

A new physical interpretation of optical and infrared variability in quasars

Nicholas P. Ross¹ et al.

¹*Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, United Kingdom*

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 identified in the infrared, and an archival spectrum from 2010 shows an intermediate phase of the transition during which the flux below rest-frame 3400\AA 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. Increases in the infrared flux should follow, occurring on a ~ 3 year observed timescale. 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 and laboratory of the nuclear central engine.

The changing-look quasar phenomenon where the dramatic disappearance, or appearance, of strong UV continuum and/or prominent broad 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).

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. In contrast, we have taken advantage of the ongoing mid-infrared Near-Earth Object WISE Reactivation mission [NEOWISE-R; 10, 11, 12], supplemented with the optical Dark Energy Camera Legacy Survey (DECaLS¹) in order to discover new changing-look quasars. While previous efforts have used the 1-year baseline of the WISE mission to identify CLQs [e.g., 13], our investigation is the first to extend this selection to the infrared using NEOWISE-R mission data and we have identified a sample of Sloan Digital Sky Survey (SDSS) quasars that show significant changes in their IR flux over the course of a few years.

The Shakura-Sunyaev α -disk model [14] has long been used to (oversimplify) describe the basic properties of the optically thick, geometrically thin accretion disks expected to orbit the supermassive black holes at the nuclei of

¹legacysurvey.org/decamls/

quasars. This accretion disk is thought to be the origin of thermal continuum emission that is observed in the rest-frame ultraviolet and optical with the key assumptions that the state of the plasma within the disk is optically thick and thermal, and that the accretion disk can be treated as a blackbody. Given the size scales associated with supermassive black holes and the associated temperatures, this implies that a substantial fraction of the bolometric luminosity should be in the form of UV photons. This feature has traditionally been called the “Big Blue Bump” [15, 16]. The thermal emission seen in the infrared is believed to originate from molecular dust, representing emission from the disk or broad line region (BLR) that has been reprocessed in this optically thick region into thermal radiation [see 17, 18, 19, for reviews].

While the mass of the black hole is large compared to the accretion disk, the angular momentum of the black hole is small. Hence angular momentum has to be lost and a kinematic viscosity of the plasma seems the likely mechanism that transports angular momentum outward. This viscosity is likely due to magnetorotational instability [MRI; 20] with additional contributions to turbulence from the effects of embedded objects in the disk e.g., [21]. However, as e.g., [22, 23] point out, the observed spectral energy distributions (SEDs) of typical quasars differ markedly from classical α -disk theoretical predictions [14, 24] with a typical observed quasar SED flat in λF_λ over several decades in wavelength [25, 26]. Furthermore, real AGN disks seem to be cooler [e.g., 27] and larger [e.g., 28, 29, 30, 31] than the α -disk model predicts. We utilize the α -disk model in this paper, noting the model is ad hoc only parameterizing disk viscosity, and does not permit predictions of global changes to the disk [32]. From there, we introduce a new model which does allow and predict global changes across the accretion disk and can be observed in the SED.

In this article we present the $z = 0.378$ quasar SDSS J110057.70-005304.5 (hereafter J1100-0053). J1100-0053 was a known quasar which was identified as interesting due to its IR light curve. We have spectral observations for J1100-0053 showing a transition in the blue-continuum 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 on the time scales of months to \sim few years.

1 Target Selection and Observations

We started by matching the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS) Data Release 12 Quasar catalog [DR12Q; 33] to the NEOWISE-R IR data (WISE W1 at $3.4\mu\text{m}$, WISE W2 at $4.6\mu\text{m}$). We found ~ 200 objects identified by a factor of 2 or more change in the observed WISE W1 and W2 bands over the course of typically three or four years [see 12, and the Supplemental Material for the detailed NEOWISE-R selection]. Visually inspecting these 200 objects, we examined the change in optical colour using the SDSS and DECaLS imaging surveys in order to identify changing-look quasars candidates. From this inspection, a list of ≈ 70 priority targets was derived, and with spectra already from SDSS and BOSS, J1100-0053 was an early target and we obtained a third epoch of optical spectroscopy from the Palomar 5m telescope.

