physical

A new interpretation of optical and infrared variability in quasars

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identified

Changing-look quasars are a recently identified class of active galaxies in which the strong UV continuum and/or broad optical hydrogen emission lines associated with unobscured quasars either appear or disappear on timescales of months to years [1, 2, 3, 4, 5]. The physical processes responsible for this behaviour are still debated, but changes in the black hole accretion rate or accretion disk structure appear more likely than changes in obscuration [6, 7]. Here we report on three epochs of spectroscopy of SDSS J110057.70-005304.5, a quasar at a redshift of $z = 0.378$ whose UV continuum and broad hydrogen emission lines have dramatically faded over the past ≈20 years. The change in this quasar was initially ~~seen~~ in the infrared, and an archival spectrum from 2010 shows an intermediate phase of the transition during which the flux below rest-frame 3400Å has collapsed. This combination is unique compared to previously published examples of changing-look quasars, and is best explained by dramatic changes in the innermost regions of the accretion disk. The optical continuum has been rising again since mid-2016, leading to a prediction of a rise in hydrogen emission line flux in the next year. If our model is confirmed, the physics of changing-look quasars are governed by processes at the innermost stable circular orbit (ISCO) around the black hole, and the structure of the innermost disk. The easily identifiable and monitored changing-look quasars would then provide a new probe of the strong gravity regime.

If I were the referee (or editor) I'd want you to come back to this point at the end. (but I'm not the referee or editor)

The changing-look quasar phenomenon, where the dramatic disappearance, or appearance, of ~~the~~ strong UV continuum and/or ~~the~~ prominent broad optical emission lines is seen on month-to-year timescales, is now widely observed [1, 2, 3, 4, 5, 8, 9], yet poorly ~~understood~~. Changes in obscuration are generally disfavoured due to the timescales currently observed [6, 7], and it is clear that changing-look quasars are a key laboratory for understanding accretion physics and active galactic nuclei (AGN).

expected to orbit the supermassive black holes at ~~center~~ the nucleus of quasars.

See e-mail

The Shakura-Sunyaev $\alpha-$disk model [10] has long been used to (over-)simply describe the basic properties of the optically thick, geometrically thin accretion disks. ~~Indeed~~ ~~we~~ We utilize the alpha-disk model in this paper, however, the model is ad hoc, only parameterizing disk viscosity, and does not permit predictions of global changes to the disk [11]. Real AGN disks seem to be cooler [e.g., 12] and larger [e.g., 13, 14, 15, 16] than the alpha-disk model predicts, and viscosity seems likely due to magnetic fields [17] with additional contributions to turbulence from the effects of embedded objects in the disk [e.g., 18].

mid-infrared

In contrast,

Changing-look quasars have traditionally been discovered by looking for large, $|\Delta m| > 1$ magnitude changes in the optical light curves of quasars or galaxies ~~(e.g. across 3720Å < λ < 5680Å, in the g-band)~~. ~~However~~, we have taken advantage of the ongoing Near-Earth Object WISE Reactivation mission [NEOWISE-R; 19, 20, 21], ~~as well as~~ the Dark Energy Camera Legacy Survey (DECaLS[1]) in order to discover new ~~changing-look~~ quasars. While ~~previous~~ efforts have used the ~~1-year baseline~~ of the WISE mission to identify CLQs [22, e.g., [], our team is the first to extend . Our team is the first to extend this selection to the infrared using NEOWISE-R mission data, and we have identified

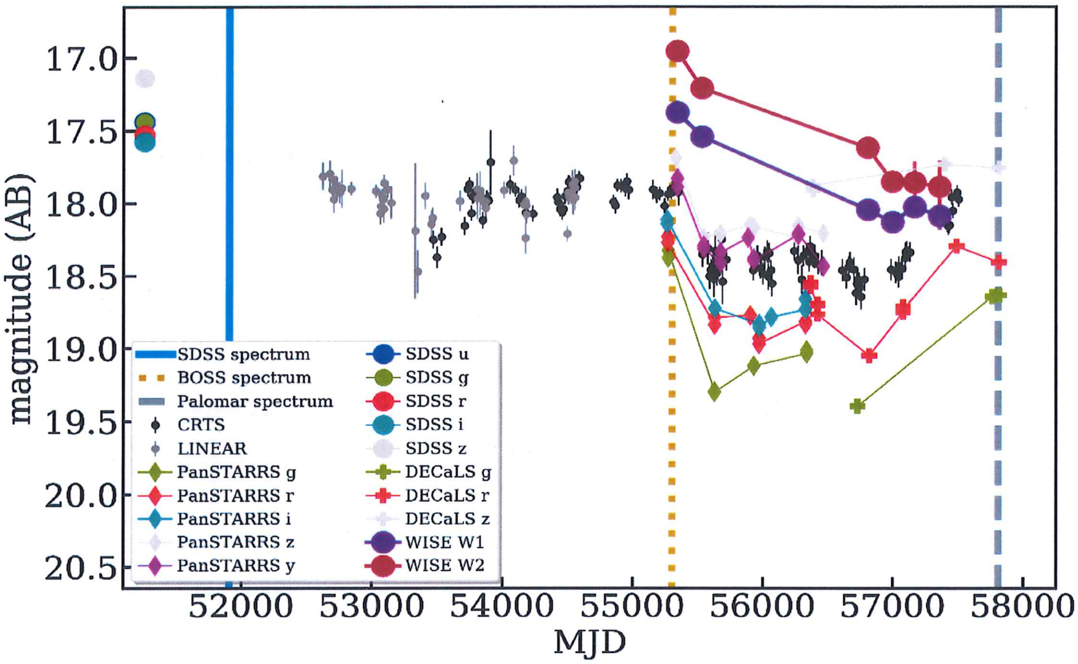
optical

supplemented with

[1] legacysurvey.org/decamls/

feels like a problem set at times....

print out to proof read



indicate

Figure 1 Multi-wavelength light curve of J1100-0053, including optical data from LINEAR, CRTS, SDSS, PanSTARRS and DECaLS, and mid-IR data from the WISE satellite. The three vertical lines ~~illustrate~~ the epochs of the three optical spectra presented in Figure 2. J1100-0053 was flagged for further study due to the extreme IR fading observed by WISE. Note that the optical emission has been recovering over the past few years; we predict the IR emission will similarly recover over the next ~~few~~ years.

have you ever answered me on this one? → changes

a sample of SDSS quasars that show dramatic decreases in their IR flux over the course of a few years. These changes are on timescales too short to be due to changes in obscuration, so a different explanation is needed.

Fix/explain

In this article we present the $z = 0.378$ quasar SDSS J110057.70-005304.5 (hereafter J1100-0053) for which we have spectral observations showing a transition in the blue-continuum slope traditionally associated with the black-body spectrum of an object with broad hydrogen emission lines, into a 'dim state' where the rest-frame UV flux is suppressed, and then returning to a blue-continuum sloped quasar. We present a model that invokes changes at the ISCO to be the triggering event for the change in the accretion disk, which along with the changes in the broad emission lines, explains a major change to the disk interior to $150r_g$ (where r_g is the gravitational radius; $r_g = \frac{GM}{c^2}$) as well as the IR light curves. Critically, our model makes predictions to the future behaviour of J1100-0053.

