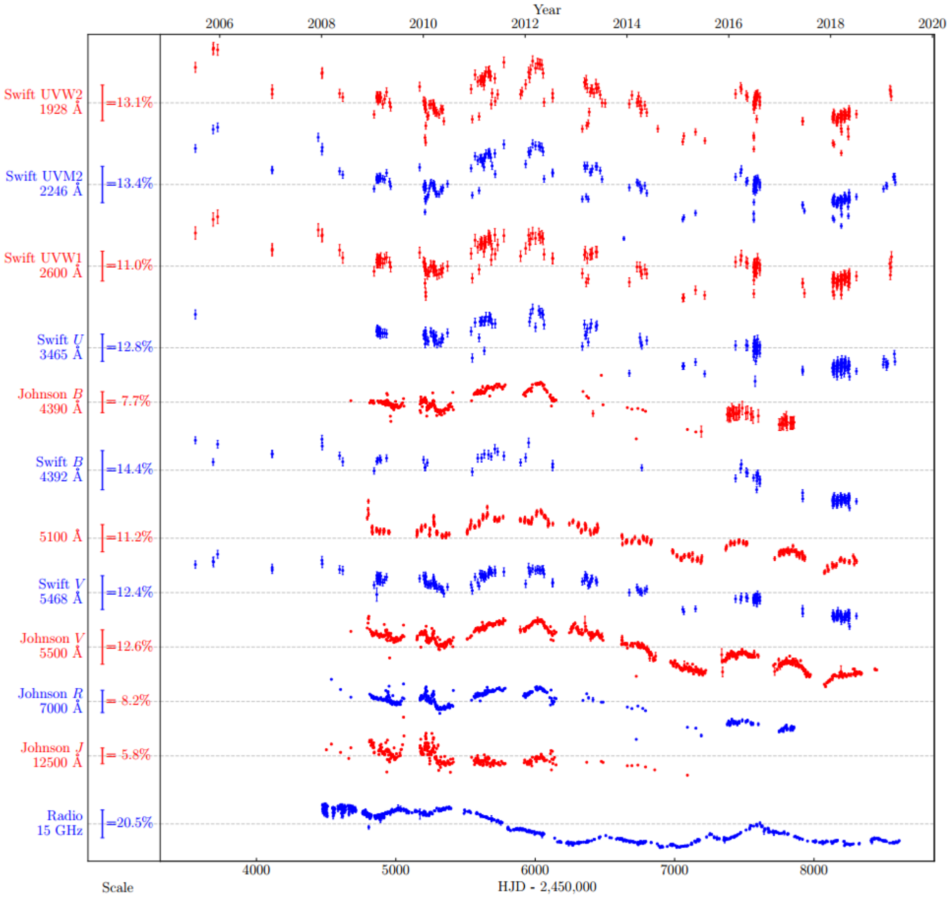
References— (1) Drake et al. (2009); (2) Shappee et al. (2014) and Kochanek et al. (2017); (3) Bonning et al. (2012); (4) Zhang et al. (2019); (5) Richards et al. (2011).

[a] "RM" means that the data is from a reverberation mapping campaign presented in Zhang et al. (2019).