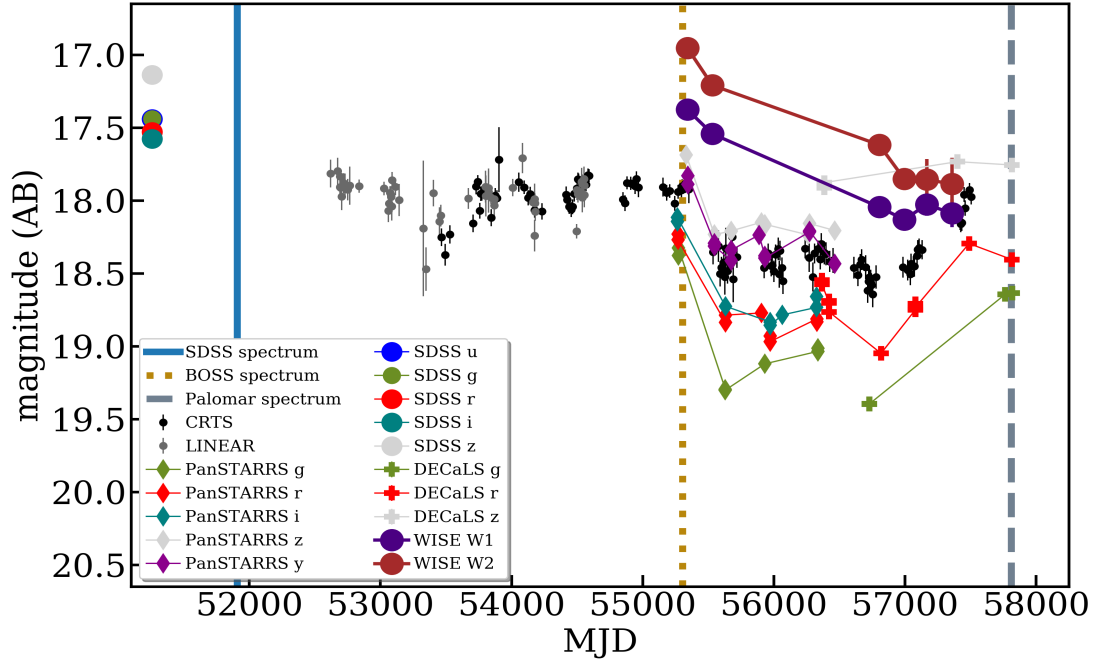


Figure 1 Multi-wavelength light curve of J1100-0053, including optical data from LINEAR, CRTS, SDSS, PanSTARRS and DECaLS, and mid-IR data from the WISE satellite. The three vertical lines illustrate the epochs of the three optical spectra presented in Figure 2. J1100-0053 was flagged for further study 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 years.

