A new physical interpretation of optical and infrared variability in quasars

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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, 6]. 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 [7, 8]. Here we report on four 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 faded, and then returned 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 3400Å has decreased by close to an order of magnitude. 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 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 $\sim$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 Shakura-Sunyaev $\alpha-$disk model [9] has long been used to (oversimply [10]) describe the basic properties of the optically thick, geometrically thin accretion disks expected to orbit the supermassive black holes at the nuclei of quasars. This accretion disk is thought to be the origin of thermal continuum emission observed in the rest-frame ultraviolet and optical. The $\alpha-$disk model makes the key assumptions that plasma within the disk is optically thick and thermal, and emission from the accretion disk can be treated as a superposition of blackbody annuli. Given the size scales and temperatures associated with supermassive black holes, a substantial fraction of the bolometric luminosity should be in the form of UV photons–the so-called "Big Blue Bump" [11, 12]. By contrast, the thermal emission seen in the infrared is believed to originate from more distant molecular dust. Thus, the IR flux is directly proportional to the emission from the disk, reprocessed by the dusty reservoir and delayed by the light-travel time between the two [see 13, 14, 15, for reviews].

For the optically thick, UV emitting disk to accrete onto the black hole, substantial angular momentum must be lost. A kinematic viscosity of the plasma, parametrized by α, seems the likely mechanism that transports angular momentum outward. This viscosity is likely due to magnetorotational instability [MRI; 16] with additional contributions to turbulence from the effects of objects embedded in the disk e.g., [17]. However, as e.g., [18, 19] point out, the observed spectral energy distributions (SEDs) of typical quasars differ markedly from classical α-disk theoretical predictions [9, 20] with a typical observed quasar SED flat in λF_λ over several decades in wavelength [21, 22]. Furthermore, real AGN disks seem to be cooler [e.g., 23] and larger [e.g., 24, 25, 26, 27] than the α-disk model predicts. The α-disk is an ad hoc parameterization of disk viscosity and does not permit predictions of global changes from local perturbations [28]. Nevertheless, in this paper, we utilize the mathematically simple α-disk model as a framework and departure point for our own disk models. Here, we build on previous work [29, 30**?**] and introduce a phenomenological model which does allow changes across the accretion disk and, crucially, makes predictions which can be observed in the SED.

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 Wide-Field Infrared Survey Explorer Reactivation mission [NEOWISE-R; 31, 32, 33], supplemented with the optical 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 changing-look quasars [e.g., 34], our investigation is the first to extend this selection to the infrared using NEOWISE-R mission data. 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. Importantly, our IR light curves enable us to set limits on SED changes due to obscuration.

In this article we present the $z = 0.378$ quasar SDSS J110057.70-005304.5 (hereafter J1100-0053). J1100-0053 was a known quasar we 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. The model we present invokes changes at the ISCO to be the triggering event for substantial changes in the wider accretion disk, including major structural changes out to $150 r_g$ (where r_g is the gravitational radius; $r_g = \frac{GM}{c^2}$). Such a model explains changes in the broad emission lines, as well as the optical and IR light curves.