Evidence

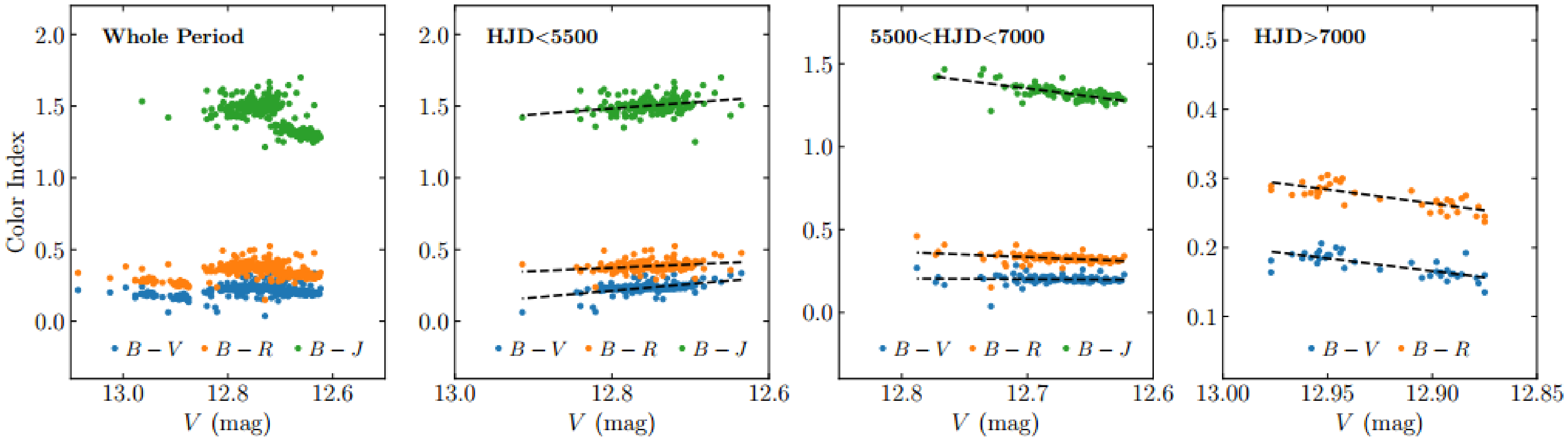
- The long trending become unclear from optical to UV band.





Evidence

Color variations show complex behaviour.



Evidence

The residuals of continuum – Hβ are good matched with the radio 15GHz light curve.