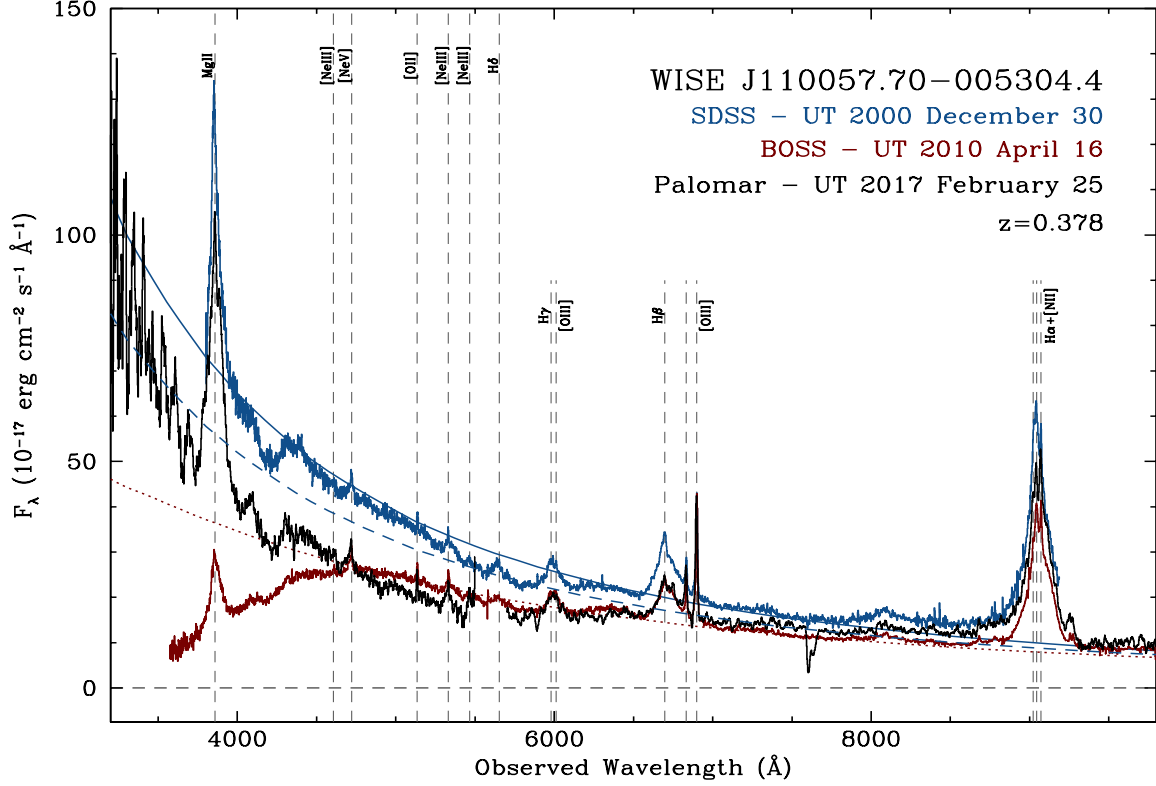


Figure 2 Optical spectra of J1100-0053 obtained on MJD 51908 (blue; SDSS), 55302 (red; BOSS) and 57809 (black; Palomar). Spectra have been renormalized to maintain a constant [O III] luminosity. Over the past two decades, the UV continuum and broad lines have changed significantly for this quasar. In particular, the 2nd-epoch BOSS spectrum from 2010 shows the rare occurrence of a temporary collapse of the UV continuum. Smooth lines show three simple thermal accretion disk models of the continuum. The solid blue line shows an inflated disk with non-zero torque at the ISCO [e.g., 23], while the dashed blue line shows the same model, but with zero torque at the ISCO [i.e., a simple α -disk model, 14]. Torque at the ISCO heats the inner disk, causing it to puff up and become more UV luminous. The dotted red line shows a modified zero-torque model where the thermal disk emission interior to $80r_g$ is suppressed by a factor of 10.

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; 34, 35], the Lincoln Near-Earth Asteroid Research [LINEAR; 36] program and the Panoramic Survey Telescope and Rapid Response System [PanSTARRS; 37, 38, 39, 40] 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 the blue continuum then collapses in the second epoch BOSS spectrum taken 10 years later. The blue continuum then returns in the third epoch spectrum taken another 7 years later, albeit at a diminished level relative to the initial spectrum. The Supplemental Material gives further observational details.

While continuum changes in the rest-frame UV/optical spectra of quasars are not a new discovery (see e.g., [41], the review by [42] and more recent studies by [43, 44, 45, 46]), the identification of the “UV collapse” has only recently been noted by [47]. Those authors report the first discovery of a UV cutoff quasar, SDSS J231742.60+000535.1 (hereafter J2317+0005; redshift $z = 0.32$) which was initially observed three times on 2000 September 29, 2001 September 25, and 2001 October 18, by the SDSS. The novelty for J2317+0005 was that the observed UV emission collapsed, the quasar transitioned to a dim state, and then recovered over the course of just a few weeks. For J1100-0053 the combination of having optical and infrared light curves, as well as observing J1100-0053 at three separate spectral stages is currently unique. As such, J1100-0053 and J2317+0005 are now two archetype objects that an accretion disk theory has to predict and explain.