[1] `legacysurvey.org/decamls/`

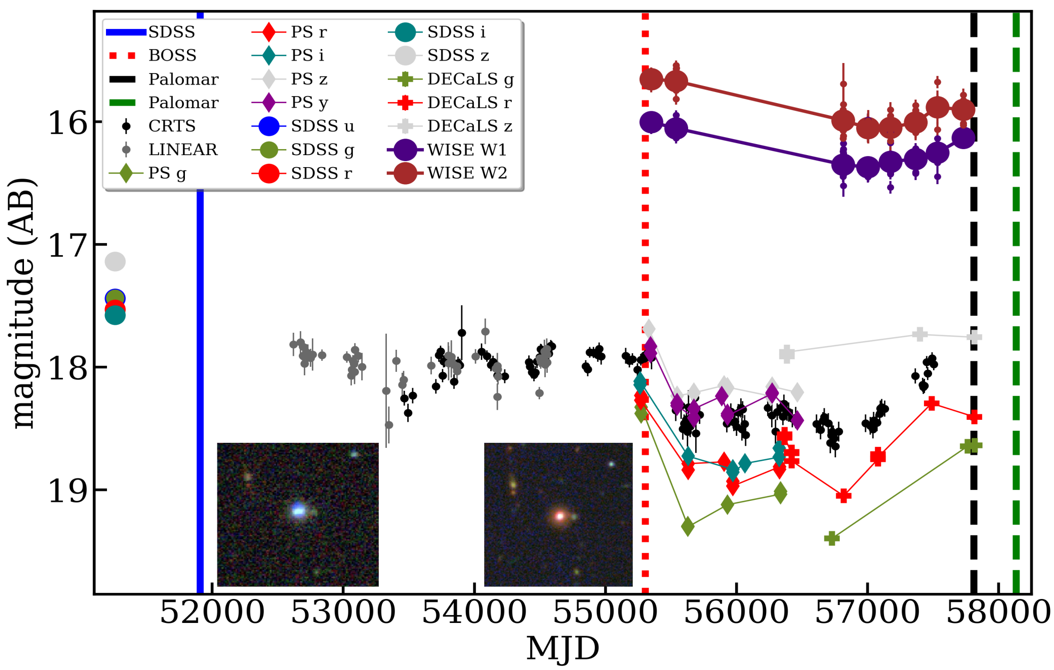

Figure 1 Multi-wavelength light curve of J1100-0053, including optical data from LINEAR, CRTS, SDSS, PanSTARRS and DECaLS, and mid-IR data from the WISE satellite. The four vertical lines illustrate the four epochs of optical spectra presented in Figure 2. J1100-0053 was flagged for further study due to the IR fading observed by WISE. Note that the optical emission has been recovering over the past few years, with the IR emission beginning to show similar behvaiour. The inserts show the images of J1100-0053 from SDSS in 1999 March and the DECaLS DR3 in 2014 March (50” on a side).