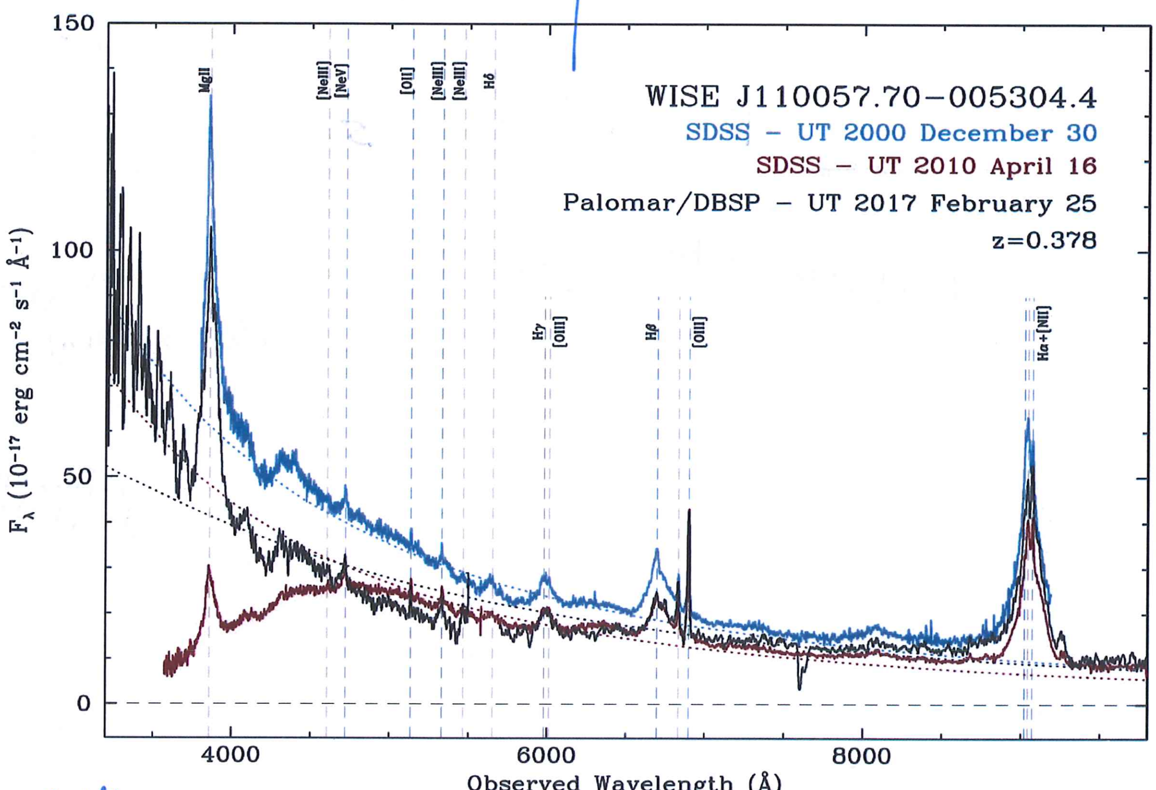
very long sentences. take your time - you have space.

1 Target Selection and Observations

We started by matching the SDSS-III BOSS Data Release 12 Quasar catalog [DR12Q; 23] to the NEOWISE-R IR data (WISE W1 at 3.4μm, WISE W2 at 4.6μm). We found ~200 objects identified by a factor of 2 or more change in

you're saying the blue slope is what's associated with the black body spectrum....

use new version



add a space

Figure 2 Optical spectra of J1100-0053 obtained on MJD 51908 (blue; SDSS), 55302, (red; BOSS) and 57809 (black; Palomar/DBSP). *Left*:: ~~The full optical spectra; *Right (top)*:: Zoom in on the Hβ-[O III] complex; *Right (bottom)*:: Zoom in on the Hα-N II complex~~.

:: → :

~~see e~~ new version in e-mail

should spell out other acronyms too— especially since you do CRTS

for which

the observed WISE W1 and W2 bands over the course of typically three or four years [see 21, and the Supplemental Material for the detailed NEOWISE-R selection]. Scanning these 200 objects, we also examined the change in optical colour using the SDSS and DECaLS imaging surveys in order to identify changes suggestive of changing-look quasars. From this inspection, a priority list of ≈ 70 quasar targets was derived ~~and~~ we obtained new optical spectroscopy from the Palomar 5m telescope. J1100-0053 was one of these 70 objects, but, critically, had spectra from both SDSS and BOSS and was thus a priority target.

Figure 1 presents the light curve of J1100-0053. Along with WISE IR data, optical data from the SDSS, Catalina Real-time Transient Survey [CRTS; 24, 25], LINEAR [26] and PanSTARRS [27, 28, 29, 30] are available. Figure 2 shows the three optical spectra of J1100-0053 from the SDSS, BOSS and Palomar observations, taken on MJD 51908 (UT 2000 December 30), 55302 (UT 2010 April 16) and 57809 (UT 2017 February 25), respectively. The first-epoch SDSS spectrum shows a typical blue quasar, but blue continuum then collapses in the second epoch BOSS spectrum taken 10 years later. ~~However,~~ T the blue continuum ~~has~~ then returned in the third epoch spectrum 7 years later, albeit at a diminished ~~flux from~~ the initial spectrum. The Supplemental Material gives further ~~observation~~ details. ~~including an achival ROSAT detection.~~

not mentioned again in main text, so I'd drop here.

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observational

2 Discussion

Our model of thermal emission from a multicolour disk implies changes in the region from the ISCO to $\sim$few tens-100 r_g are required to suppress flux into the observed g-band. In particular, we suggest a physical collapse of the disk scale height due to a cooling front propagating outward from the ISCO.