2 Discussion

Our theoretical explanation of the behaviour of J1100-0053 (and J2317+0005) starts with the models of [23] and [48]. [23] introduce a model where the outer parts of the accretion disk are heated sufficiently to maintain gravitational stability, the luminosity of the disc becomes sensitive to its opacity and the theoretical SEDs have a second peak in the near-infrared that is energetically comparable with the Big Blue Bump. [48] prescribes the small r_g behaviour. Starting with a multitemperature blackbody (MTB) model, the key idea here is the level of torque, essentially ‘zero’ or ‘non-zero’, that is applied as a boundary condition to the innermost edge of the accretion disk. [48] introduce the idea that the viscous torque at the inner edge of a very thin accretion disk is vanishingly small and effectively zero. This changes the behavior of the disk temperature profile as a function of accretion radius, with the zero-torque temperature T_{ZT} going to zero at the inner edge of the disk (since the torque vanishes there) whereas the standard, non-zero torque temperature T_{NZT} reaches its maximum value at the inner edge (where the torque is maximal).

Our model of thermal emission from a MTB 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.

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 $h/r \sim 0.2$ (where h and r are the scale-height and radius of the accretion disk respectively) 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., 49, 50]. A non-zero torque at the ISCO maintains a hotter innermost disk than a condition of zero torque at