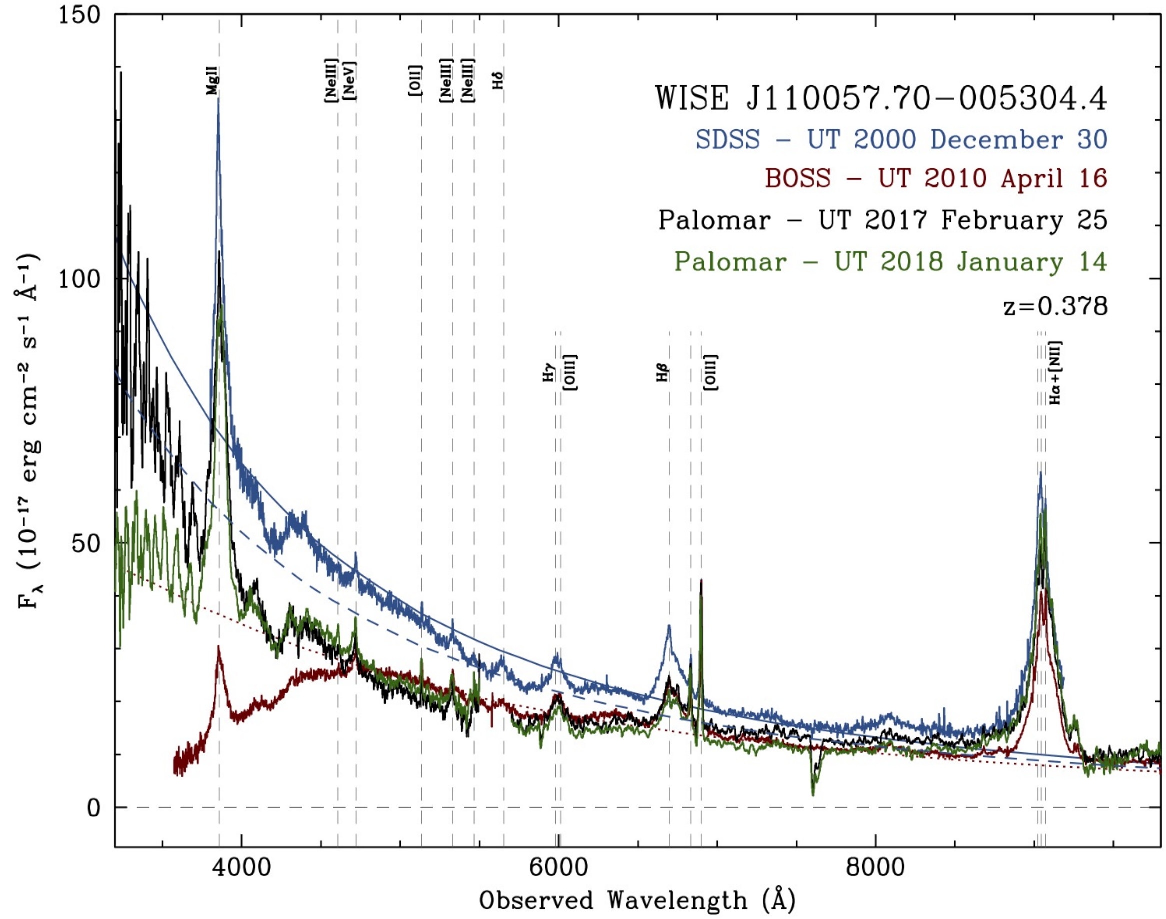

Figure 2 Optical spectra of J1100-0053 obtained on MJD 51908 (blue; SDSS), 55302 (red; BOSS), 57809 (black; Palomar) and 58132 (green; Palomar). Spectra have been renormalized to maintain a constant [O III] luminosity. Over the past two decades, the UV continuum and broad lines have changed significantly 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., 19], while the dashed blue line shows the same model, but with zero torque at the ISCO [i.e., equivalent to a simple α-disk model, 9]. Torque at the ISCO, possibly due to magnetic fields threading the inner disk and plunging region, 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 $80r_{\rm g}$ is suppressed by a factor of 10.

1 Target Selection and Observations

We started by matching the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS) Data Release 12 Quasar catalog [DR12Q; 35] to the NEOWISE-R IR data (WISE W1 at 3.4μm, WISE W2 at 4.6μm). We found $\approx$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 33, 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 quasar candidates. From this inspection, a list of $\approx$70 priority targets was derived, and with spectra already from SDSS and BOSS, J1100-0053 was an early target. We obtained a third and fourth epoch of optical spectroscopy from the Palomar 5m telescope.

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; 36, 37], the Lincoln Near-Earth Asteroid Research [LINEAR; 38] program and the Panoramic Survey Telescope and Rapid Response System [PanSTARRS; 39, 40, 41, 42] are available. Figure 2 shows the four optical spectra of J1100-0053 from SDSS, BOSS and Palomar observations. The first-epoch SDSS spectrum shows a typical blue quasar, but the blue continuum decreases by nearly a factor or ten in flux 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 fourth epoch spectrum is very similar to the third epoch. 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., [43], the review by [44] and more recent studies by [45, 46, 47, 48]), the identification of a “UV collapse” has only recently been noted by [49]. Those authors report the first discovery of a UV cutoff quasar, SDSS J231742.60 +000535.1 (hereafter J2317+0005; redshift $z = 0.32$), observed by SDSS three times, on 2000 September 29, 2001 September 25, and 2001 October 18. In the case of J2317+0005, a cycle of UV emission collapse, quasar dimming, and recovery was observed over the course of just a few weeks. For J1100-0053, the cycle is far longer; however the combination of optical and infrared light curves, as well as observing J1100-0053 at four separate spectral stages is currently unique. As such, J1100-0053 and J2317+0005 are now two archetypal objects that any accretion disk model must predict and explain [10].

2 Discussion

Our theoretical explanation for the behaviour of J1100-0053 (and J2317+0005) starts from the more-realistic, but α-parameterized disk model of [19]. In their model, the outer accretion disk is heated sufficiently to maintain stability against gravitational collapse, and small changes in temperature can lead to large changes in opacity and thus disk luminosity. In addition, the theoretical SEDs have a second peak in the near-infrared that is energetically comparable with the Big Blue Bump. [19] assume that the viscous torque at the inner edge of their accretion disks is vanishingly small and effectively zero. This is a good assumption for very thin disks and *as long as there is no connection between material inside the ISCO, i.e. the plunging region, and material at the ISCO*.

However, with magnetized gas losing angular momentum powering the accretion disk, it is reasonable that a