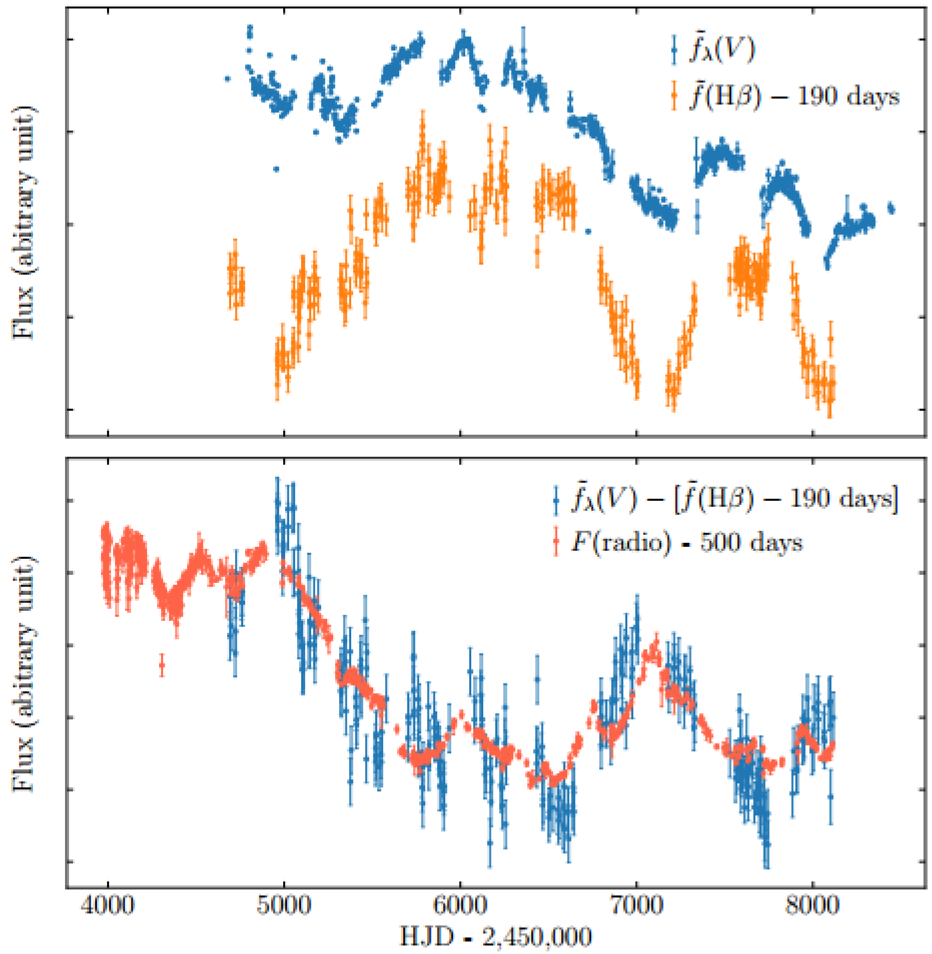