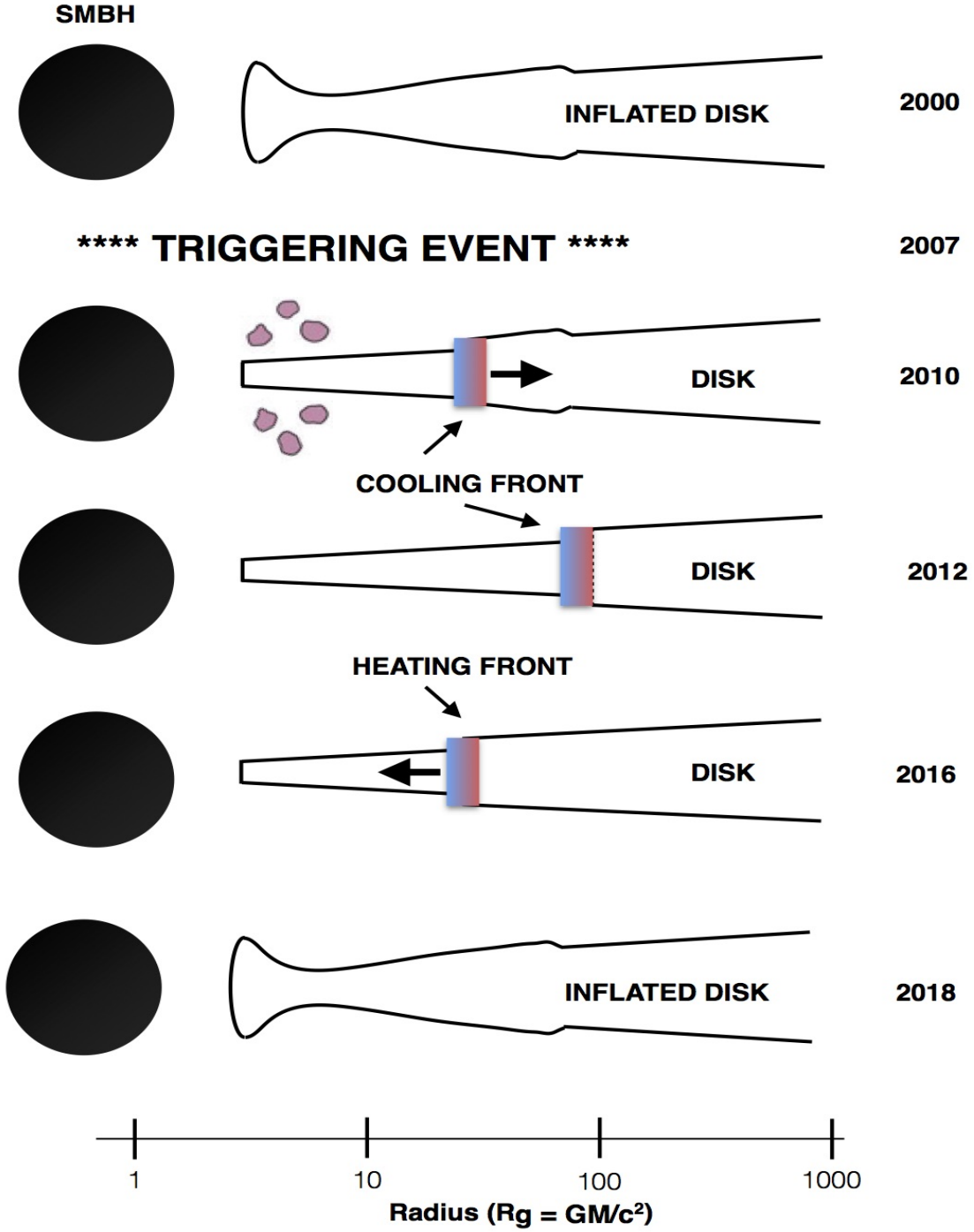


Figure 3 Cartoon illustration of our model explaining the unusual spectral evolution of J1100-0053. In 2000, corresponding to the SDSS spectral epoch, the quasar has a standard inflated accretion disk, i.e., where non-zero torque at the ISCO heats the inner radii of the accretion disk, causing it to puff up [e.g., 48]. Circa 2007, a triggering event occurs that deflates the inner disk, possibly due to a shift in the magnetic field configuration leading to zero torque at the ISCO. This event leaves some scattering clouds, and causing a cooling front to propagate outwards in the accretion disk, traveling on the t_{front} time-scale. Circa 2012, the cooling front reaches a predicted kink in the accretion disk profile at $\sim 100 r_g$, associated with a shift in the accretion disk opacity [e.g., Figure 2 of 23]. The cooling front then reflects back, re-heating the inner accretion disk. We predict that in the next year, the quasar should roughly return to its initial state.

the ISCO, and an assumption of non-zero torque is particularly appropriate if disk viscosity and accretion are 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_{front} . The front propagation timescale is $t_{\text{front}} \sim 10 \text{ years} \left(\frac{h/r}{0.05} \right)^{-1} \left(\frac{\alpha}{0.3} \right)^{-1} \left(\frac{r}{225r_g} \right)^{3/2} \frac{r_g}{c}$, and α is the traditional kinematic viscosity. One simple, plausible trigger for this cooling front is that the non-zero torque condition at the ISCO changes to a (more nearly) zero-torque condition. This dramatic decrease in the torque at the ISCO leads to a dramatically cooler, thinner innermost disk. As the cooling front propagates, the drop in temperature leads to a drop in flux. Our model has the cooler regions behind the front emitting 10% the flux of the initial hotter disk, and the disk height drops by a factor ~ 2 . The dimming of the inner disk causes a drop in the ionizing photon flux, which will cause the Balmer lines to drop in flux after a light travel time of months and the IR emission from the outer disk/torus to drop in flux after a light travel time of ~ 3 years [23, 51].

If the inner accretion disk is usually inflated [see e.g., 23, 52, 53], such a cooling front will naturally produce a collapse in the scale height of the disk, a decrease in flux moving from UV to longer optical wavelengths and, 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 collapse) as a front will move more slowly in a thinner disk (see Fig. 3). 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., 51].