This dramatic decrease in the torque at the ISCO leads

For J1100-0053 we apply our model as follows. We start with an inflated (slim) disk. We assume a non-zero torque at the ISCO and $h/r \sim 0.2$ inside of $r \sim 100r_g$. This is the initial state circa 2000 (MJD 51900). A non-zero torque at the ISCO implies that matter in the plunging region is connected (however weakly) to matter outside the ISCO, probably by magnetic fields [e.g., 31, 32]. A non-zero torque at the ISCO maintains a hotter innermost disk than a condition of zero torque at the ISCO, and an assumption of non-zero torque is particularly appropriate if disk viscosity and accretion are ~~indeed~~ driven by magnetic fields. ~~In order~~ to explain data subsequent to 2007, we assume a cooling front propagates out from the ISCO over a timescale $t_{\rm front}$. ~~The simplest explanation is~~ that the non-zero torque condition at the ISCO changes to a (more nearly) zero-torque condition, ~~leading~~ to a dramatically cooler, thinner disk ~~near the ISCO~~. As the cooling front propagates, the drop in temperature leads to a drop in flux. Our model ~~requires~~ cooler regions behind the front ~~to emit~~ 10% the flux of the initial hotter disk, and the disk height drops by a factor $\sim$2. The dimming of the inner disk causes a drop in the ionizing photon flux ($L_{\rm ion}$), which will causes the Balmer lines to drop in flux after a light travel time of months and the IR from the outer disk/torus to drop in flux after a light travel time of $\sim$3 years.

innermost

has the

Q

give equation here

emitting

if not used later, drop

justify

If the inner accretion disk is usually inflated [see e.g., 33, 34, 35], such a cooling front will naturally produce: 1) a collapse in the scale height of the disk; 2) a decrease in flux moving from UV to longer optical wavelengths; 3) a temporarily thicker scattering atmosphere, further decreasing flux at short wavelengths. This model implies changes to the optical emission moving from shorter to longer wavelengths (as the radius of the cooling front increases), on months-to-years-long timescales. It also predicts a longer time to recover the original flux (compared to the initial

strange to have these lists back-2-back

One simple, plausible trigger for this cooling front is

possibly due to... [help us here, theorists]

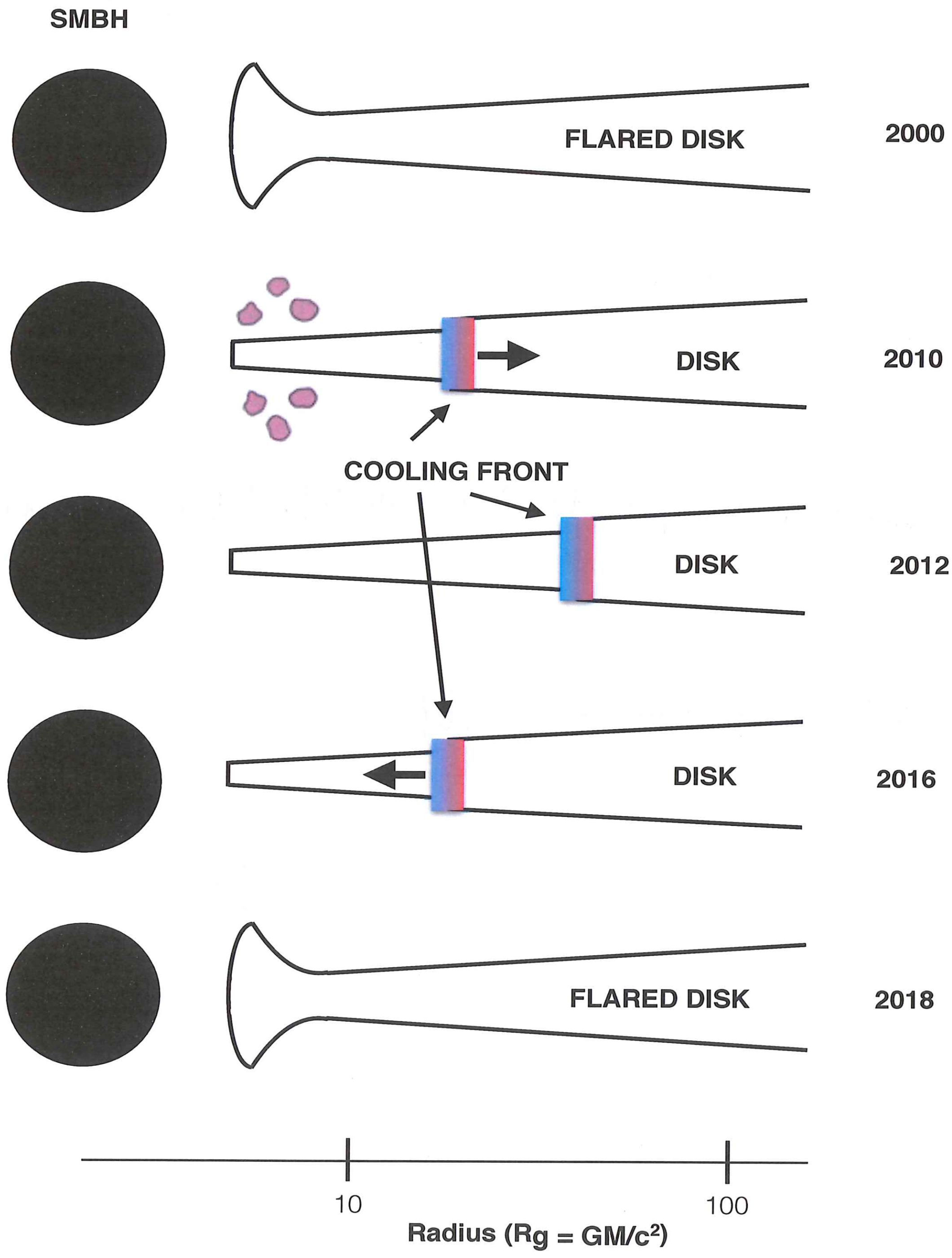

Figure 3 A cartoon illustration of our model explaining the unusual spectral evolution of J1100-0053. In 2000, corresponding to the SDSS spectral epoch, the quasar has a standard modified α-disk, with a geometrically thin, optically thick disk that is inflated near the ISCO, i.e., the inner edge of the accretion disk. Circa 2007, an event occurs that deflates the inner disk, leaving some scattering clouds, and causing a cooling front to propogate inwards. Circa 2012, the front reflects back, re-heating the inner accretion disk. We predict that in the next year, the quasar should roughly return to its initial state.

presumably the eq'n giving t(front) will make this obvious?

collapse) as a front will move more slowly in a thinner disk (see Fig. 2). A decrease in the UV flux would be expected to cause a decrease in IR flux, as the heating of the IR-emitting dusty torus is reduced; however, there should be a delay due to light travel time as well [e.g., 36].

repetitive with previous ¶

Since we assume the disk starts in a puffed-up state ($h/r \sim 0.2$) and since the front cooling time (equation 5 in the Supplemental Material) is inversely proportional to h/r and α, the front propagates faster in a puffed-up disk than in a thinner disk. By 2010 (MJD 55300) the front has reached $r \sim 50r_g$. During that time, the collapsing disk height increases the number density of scatterers and the temporary cold phase formed during cooling produces the remarkable blue downturn in the 2010 spectrum. The cooling front continues to propagate radially outward but cools less efficiently at larger disk radii. Eventually, a heating front propagates back inwards, analagous to the well-known accretion disk limit cycle mechanism in models of dwarf novae outbursts [e.g., 37]. The returning heating front travels more slowly because the disk is thinner (and $t_{\rm front}$ is inversely proportional to h/r), and will re-inflate the disk as it propagates inwards towards the SMBH. This means the return to normal wll be asymmetric in time, as observed, and the g-band bottoms out first, because that wavelength is dominated by emission coming from $r \sim 100r_g$ (see discussion inthe Supplemental Material).

too short, and implies Fig. 3 is a model. It's a cartoon

Using [38] and [33], Figure 3 shows a model for a $M_{\rm BH} = 3 \times 10^8 M_\odot$, radiative efficiency of $\varepsilon = 0.1$, accretion rate in units of Eddington accretion, $\dot{M} = 0.032$, inner disk radius of $6r_{\rm g}$ and outer disk radius of $10,000r_g$. The resulting model spectra can be seen in Figure 3. We expect the front to return to the ISCO in about 2018. That means the broad Balmer lines will come back a few months later, but the WISE IR flux should not come back until about 2021.

too short to be useful

[39] observed a similar event to J1100-0053 with the source SDSS J231742.60+000535.1. However, their object provided an ambiguous case, as the IR brightness of their source did not decline. This is consistent with our model, as their cooling event is relatively brief. We discuss this object and the [39] result further in the Supplemental Material.

how?