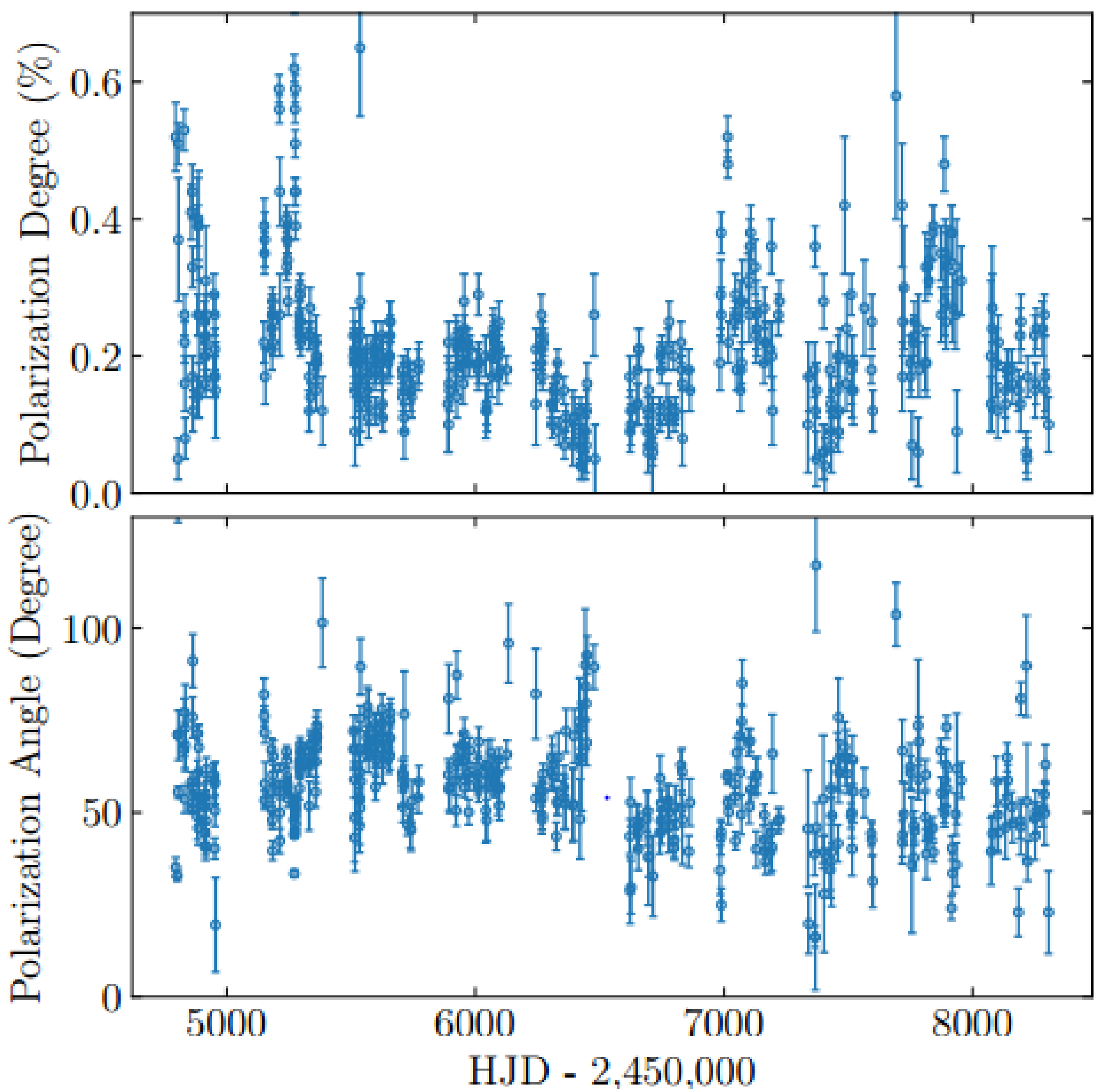