Since we assume the disk starts in a puffed-up state ($h/r \sim 0.2$) and since the front cooling time 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, analogous to the well-known accretion disk limit cycle mechanism in models of dwarf novae outbursts [e.g., 54]. The returning heating front travels more slowly because the disk is thinner (and t_{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 will 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 in the Supplemental Material).

Using [55] and [23], Figure 3 shows a model for a $M_{\text{BH}} = 7 \times 10^8 M_{\odot}$, with an accretion rate in units of Eddington accretion, $\dot{M} = 0.070$ (as in appropriate for J1100-0053), radiative efficiency of $\epsilon = 0.1$ inner disk radius of $6r_g$ 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. The IR brightness of J2317+0005 did not decline (cf. J1100-0053). However as the change in the UV for J2317+0005 was so rapid, indicating that the cooling event was brief, this is consistent with our model.

In conclusion, by monitoring changing look quasars we introduce new tests of models of accretion disk physics. 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, if confirmed, implies that changing looking quasars as a class are driven by changes near the ISCO, close to the SMBH. The discovery of J1100-0053 (and J2317+0005) are specific key examples of time-domain astronomy and the resulting astrophysics to be studied. However, even with the coverage from WISE, PanSTARRS, SDSS, DECaLS and CRTS, we have a relatively sparse dataset that we aim to fit a theoretical model to. In the immediate future, the Zwicky Transient Facility (**REFERENCE??**) and in the very near future the Large Synoptic Survey Telescope [56, 57] will open a new data space with high cadence, multi-band photometric monitoring. Identification of the types of events such as J1100-0053 and J2317+0005 will be possible while they are occurring allowing spectroscopic monitoring. We will be able to see how long a UV collapse lasts and and evolves, leading to the test of models at much higher fidelity than what we are able to do with the current CLQ samples.

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.
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. Mainzer, A. *et al.* Initial Performance of the NEOWISE Reactivation Mission. *ApJ* **792**, 30 (2014). 1406.6025.
11. 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.
12. Meisner, A. M. *et al.* Searching for Planet Nine with Coadded WISE and NEOWISE-Reactivation Images. *AJ* **153**, 65 (2017). 1611.00015.
13. Assef, R. J. *et al.* The WISE AGN Catalog. *1706.09901v1* (2017). 1706.09901.
14. Shakura, N. I. & Sunyaev, R. A. Black holes in binary systems. Observational appearance. *A&A* **24**, 337 (1973).
15. Shields, G. A. Thermal continuum from accretion disks in quasars. *Nature* **272**, 706–708 (1978).

16. Malkan, M. A. & Sargent, W. L. W. The ultraviolet excess of Seyfert 1 galaxies and quasars. *ApJ* **254**, 22–37 (1982).
17. Antonucci, R. Unified models for active galactic nuclei and quasars. *ARA&A* **31**, 473–521 (1993).
18. Perlman, E., Addison, B., Georganopoulos, M., Wingert, B. & Graff, P. Thermal AGN signatures in blazars. In *Blazar Variability across the Electromagnetic Spectrum*, 9 (2008). 0807.2119.
19. Lasota, J.-P. Black Hole Accretion Discs. In Bambi, C. (ed.) *Astrophysics of Black Holes: From Fundamental Aspects to Latest Developments*, vol. 440 of *Astrophysics and Space Science Library*, 1 (2016). 1505.02172.
20. 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).
21. 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.
22. Koratkar, A. & Blaes, O. The Ultraviolet and Optical Continuum Emission in Active Galactic Nuclei: The Status of Accretion Disks. *PASP* **111**, 1–30 (1999).
23. Sirko, E. & Goodman, J. Spectral energy distributions of marginally self-gravitating quasi-stellar object discs. *MNRAS* **341**, 501–508 (2003). astro-ph/0209469.
24. Pringle, J. E. Accretion discs in astrophysics. *ARA&A* **19**, 137–162 (1981).
25. Elvis, M. *et al.* Atlas of quasar energy distributions. *ApJS* **95**, 1–68 (1994).
26. Richards, G. T. *et al.* Spectral Energy Distributions and Multiwavelength Selection of Type 1 Quasars. *ApJS* **166**, 470–497 (2006). arXiv:astro-ph/0601558.
27. Lawrence, A. The UV peak in active galactic nuclei: a false continuum from blurred reflection? *MNRAS* **423**, 451–463 (2012). 1110.0854.
28. 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.
29. 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.
30. 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.
31. Mosquera, A. M. & Kochanek, C. S. The Microlensing Properties of a Sample of 87 Lensed Quasars. *ApJ* **738**, 96 (2011). 1104.2356.
32. King, A. Accretion disc theory since Shakura and Sunyaev. *Mem. Soc. Astron. Italiana* **83**, 466 (2012). 1201.2060.
33. 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.