In this letter, we have shown that a simple phenomenological model with a propagating cooling front is capable of describing the gross spectral and temporal variations in a changing looking quasar. Our model makes a prediction for this source, testable over the next few years and implies that changing looking quasars as a class are driven by changes near the ISCO, close to the SMBH. By monitoring changing look quasars we introduce new tests of models of accretion disk physics and a new probe of the strong gravity regime.

1. LaMassa, S. M. *et al.* The Discovery of the First "Changing Look" Quasar: New Insights Into the Physics and Phenomenology of Active Galactic Nucleus. ApJ **800**, 144 (2015). 1412.2136.

2. Runnoe, J. C. *et al.* Now you see it, now you don't: the disappearing central engine of the quasar J1011+5442. MNRAS **455**, 1691–1701 (2016). 1509.03640.

3. MacLeod, C. L. *et al.* A systematic search for changing-look quasars in SDSS. MNRAS **457**, 389–404 (2016). 1509.08393.

4. Ruan, J. J. *et al.* Toward an Understanding of Changing-look Quasars: An Archival Spectroscopic Search in SDSS. ApJ **826**, 188 (2016). 1509.03634.

I think stronger w/ ties to near-future w/ ZTF & LSST

5. Yang, Q. *et al.* Discovery of 21 New Changing-look AGNs in Northern Sky. *ArXiv e-prints* (2017). 1711.08122v1.

6. Hutsemékers, D., Agís González, B., Sluse, D., Ramos Almeida, C. & Acosta Pulido, J.-A. Polarization of the changing-look quasar J1011+5442. A&A **604**, L3 (2017). 1707.05540.

7. Sheng, Z. *et al.* Mid-infrared Variability of Changing-look AGNs. ApJ **846**, L7 (2017). 1707.02686.

8. Gezari, S. *et al.* iPTF Discovery of the Rapid "Turn-on" of a Luminous Quasar. ApJ **835**, 144 (2017). 1612.04830.

9. Rumbaugh, N. *et al.* Extreme variability quasars from the Sloan Digital Sky Survey and the Dark Energy Survey. *ArXiv e-prints* (2017). 1706.07875.

10. Shakura, N. I. & Sunyaev, R. A. Black holes in binary systems. Observational appearance. A&A **24**, 337 (1973).

11. King, A. Accretion disc theory since Shakura and Sunyaev. Mem. Soc. Astron. Italiana **83**, 466 (2012). 1201.2060.

12. Lawrence, A. The UV peak in active galactic nuclei: a false continuum from blurred reflection? MNRAS **423**, 451–463 (2012). 1110.0854.

13. Pooley, D., Blackburne, J. A., Rappaport, S. & Schechter, P. L. X-Ray and Optical Flux Ratio Anomalies in Quadruply Lensed Quasars. I. Zooming in on Quasar Emission Regions. ApJ **661**, 19–29 (2007). astro-ph/0607655.

14. Morgan, C. W., Kochanek, C. S., Morgan, N. D. & Falco, E. E. The Quasar Accretion Disk Size-Black Hole Mass Relation. ApJ **712**, 1129–1136 (2010). 1002.4160.

15. Morgan, C. W. *et al.* Further Evidence that Quasar X-Ray Emitting Regions are Compact: X-Ray and Optical Microlensing in the Lensed Quasar Q J0158-4325. ApJ **756**, 52 (2012). 1205.4727.

16. Mosquera, A. M. & Kochanek, C. S. The Microlensing Properties of a Sample of 87 Lensed Quasars. ApJ **738**, 96 (2011). 1104.2356.

17. Balbus, S. A. & Hawley, J. F. A powerful local shear instability in weakly magnetized disks. I - Linear analysis. II - Nonlinear evolution. ApJ **376**, 214–233 (1991).

18. McKernan, B., Ford, K. E. S., Kocsis, B., Lyra, W. & Winter, L. M. Intermediate-mass black holes in AGN discs - II. Model predictions and observational constraints. MNRAS **441**, 900–909 (2014). 1403.6433.

19. Mainzer, A. *et al.* Initial Performance of the NEOWISE Reactivation Mission. ApJ **792**, 30 (2014). 1406.6025.

20. Meisner, A. M., Lang, D. & Schlegel, D. J. Deep Full-sky Coadds from Three Years of WISE and NEOWISE Observations. AJ **154**, 161 (2017). 1705.06746.

21. Meisner, A. M. *et al.* Searching for Planet Nine with Coadded WISE and NEOWISE-Reactivation Images. AJ **153**, 65 (2017). 1611.00015.

22. Assef, R. J. *et al.* The WISE AGN Catalog. *1706.09901v1* (2017). 1706.09901.

23. Pâris, I., Petitjean, P., Ross, N. P. *et al.* The Sloan Digital Sky Survey Quasar Catalog: Twelfth data release. A&A **597**, A79 (2017). 1608.06483.

24. Drake, A. J. *et al.* First Results from the Catalina Real-Time Transient Survey. ApJ **696**, 870–884 (2009). 0809.1394.

25. Mahabal, A. A. *et al.* Discovery, classification, and scientific exploration of transient events from the Catalina Real-time Transient Survey. *Bulletin of the Astronomical Society of India* **39**, 387–408 (2011). 1111.0313.

26. Sesar, B. *et al.* Exploring the Variable Sky with LINEAR. I. Photometric Recalibration with the Sloan Digital Sky Survey. AJ **142**, 190 (2011). 1109.5227.

27. Kaiser, N. *et al.* The Pan-STARRS wide-field optical/NIR imaging survey. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 7733 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 0 (2010).

28. Stubbs, C. W. *et al.* Precise Throughput Determination of the PanSTARRS Telescope and the Gigapixel Imager Using a Calibrated Silicon Photodiode and a Tunable Laser: Initial Results. ApJS **191**, 376–388 (2010). 1003.3465.

29. Tonry, J. L. *et al.* The Pan-STARRS1 Photometric System. ApJ **750**, 99 (2012). 1203.0297.

30. Magnier, E. A. *et al.* The Pan-STARRS 1 Photometric Reference Ladder, Release 12.01. ApJS **205**, 20 (2013). 1303.3634.