Figure 5. (Top) The scaled V-band light curve denoted by $\tilde{f}(V)$ and scaled and shifted Hβ light curve denoted by $\tilde{f}(H\beta)$. (Bottom) The residuals $\tilde{f}(V) - \tilde{f}(H\beta)$, on which superposed is the scaled radio 15 GHz light curve denoted by F(radio). Note that $\tilde{f}(H\beta)$ and F(radio) are additionally shifted backward by 190 and 500 days, respectively. See 3.4 for the definitions of $\tilde{f}(V)$ and $\tilde{f}(H\beta)$.



Polarization Degree (%)
0.0
0.2
0.4
0.6
Polarization Angle (Degree)
0
50
100
5000
6000
7000
8000
HJD - 2,450,000

Model

- The optical continuum is deemed to be a combination of the disk and jet emissions:

$$C_{\rm t}(t) = C_{\rm d}(t) + C_{\rm j}(t),$$

- the jet emissions at optical and radio wavelengths are linked with a transfer function:

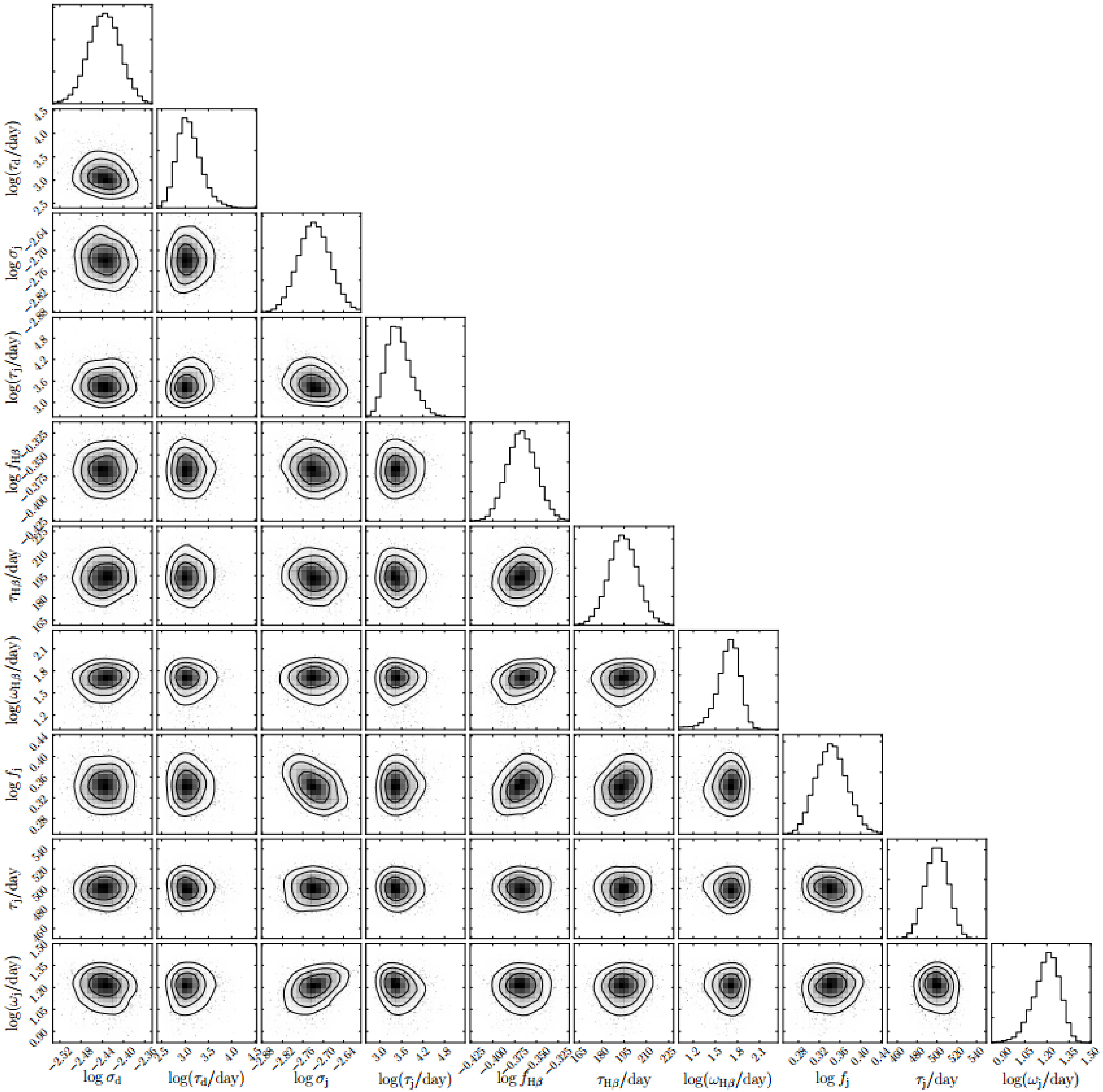
$$R_{\rm j}(t) = \int \Psi_{\rm j}(\tau) C_{\rm j}(t-\tau) d\tau,$$