34. Drake, A. J. *et al.* First Results from the Catalina Real-Time Transient Survey. *ApJ* **696**, 870–884 (2009). 0809.1394.
35. 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.
36. 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.
37. 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).
38. 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.
39. Tonry, J. L. *et al.* The Pan-STARRS1 Photometric System. *ApJ* **750**, 99 (2012). 1203.0297.
40. Magnier, E. A. *et al.* The Pan-STARRS 1 Photometric Reference Ladder, Release 12.01. *ApJS* **205**, 20 (2013). 1303.3634.
41. Clavel, J. *et al.* Steps toward determination of the size and structure of the broad-line region in active galactic nuclei. I - an 8 month campaign of monitoring NGC 5548 with IUE. *ApJ* **366**, 64–81 (1991).
42. Ulrich, M.-H., Maraschi, L. & Urry, C. M. Variability of Active Galactic Nuclei. *ARA&A* **35**, 445–502 (1997).
43. Vanden Berk, D. E. *et al.* The Ensemble Photometric Variability of ~25,000 Quasars in the Sloan Digital Sky Survey. *ApJ* **601**, 692–714 (2004). arXiv:astro-ph/0310336.
44. Pereyra, N. A. *et al.* Characteristic QSO Accretion Disk Temperatures from Spectroscopic Continuum Variability. *ApJ* **642**, 87–95 (2006). astro-ph/0506006.
45. MacLeod, C. L. *et al.* Modeling the Time Variability of SDSS Stripe 82 Quasars as a Damped Random Walk. *ApJ* **721**, 1014–1033 (2010). 1004.0276.
46. Guo, H. & Gu, M. The Optical Variability of SDSS Quasars from Multi-epoch Spectroscopy. II. Color Variation. *ApJ* **822**, 26 (2016). 1603.06876.
47. 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.
48. Zimmerman, E. R., Narayan, R., McClintock, J. E. & Miller, J. M. Multitemperature Blackbody Spectra of Thin Accretion Disks with and without a Zero-Torque Inner Boundary Condition. *ApJ* **618**, 832–844 (2005). astro-ph/0408209.
49. Gammie, C. F. Efficiency of Magnetized Thin Accretion Disks in the Kerr Metric. *ApJ* **522**, L57–L60 (1999). astro-ph/9906223.
50. 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.

51. Jun, H. D. *et al.* Infrared Time Lags for the Periodic Quasar PG 1302-102. *ApJ* **814**, L12 (2015). 1511.01515.
52. 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.
53. 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.
54. Cannizzo, J. K. On the $M_V(\text{peak})$ versus Orbital Period Relation for Dwarf Nova Outbursts. *ApJ* **493**, 426–430 (1998). astro-ph/9712210.
55. Ford, K. E. S. *et al.* *in prep.* (2018).
56. Ivezić, Z. & Tyson, J. A. f. LSST: from Science Drivers to Reference Design and Anticipated Data Products. *ArXiv e-prints* (2008). 0805.2366.
57. LSST Science Collaborations *et al.* LSST Science Book, Version 2.0. *ArXiv e-prints* (2009). 0912.0201.