31. Gammie, C. F. Efficiency of Magnetized Thin Accretion Disks in the Kerr Metric. ApJ **522**, L57–L60 (1999). astro-ph/9906223.

32. Agol, E. & Krolik, J. H. Magnetic Stress at the Marginally Stable Orbit: Altered Disk Structure, Radiation, and Black Hole Spin Evolution. ApJ **528**, 161–170 (2000). astro-ph/9908049.

33. Sirko, E. & Goodman, J. Spectral energy distributions of marginally self-gravitating quasi-stellar object discs. MNRAS **341**, 501–508 (2003). astro-ph/0209469.

34. Thompson, T. A., Quataert, E. & Murray, N. Radiation Pressure-supported Starburst Disks and Active Galactic Nucleus Fueling. ApJ **630**, 167–185 (2005). astro-ph/0503027.

35. Hopkins, P. F. & Quataert, E. An analytic model of angular momentum transport by gravitational torques: from galaxies to massive black holes. MNRAS **415**, 1027–1050 (2011). 1007.2647.

36. Jun, H. D. *et al.* Infrared Time Lags for the Periodic Quasar PG 1302-102. ApJ **814**, L12 (2015). 1511.01515.

37. Cannizzo, J. K. On the M_V(peak) versus Orbital Period Relation for Dwarf Nova Outbursts. ApJ **493**, 426–430 (1998). astro-ph/9712210.

38. Ford, K. E. S. *et al.* *in prep.* (2018).

39. Guo, H. *et al.* The Optical Variability of SDSS Quasars from Multi-epoch Spectroscopy. III. A Sudden UV Cutoff in Quasar SDSS J2317+0005. ApJ **826**, 186 (2016). 1605.07301.

Supplemental Material

December 5, 2017

So not detected by poss in the 1950's?

what's low-redshift? $z<2$?

in spectroscopic observation details, I typically like a bit more info, like instrument configuration / spectral range, spectral resolution

Further Observational Details

Selection in SDSS-III BOSS of J1100-0053

SDSS J1100-0053.71-005304.5 was first detected by the ROSAT ~~and~~ appears in the All-Sky Survey Bright Source Catalogue [RASS-BSC; 6, 35]. J1100-0053 was then imaged by the Sloan Digital Sky Survey (SDSS) and satisfied a number of spectroscopic targeting flags[1] making it a quasar target. A spectrum was obtained on MJD 51908 (Plate 277, Fiber 212) and the spectrum of a $z = 0.378$ quasar was catalogued in the SDSS Early Data Release [28, 33]. The physical properties of J1100-0053, derived from the MJD 51908 spectrum and using the methods in Shen et al. [30], are given in Table 1.

redshift

The second epoch spectrum is from the SDSS-III Baryon Oscillation Spectroscopic Survey [BOSS; 8] and shows the downturn at $\lesssim$4300Å . SDSS-III BOSS actively vetoed low-z QSOs [27], and it was due to J1100-0053 being selected as an ancillary target via a white dwarf program [14, 15] that a second spectral epoch was obtained. Since J1100-0053 was not a BOSS QSO target, it is not subject to the "blue offset", see Margala et al. [18].

explain briefly

A third epoch spectrum was obtained from the Palomar Hale 5m telescope using the DBSP instrument. ~~Two~~ E exposures of 600s and 300s were taken in good conditions. Features to note include the continuum straddling Mg II being blue in the 2017 spectrum, as it was for the SDSS spectrum in 2000, as opposed to red, as it was for the BOSS spectrum in 2010.

J1100-0053 is in Data Release 3 (DR3) of the Dark Energy Camera Legacy Survey (DECaLS), where there are 8, 3 and 9 exposures in the g, r and z-band respectively. The g- and r-band observations span ~~are separated by~~ roughly a year, ($56707 \leq g_{\rm MJD} \leq 56727$ and $56367 \leq r_{\rm MJD} \leq 56367$), ~~The~~ z-band observations span almost 3 years ($56383 \leq z_{\rm MJD} \leq 57398$).

white the passive voice

Selection in NEOWISE-R of J1100-0053

WISE W1 and W2 lightcurves for ~200,000 SDSS spectroscopic quasars were obtained. These light curves span from the beginning of the WISE mission (2010 January) through the first-year of NEOWISE-R operations (2014 December). The W1/W2 light curves are obtained by performing forced photometry

[1] SERENDIP_BLUE, ROSAT_D, ROSAT_C, ROSAT_B, QSO_SKIRT, ROSAT_A, see Stoughton et al. [32] and Richards et al. [26] for flag descriptions.

shifting tense?

mention the gap

Quantity	Value
SDSS name	J1100-0053.71-005304.5
R.A. / deg	165.240463
Declination / deg	-0.884586
redshift, z	0.3778±0.0003
$M_i(z=2)$ / mag	-24.48
log ($L_{\rm bol}$/ergs^{-1})	45.78±0.02
log ($M_{\rm BH}/M_\odot$)	8.83±0.14
Eddington ratio	0.070

necessary? useful?

Table 1: Physical properties of J1100-0053 using the methods from Shen et al. [30].

what's that? reader doesn't know...

at the locations of DECam-detected optical sources [17, 20, 21]. This forced photometry is performed on time-resolved unWISE coadds [17], each of which represents a stack of $\sim$12 exposures. A given sky location is observed by WISE for $\sim$1 day once every six months, which means that the forced photometry light curves typically have four coadd epochs available. Coadd epochs of a given object are separated by a minimum of six months and a maximum of four years. The coaddition removes the possibility of probing variability on $\lesssim$1 day time scales, but pushes $\approx$1.4 magnitudes deeper than individual exposures while removing virtually all single-exposure artifacts (e.g. cosmic rays and satellites).

Approximately $\sim$30,000 of the SDSS/BOSS quasars with W1/W2 light-curves available are "IR-bright", in that they are above both the W1 and W2 single exposure thresholds and therefore detected at very high significance in the coadds. For this ensemble of objects, the typical variation in each quasar's measured (W1-W2) color is 0.06 magnitudes. This includes statistical and systematic errors which are expected to contribute variations at the few hundredths of a magnitude level. The typical measured single-band scatter is 0.07 magnitudes in each of W1 and W2.

We undertook a search for outliers relative to these trends. Specifically, we selected objects with the following characteristics:

should we define?

- Monotonic variation in both W1 and W2.
- W1 versus W2 flux correlation coefficient ≥ 0.9.
- > 0.5 mag peak-to-peak variation in either W1 or W2.

acronym REF

This yields a sample of 248 sources. 31 of these are assumed to be blazars due to the presence of FIRST radio counterparts, and we discount them in the further analyses here. Another 22 are outside of the FIRST footprint, leaving 195 quasars in our IR-variable sample.

DROP.