- The Hβ emission line responds to the continuum emission from the accretion disk:

$$L_{\rm H\beta}(t) = \int \Psi_{\rm H\beta}(\tau) C_{\rm d}(t-\tau) d\tau,$$

$$p(t) = \frac{C_{\rm j}(t) p_{\rm j}(t)}{C_{\rm j}(t) + C_{\rm d}(t)} = \frac{C_{\rm j}(t)}{C_{\rm t}(t)} p_{\rm j}(t),$$

- Using the damped random walk to reconstruct the light curves.

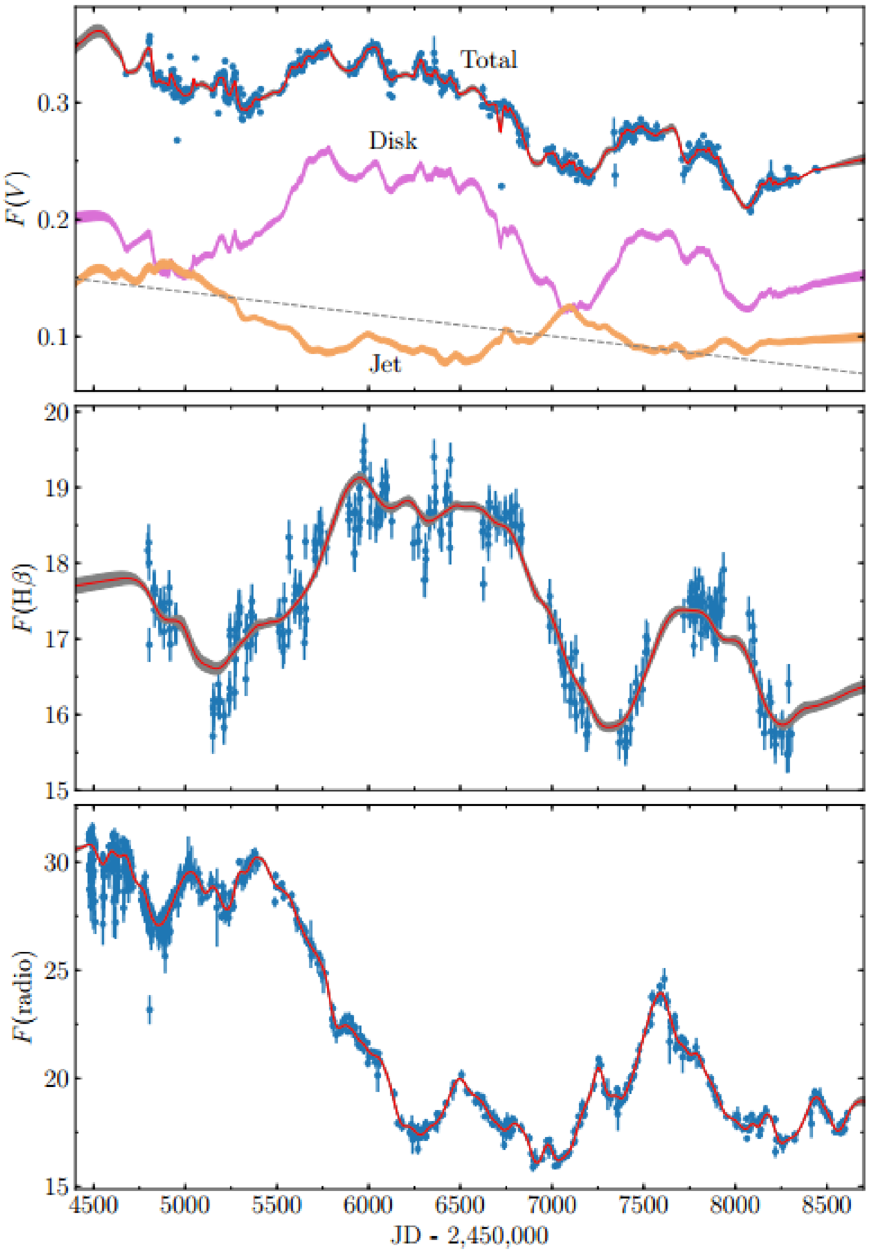

log σ_d
log(τ_d/day)
log σ_j
log(τ_j/day)
log f_Hβ
τ_Hβ/day
log(ω_Hβ/day)
log f_j
τ_j/day
log(ω_j/day)

Results

Table 3. Inferred Parameter Values and Uncertainties.

Parameter	Value
$\log \sigma_d$	$-2.435^{+0.029}_{-0.026}$
$\log(T_d/\text{day})$	$3.05^{+0.26}_{-0.18}$
$\log \sigma_j$	$-2.725^{+0.044}_{-0.046}$
$\log(T_j/\text{day})$	$3.51^{+0.30}_{-0.26}$
$\log f_{H\beta}$	$-0.368^{+0.016}_{-0.013}$
$\tau_{H\beta}/\text{day}$	$194.9^{+9.7}_{-9.8}$
$\log(\omega_{H\beta}/\text{day})$	$1.69^{+0.09}_{-0.16}$
$\log f_j$	$0.343^{+0.026}_{-0.024}$
τ_j/day	$501.0^{+7.5}_{-10.2}$
$\log(\omega_j/\text{day})$	$1.202^{+0.072}_{-0.093}$
f_q	$0.594^{+0.014}_{-0.014}$
$\bar{p}_j/\%$	$0.569^{+0.022}_{-0.022}$

NOTE—Parameter values are determined from the medians of the posterior probability distributions and the uncertainties represent the 68.3% confidence intervals.