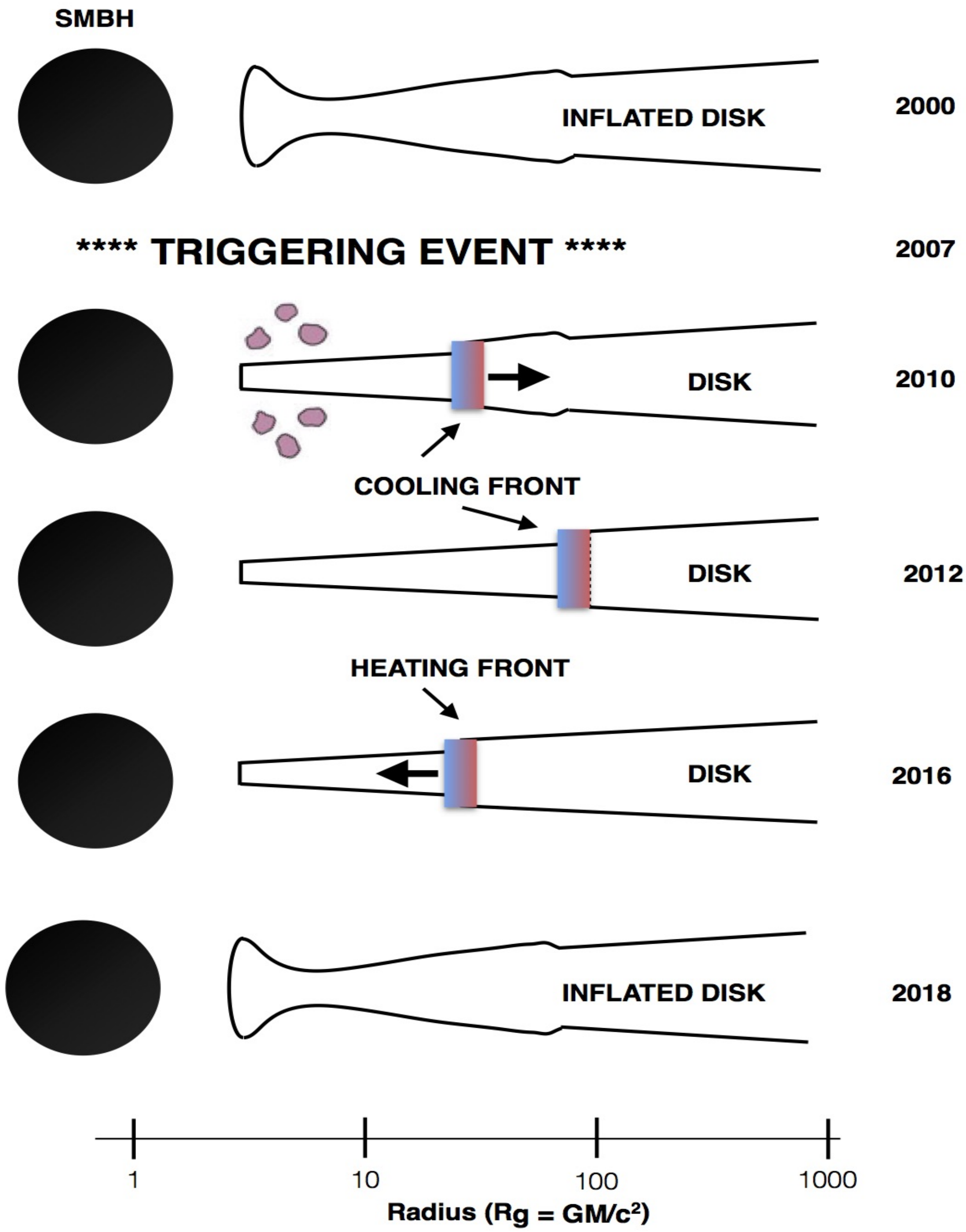

Figure 3 Cartoon illustration of our model explaining the unusual spectral evolution of J1100-0053. In 2000, corresponding to the SDSS spectral epoch, the quasar has a standard inflated accretion disk, i.e., where non-zero torque at the ISCO heats the inner radii of the accretion disk, causing it to puff up [e.g., 29]. 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 $t_{\rm front}$ time-scale [see also 30]. 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 [19]. A heating front then travels radially inwards, re-heating the inner accretion disk but on longer timescales, due to the thinner disk. We predict that in the next year, the quasar should roughly return to its initial state.

considerable quantity of the magnetic field gets dragged across the ISCO, into the plunging zone with the infalling gas. Thus, there are likely to be magnetic fields connecting gas in the plunging region to the gas still behind the ISCO. A drop in the quantity of magnetized material in the plunging region, so that thereis less back-reaction from there on the material at the ISCO, would then lead to a change in the torque at the ISCO. This is most likely due to a change in $\dot{M}$ across the ISCO, which in turn could be due to a change in the α viscosity, or a stochastic variation in the mass supply. This "triggering event", by reducing the torque at the ISCO, also reduces the local viscosity and local $\dot{M}$.