A link to our sample can be found here: `qso_pages_v01` and links to the catalogs are given here: `dr3_wise_lc_sample.fits.gz` and here: `dr3_wise_lc_sample.fits.gz`. The first catalog has 248 rows, which are the highly IR-variable sample of objects. The second catalog is the full 200 622 quasar sample quasars that have "good" WISE light curves available in DECaLS DR3. In each file, there are 3 extensions: the first extension are the WISE light curve summary metrics; the second extension the DECaLS DR3 data for each object, and the third extension, the SDSS data for each object. A full characterization of the typical mid-IR quasar variability will be presented separately.

Additional Multiwavelength data for J1100-0053

~~Swift~~ GALEX?

Checking the data archives we found there was no source within 30 arcsec in the VLA FIRST, i.e., at 21 cm radio frequencies for J11057. None of the *Hubble Space Telescope*, the *Spitzer Space Telescope* or the *Kepler* missions have observed J1100-0053. It is also not in the Hyper Suprime-Cam (HSC) Data Release 1 [5] footprint. There is the detection in ROSAT (which triggers using the 2nd all-sky survey (2RXS; Boller et al. 2016, A&A, 588, 103) as 2RXS J110058.1-005259 with 27.00 counts (count error 6.14) and a count rate = 0.06 ± 0.01. The NASA/IPAC Extragalactic Database (NED)[2] gives J1100-0053 as $1.27\pm0.28\times^{-12}$ erg/cm^2/s in the 0.1-2.4 keV range (unabsorbed flux). J1100-0053 is not in either the *Chandra* or *XMM-Newton* archives.

units

Further Model Details

to the disk emission

In this section we discuss several models trying to explain the light curve and spectral behaviour of J1100-0053. Ultimately, we are forced towards a model that combines a cooling front propagating in the accretion disk along with changes in the disk opacity.

[2]https://ned.ipac.caltech.edu/

disk opacity? or additional source of opacity, likely associated with an atmosphere left temporarily when the disk collapses?

↳ Why not just an eclipse event (but not totality)?

Scenario I: Obscuring Cloud model

We first explore the possibility that an obscuring cloud, or clouds, cause the observed light curve and spectral behaviour of J1100-0053. In this scenario, one would require the obscuring cloud(s) to cross the line of sight. In order to explain both the IR drop and broadline disappearance, one would also need the cloud(s) to block most of the inner disk such that the ionizing radiation could not impact on the BLR or the torus for a period of months-years. Another requirement is an explanation of why the light curves 'recover' after a period of ~ 2500 days (observed-frame); i.e., the light curves do not rapidly return to their original flux levels once the obscuring event is over.

not very coherent/clear

Clouds should not typically infall; they need to lose angular momentum if they are drawn from a distribution with Keplerian orbits, and even if they do lose angular momentum, e.g., in a collision with approximately equal mass, they would likely be either destroyed or no longer coherent. Further issues arise, since the freefall timescales are,

$$t_{\rm ff} \sim 100{\rm yr}\left(\frac{\rm r}{0.4{\rm pc}}\right)^{3/2}\left(\frac{\rm M}{10^8{\rm M}_\odot}\right)^{-1} \tag{1}$$

and Kelvin-Helmholtz instabilities would destroy the clouds within the cloud-crushing time, [e.g., 7, 13, 22, 31], given by

$$t_{\rm cc} \sim 100{\rm yr}\left(\frac{\rho_{\rm cloud}/\rho_{\rm medium}}{10^6}\right)^{1/2}\left(\frac{\rm r_{cloud}}{4\times10^{10}{\rm km}}\right)\left(\frac{\rm v_{rel}}{10^4{\rm km/s}}\right)^{-1} \tag{2}$$

Thus, even if clouds did infall, they would end up fragmented, which should pollute the inner disk (see below for this discussion applied to the circumstances in Guo et al. [12]).

The dust in the cloud is then well inside the dust sublimation radius

$$R_{\rm dust} \approx 0.4{\rm pc}\left(\frac{\rm L}{10^{45}{\rm erg/s}}\right)^{1/2}\left(\frac{\rm T_{sub}}{1500{\rm K}}\right)^{2.6} \tag{3}$$

and so the dust will be destroyed in the $\sim$100 year free-fall from the dust-sublimation region. Hence, one can not absorb the UV spectrum with dust, since it will have been sublimated well before it arrives at the inner disk.

Typical extinction profiles from clouds with hydrogen column densities of $N_H \sim 10^{21} - 10^{22}{\rm cm}^{-2}$ (comparable to the range expected for NLR-BLR cloud densities) are linear in $1/\lambda$ with the 2175 Å feature, [e.g., Figure 4 of 11], and not at all like the asymptotic drop off at $1/\lambda = 3(\mu m^{-1}) = 1/300$nm in Guo et al. [12] or in our 2010 spectrum. Note that in the extinction profiles in Gordon et al. [11], there is a local maximum near $4.5 \sim 1/\lambda(\mu m^{-1})$, implying $\lambda \sim 0.2\mu$m in these cloud extinction profiles. This could correspond to broadened Lyα absorption; if this is broadened in a turbulent environment and combined with strong oxygen and carbon edges in a colder phase medium, it is possible to generate the falling off at 1/(200-300nm) in our 2010 spectrum (and Guo et al.'s spectrum). With all these considerations, we make a strong case that the behaviour observed in J1100-0053 *cannot* be extinction due to a dusty cloud.

is it? not from our Fig. 2?

Scenario II: Accretion Disk model

Having discounted an obscuring event as the explanation for J1100-0053, we turn to an accretion disk model. December 2000

The ~~early 2000~~s spectrum is well fit with a thin, Shakura & Sunyaev [29] α-disk. The 2010 spectrum and the sharp fall-off at $\sim 200-300$nm, is not reproducible using a different temperature profile alone, even one where the entire inner disk (unphysically) vanishes. This is due to the width of the Planck function in wavelength space. For the same reasons, a gray absorber model with uniformly suppressed emission at small disk radii is also incapable of fitting our 2010 (or Guo et al.'s) spectrum. Wavelength dependent absorption, combined with a lower disk emissivity is required.

MODEL "A": SWITCHING STATES TO AN ADAF: The broadband spectrum of NGC 1097 from Nemmen et al. [25] initially appears similar to the UV/optical 2010 spectrum of J1100-0053. In Nemmen imagine the reader hasn't read Nemmen et al. — explain their paper briefly...