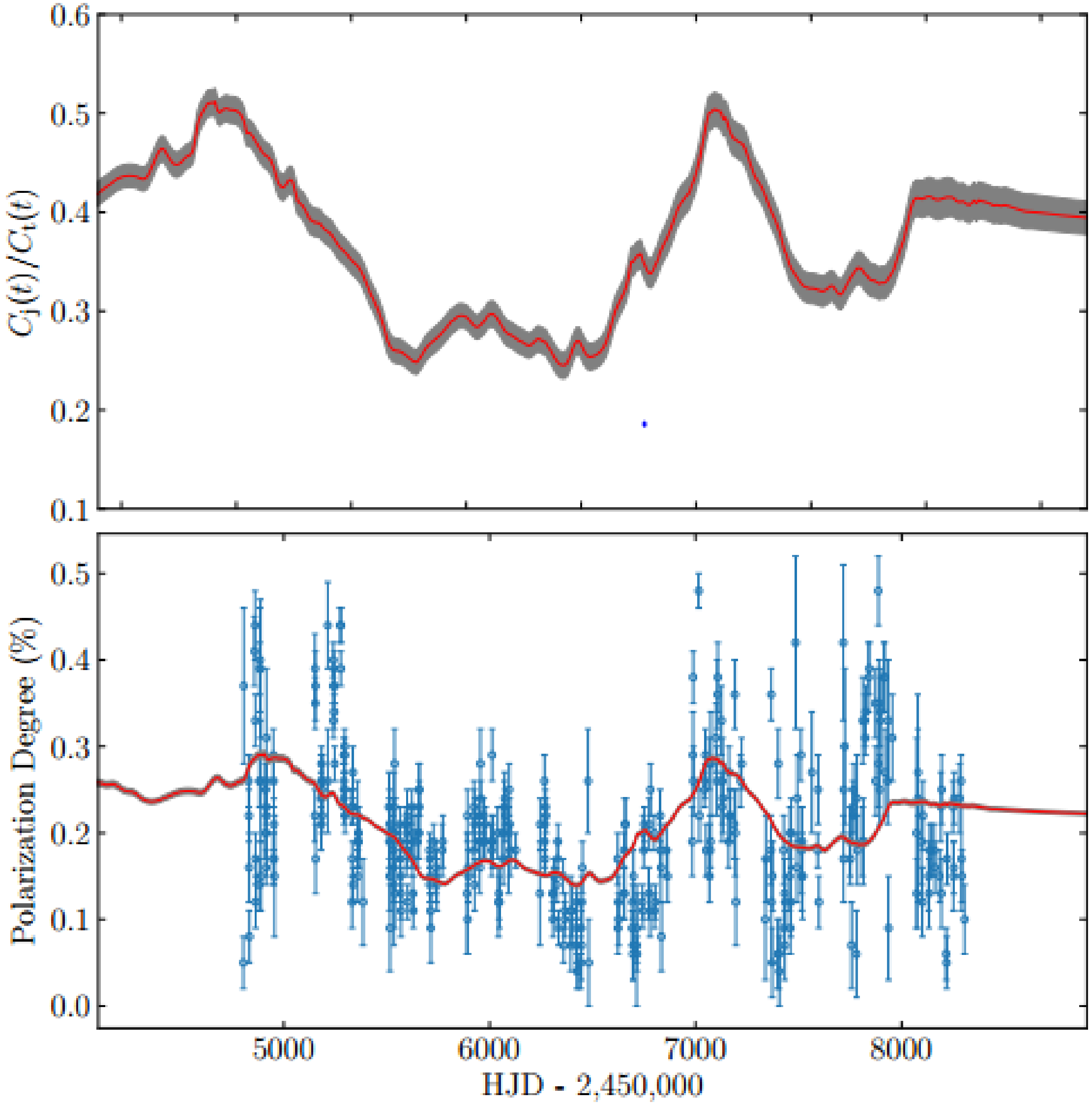


Figure 9. (Top) The ratio of the decomposed optical jet flux to the total optical flux. (Bottom) Fits to the polarization data. Points with error bars represent the observed polarization degrees and the solid line with shaded areas represent the best fits.

Summary

- The time lags of Balmer emission lines are about 150 days in rest frame.
- Fe II time lag $\tau_{\rm Fe} = 322.0^{+55.5}_{-57.9}$ days, which follows the $\frac{\tau_{\rm Fe}}{\tau_{\rm H\beta}} - \frac{F_{\rm Fe}}{F_{\rm H\beta}}$ correlation found in Hu et al. (2015).
- The velocity-resolved time lags show the signature of a rotation-dominated disk.
- With the UV lines, we find 3C 273 has a stratified structure in its BLR.
- Adopting a virial factor of $f_{\rm BLR} = 1.3$, 3C 273 has a BH mass of $M_\bullet = 4.1^{+0.3}_{-0.4} \times 10^8 M_\odot$ and is accreting with a rate of $9.3 L_{\rm Edd} c^{-2}$
- The long trending in the continuum light curve may be due to the jet contribution.

Thank You