We then consider [29] who compare models with 'zero' and 'non-zero' torque at the ISCO, and the impact on the temperature profile of the corresponding accretion disk, when the torque changes. In zero-torque models, temperature $T_{\rm ZT}$ goes to zero at the inner edge of the disk (since the torque vanishes there) whereas a non-zero torque temperature profile, $T_{\rm NZT}$ reaches its maximum value at the inner edge of the disk (where the torque is maximal). Given a multi-temperature blackbody (MTB) model for disk emission, these differences at small $r_{\rm g}$ translate to large differences in the SED. 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., 50, 51]. 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 driven by magnetic fields. Our model of thermal emission from a MTB implies changes in the region from the ISCO to $\sim$few tens-100 $r_{\rm g}$ 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. As [52] describe in detail, the change at the ISCO is physically related to this thermal front.

We note that [30] investigate thermal-viscous instabilities in AGN, and find that a physical mechanism of propogating cooling and heating fronts is found, and that these fronts propagate on much shorter time scales than the viscous time. The model in [30] makes a firm prediction of this back and forth propagation of cooling and heating fronts on a short time scale, while noting that the surface density at smaller radii does not change so quickly and hence $\dot{M}$ fluctuates on a longer timescale.

For J1100-0053 we apply our model as follows, with a diagramatic illustration given in Figure 3. 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 $r \sim 100 r_{\rm g}$. This is the initial state circa 2000 (MJD 51900). 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 front propagation timescale is $t_{\rm front} \sim 10$ years $\left(\frac{h/r}{0.05}\right)^{-1} \left(\frac{\alpha}{0.3}\right)^{-1} \left(\frac{r}{225 r_g}\right)^{3/2} \frac{r_g}{c}$, and α is the traditional kinematic viscosity. As noted above, one simple, plausible trigger for this cooling front is that the non-zero torque condition at theISCO changes to a (more nearly) zero-torque condition. This dramatic decrease in the torque at the ISCO leads to a drastically cooler, thinner innermost disk. As the cooling front propagates, the drop in temperature leads to a drop in flux. To fit the observed spectra, our model has the cooler regions behind the front emitting 10% the flux of the initial hotter disk, and assumes the disk height drops by a factor $\sim$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 $\sim$3 years [19, 53, 54].

If the inner accretion disk is usually inflated [see e.g., 19, 55, 56], such a cooling front will naturally produce a collapse in the disk scale height, triggering a decrease in flux moving from UV to longer optical wavelengths, and a temporarily thicker scattering atmosphere, further decreasing flux at short wavelengths (see Fig. 3). Given our disk parameters, outward front propagation timescales are months-to-years, corresponding with observed timescales for optical emission moving from shorter to longer wavelengths as the radius of the cooling front increases. 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 [e.g., 54]. 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 at the disk surface 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, very much in the same vein as discussed by **(author?)** [30], somewhere in the disk, Σ reaches the critical surface density $\Sigma_{\rm max}$, and that triggers the heating instability. A heating front propagates back inwards, analagous to the well-known accretion disk limit cycle mechanism in models of dwarf novae outbursts [e.g., 57]. 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 will be asymmetric in time, as observed, and the shortest wavelength bands bottom out first, because that wavelength is dominated by emission coming from $r \sim 100r_g$ (see also discussion in the Supplemental Material).

Using [58] and [19], Figure 3 shows a model for a $M_{\rm BH} = 7 \times 10^8 M_\odot$, with an accretion rate in units of Eddington accretion, $\dot{M} = 0.070$ (appropriate for J1100-0053), radiative efficiency of $\varepsilon = 0.1$ inner disk radius of $6r_{\rm g}$ and outer disk radius of $10,000r_g$. The resulting model spectra can be seen in Figure 2. We expect the front to return to the ISCO in mid-to-late 2018. That means the broad Balmer lines will come back a few months later, but the WISE IR flux should not return to full flux until 2021. We note the IR brightness of J2317+0005 never declined (cf. J1100-0053). However as the change in the UV for J2317+0005 was rapid, indicating that the cooling event was brief, this is consistent with our model.

3 Conclusions

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 which cannot tightly constrain our theoretical model. The Zwicky Transient Facility [ZTF; 59] has very recently started and will open a new data space with high cadence, multi-band photometric monitoring. Along with ZTF in the very near future, the Large Synoptic Survey Telescope [60, 61] will allow identification of the types of events such as J1100-0053 and J2317+0005 *while they are occurring*, allowing spectroscopic monitoring. We will be able to see how long a UV collapse lasts and closely follow its evolution. Such data will stringently test models of AGN disks at much higher fidelity than we are able to do with current 'Changing-Look' quasar samples.

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