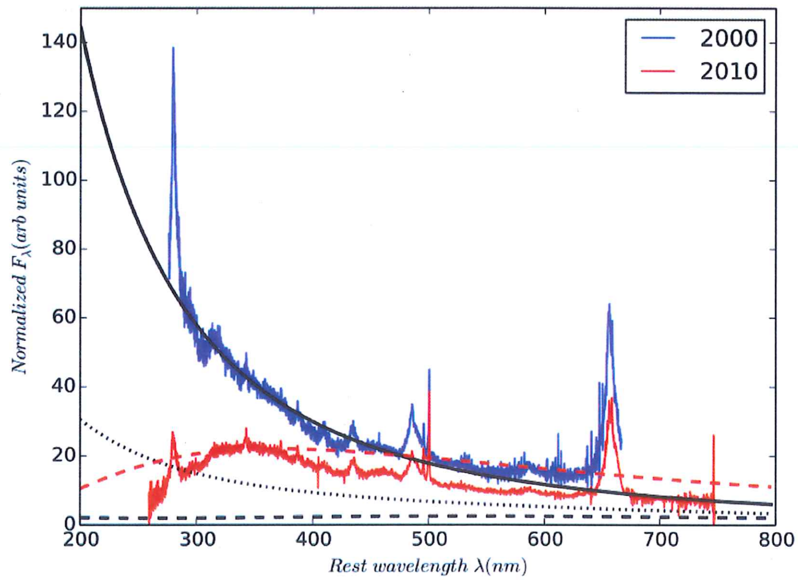

Figure 1: J1100-0053 data (blue line 2000 spectrum; red line 2010 spectrum) and 4 models. Solid black line shows non-zero torque at ISCO [following 3]; dotted and dashed black lines show temperature suppression inside $r_{\rm alt} = 225r_{\rm g}$, such that the spectral flux is $f_{\rm dep} = 0.2$ or 0.01 (respectively) compared to a zero torque model; dashed red line shows zero flux inside $r_{\rm alt} = 80r_{\rm g}$ and arbitrary normalization to match peak of 2010 spectrum. Note the poor fit due to the intrinsic width of the thermal peak.

et al. [25, e.g., their Figure 4], there are disk model components that look similar to the fall-off at 200nm observed in the J11057 2010 spectrum. This would involve a thin disk component extending from $\sim 450r_g$ to the outer regions of the disk. Figure 4 in Nemmen et al. [25] shows the Multicolor Disk (MCD) blackbody-like model component from the thin disk at $r > 225r_g$ (their long dashed line) dramatically decreasing at $\sim 10^{15}$Hz ($\sim$ 300nm). Nemmen et al. [25] model the disk region interior to this as an advection-dominated accretion flow (ADAF), at a power (in νL_ν), an order of magnitude lower than the MCD in the optical, but spanning from the X-ray to the far-IR.[3]

Can J1100-0053 switch states from a thin disk quasar to an ADAF at small radii with the thin disk surviving at large radii? Assuming the transition happens due to an instability on the thermal timescale of the disk, then at large radii the thermal timescale is

$$t_{\rm th} \sim 14 \text{ years} \left(\frac{\alpha}{0.03}\right)^{-1} \left(\frac{r}{225r_g}\right)^{3/2} \frac{r_g}{c} \tag{4}$$

???

and is too long given the observations. However, if the viscosity parameter α increases to $\alpha \approx 0.3$, as suggested by King et al. [16], then the thermal timescale is $t_{\rm th} \sim 1.4$ year and the front timescale is

$$t_{\rm front} \sim 10 \text{ years} \left(\frac{h/r}{0.05}\right)^{-1} \left(\frac{\alpha}{0.3}\right)^{-1} \left(\frac{r}{225r_g}\right)^{3/2} \frac{r_g}{c} \tag{5}$$

which is plausible, if there exists a very viscous disk and the effect propagates outwards on a timescale of ≤ 10 years from the inner disk. This would suppress the UV/X-ray emission from the RIAF (down by a few orders of magnitude from the intensity expected from a thin disk intensity) and explain the broadline behaviour. ADAF spectra are flat in νL_ν Abramowicz & Fragile [1], Abramowicz et al. [2], Narayan

[3] A change to a radiatively inefficient accretion flow (RIAF) is also possible in this model.

parentheses missing?

defined?

et al. [24], and convective ADAFs rise towards X-ray energies. ADAFs exist at lower luminosity, where $\varepsilon \sim 0.005$ for $L = \varepsilon \dot{M} c^2$, lower than the fiducial $\varepsilon \sim 0.1$ for a classic thin disk luminosity.

However, suppressing the flux from the inner disk radii ($\lesssim 225 r_g$) in the low temperature thin disk model [3, 4, 9, 10, 23], by a factor of 20 would still not describe the 2010 spectrum. To restore the thin disk spectrum by 2016, the disk change has to propagate back inwards, most of the way to the ISCO and therefore $t_{\rm front}$ needs to be shorter. This requires h/r to be larger in Equation above, by a factor of ~ 2.

It is unclear what physical processes would trigger the change of state to an ADAF and then cool back down to a thin disk. However, more of an issue is that supressing the MCD temperature profile inside a radius of $r_{alt} = 225 r_g$ leads to a collapse in the total flux compared to unperturbed disk. We show some example cases in 1. Clearly, these scenarios are difficult to reconcile with our data.

???

Model "B": Propagating of a Cooling Front: An alternative model connected to the accretion disk is that a *cooling* front propagates through the thin disk. In order to reproduce the steep fall at $\lambda \leq 200$nm in the 2010 spectrum, a cool phase leads to absorption at short wavelengths.

Initially a modestly fat disk ($h/r \sim 0.2$) with a modest α, cools from the ISCO and propagates outward in a cooling front, collapsing the disk. As the hot disk ($\sim 10^{5-6}$K) cools, it fragments into cooler clumps around $\sim 10^4$K [see e.g., 19]. The main coolants are resonance lines in carbon and oxygen [see e.g., Fig. 18 in 34]. The ionization energies for carbon and carbon are 11.26 and 13.61 eV, respectively, i.e., ~ 100nm, and hence at wavelengths < 100nm the disk opacity will increase dramatically in an edge. ??
However, the gas in the disk is both pressure, turbulent and Doppler broadened, so these ionization edges will manifest around 100nm ~~with~~ decreasing opacity to shorter wavelengths as

usually 2 things, not 3

$$\kappa \propto \rho T^{-1/2} \nu^{-3} \tag{6}$$

for Kramers' opacities. This implies $\kappa \propto \lambda^3$ at increasing wavelengths up to the ionization edge around 100nm. These features will be blurred (by the broadening) and the ionization edges due to the C and O resonance lines in the cool phase of this disk will be span $50-200$nm, depressing the flux at these energies.

The 2010 spectrum in this model comes from a cooler disk plus the increased opacity at short wavelengths in the cooler phase. Heating occurs from the outside in, explaining the 2016 spectrum and asymmetric recovery in photometry. Since the optical continuum has been rising again since mid-2016, this leads to a prediction of a rise in hydrogen emission line flux in the next few months (2018). The infrared flux ~~returns~~ in 2021.

is predicted to return

Comparison with SDSS J2317+0005 from Guo et al. 2016

avoid referencing figures in papers.

Figure 1 of Guo et al. (2016) shows a UV collapse in the quasar SDSS J231742.60+000535.1 (hereafter J2317+0005, ~~with~~ redshift $z = 0.32$), similar to that of J1100-0053. In Figure 2 we show the five SDSS/BOSS spectra from J1100-0053 and J2317+0005 (top panel), and their ratios (bottom panel). The collapse in J2317+0005 happens in 23 days [Figure 2 of 12]; this object was observed by SDSS on MJD 52177 (normal) and then on MJD 52200. In the second epoch spectrum, there is a drop of 1.2 mag in the u-band and 0.5mag in g-band. The r, i, z-bands are all consistent with the earlier observation. J2317+0005 is observed with SDSS ~a year later and (u, g, r, i, z) are all consistent with the earlier MJD 52177 spectrum. XMM-Newton spectra straddle this time period, from 2001 June 03 to 2001 November 28. Both X-ray spectra are consistent with no neutral absorption in the rest-frame. This implies the sightline is clear on both of those dates. Guo et al. [12] also find that the IR does not significantly change and that the broad lines are consistent with being constant over time.

Guo et al. [12] discuss two scenarios to explain this behaviour: *(i)* an inner accretion disk change and *(ii)* an eclipse by an optically thick cloud. Guo et al. [12] note that in principle both models could explain the observation. In the inner accretion disk scenario, turning off the disk at $r < 60 r_g$ would explain the J2317+0005 spectra, though the detailed MCD fit is far from ideal, in much the same manner as for J11057. However, Guo et al. [12] find this explanation unconvincing since "quasars are not observed to flicker like this typically". The second scenario is favoured based on the initial optical spectrum (23 days before the u-band dip) and the 2001 November X-ray spectrum (45 days after the u-band dip). For the

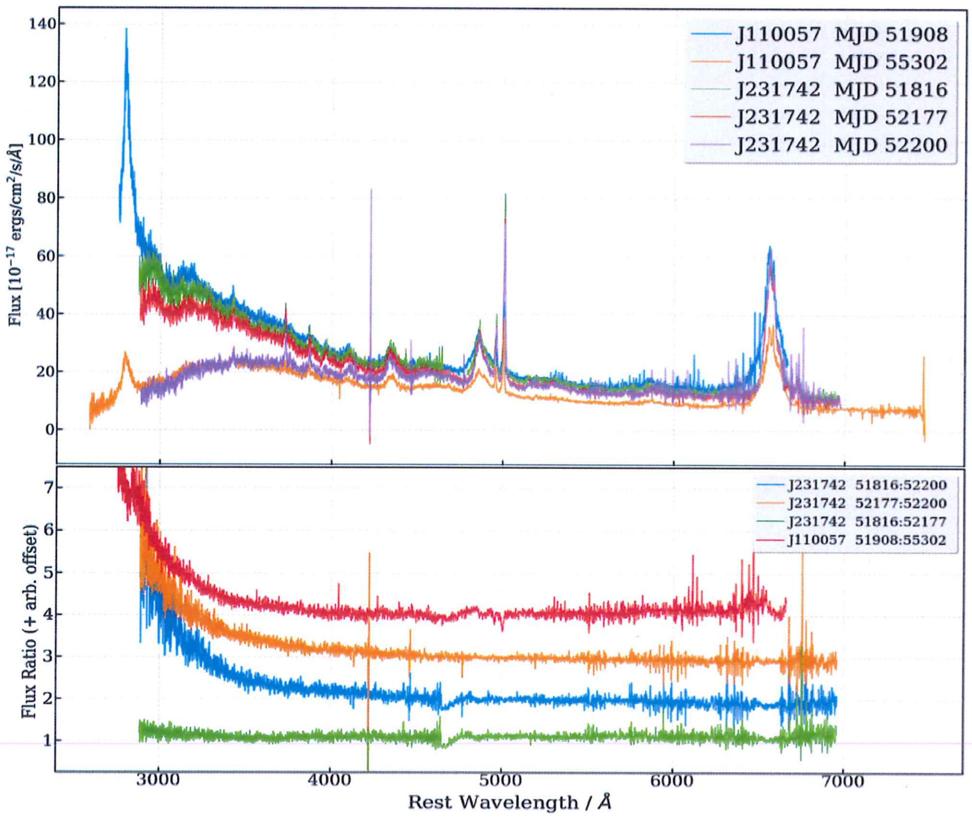

Figure 2: *Top::* The five SDSS/BOSS spectra of J2317+0005 and J1100-0053. The striking similarity between the two spectra downturned in the blue can be seen. *Bottom::* The ratio of the different epoch spectra.

of what to what?

reasons given above for J1100-0053, and in particular with our infrared light curve data, we suggest $\approx$45 days is too short for an obscuration event, and hence suggest that the same initial cause (model B above: a cooling front propagating from the inner accretion disk) explains *both* the Guo et al. [12] spectrum and our 2010 spectrum. In the case of the Guo et al. [12] source, the fact that the IR and broad lines are unchanged implies that the temporary disk dimming is very short-lived. Therefore, in the case of Guo et al. [12], the restoring heating front must propagate outwards from the inner disk. This is unlike J1100-0053 (model B above), where the restoring heating front must propagate inwards from the outer disk in order to explain the restoration of g-band before u-band and the long-term supression of broad lines and IR.

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References

[1] Abramowicz M. A., Fragile P. C., 2013, Living Reviews in Relativity, 16, 1

[2] Abramowicz M. A., Igumenshchev I. V., Quataert E., Narayan R., 2002, ApJ, 565, 1101

[3] Afshordi N., Paczyński B., 2003, ApJ, 592, 354

[4] Agol E., Krolik J. H., 2000, ApJ, 528, 161

[5] Aihara H., et al., 2017, ArXiv e-prints

[6] Appenzeller I., et al., 1998, ApJS, 117, 319

[7] Bae H.-J., Woo J.-H., 2016, ApJ, 828, 97

[8] Dawson K., et al., 2013, AJ, 145, 10

[9] Ford K. E. S., et al., 2018, in prep.

[10] Gammie C. F., 1999, ApJ Lett., 522, L57

[11] Gordon K. D., Clayton G. C., Misselt K. A., Landolt A. U., Wolff M. J., 2003, ApJ, 594, 279

[12] Guo H., et al., 2016, ApJ, 826, 186

[13] Hopkins P. F., 2013, MNRAS, 428, 2840

[14] Kepler S. O., et al., 2015, MNRAS, 446, 4078

[15] Kepler S. O., et al., 2016, MNRAS, 455, 3413

[16] King A. R., Pringle J. E., Livio M., 2007, MNRAS, 376, 1740

[17] Lang D., 2014, AJ, 147, 108

[18] Margala D., Kirkby D., Dawson K., Bailey S., Blanton M., Schneider D. P., 2016, ApJ, 831, 157

[19] McCourt M., Oh S. P., O'Leary R. M., Madigan A.-M., 2016, ArXiv e-prints

[20] Meisner A. M., Bromley B. C., Nugent P. E., Schlegel D. J., Kenyon S. J., Schlafly E. F., Dawson K. S., 2017, AJ, 153, 65

[21] Meisner A. M., Lang D., Schlegel D. J., 2017, AJ, 154, 161

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