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]. 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 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.

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 (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 [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 SDSS quasars that show significant changes in their IR flux over the course of a few years.

The Shakura-Sunyaev $\alpha-$disk model [14] has long been used to (over-)simply describe the basic properties of the optically thick, geometrically thin accretion disks expected to orbit the supermassive black holes at the nuclei of quasars. As is prescribed in [e.g. 15], this accretion disk is thought to be the origin of thermal continuum emission

[1] `legacysurvey.org/decamls/`

that is observed in the rest-frame ultraviolet and optical. The radial distribution of effective temperature across this steady disc t $T(R) \propto R^{-3/4}$. The thermal emission seen in the infrared is believed to originate in the dusty, molecular torus, representing emission from the disk or BLR that has been reprocessed in this optically thick region into thermal radiation [see e.g., 16, 17, 18, for reviews].

While the mass of the black hole is large compared to the accretion disk, the angular momentum of the black hole hole is small compared to the accretion disk. Hence angular momentum has to be lost from the accretion disk. A kinematic viscosity seems the likely mechanism that angular momentum is transported outward. This viscosity is likely due to magnetorotational instability [MRI 19] with additional contributions to turbulence from the effects of embedded objects in the disk [e.g., 20].

While we utilize the α-disk model in this paper, the model is ad hoc only parameterizing disk viscosity, and does not permit predictions of global changes to the disk [21]. Real AGN disks seem to be cooler [e.g., 22] and larger [e.g., 23, 24, 25, 26] than the α-disk model predicts.

In this article we present the $z = 0.378$ quasar SDSS J110057.70-005304.5 (hereafter J1100-0053). We have spectral observations for J1100-0053 showing a transition in the blue-continuum slope

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 $r_{\rm g}$ is the gravitational radius; $r_{\rm g} = \frac{GM}{c^2}$) as well as the IR light curves. Critically, our model makes predictions to the future behaviour of J1100-0053.

1 Target Selection and Observations

We started by matching the SDSS-III BOSS Data Release 12 Quasar catalog [DR12Q; 28] to the NEOWISE-R IR data (WISE W1 at 3.4μm, WISE W2 at 4.6μm). We found $\sim$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]. 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; 29, 30], LINEAR [31] and PanSTARRS [32, 33, 34, 35] 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, the blue continuum has then returned in the third epoch spectrum 7 years

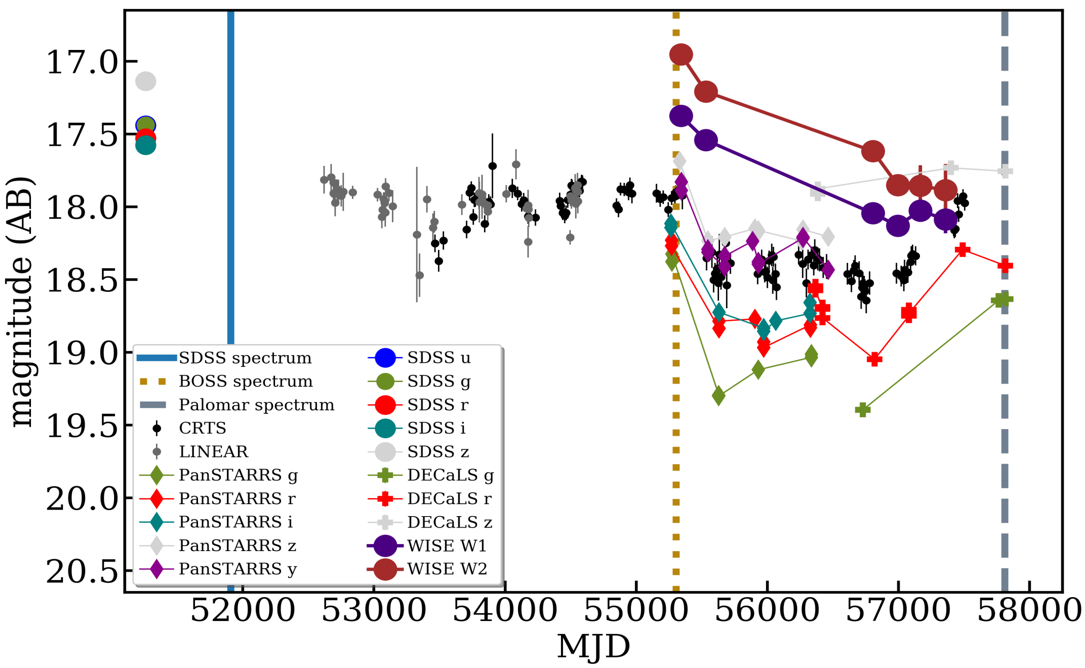

Figure 1 Multi-wavelength light curve of J1100-0053, including optical data from LINEAR, CRTS, SDSS, PanSTARRS and DECaLS, and mid-IR data from the WISE satellite. The three vertical lines illustrate the epochs of the three optical spectra presented in Figure 2. J1100-0053 was flagged for further study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

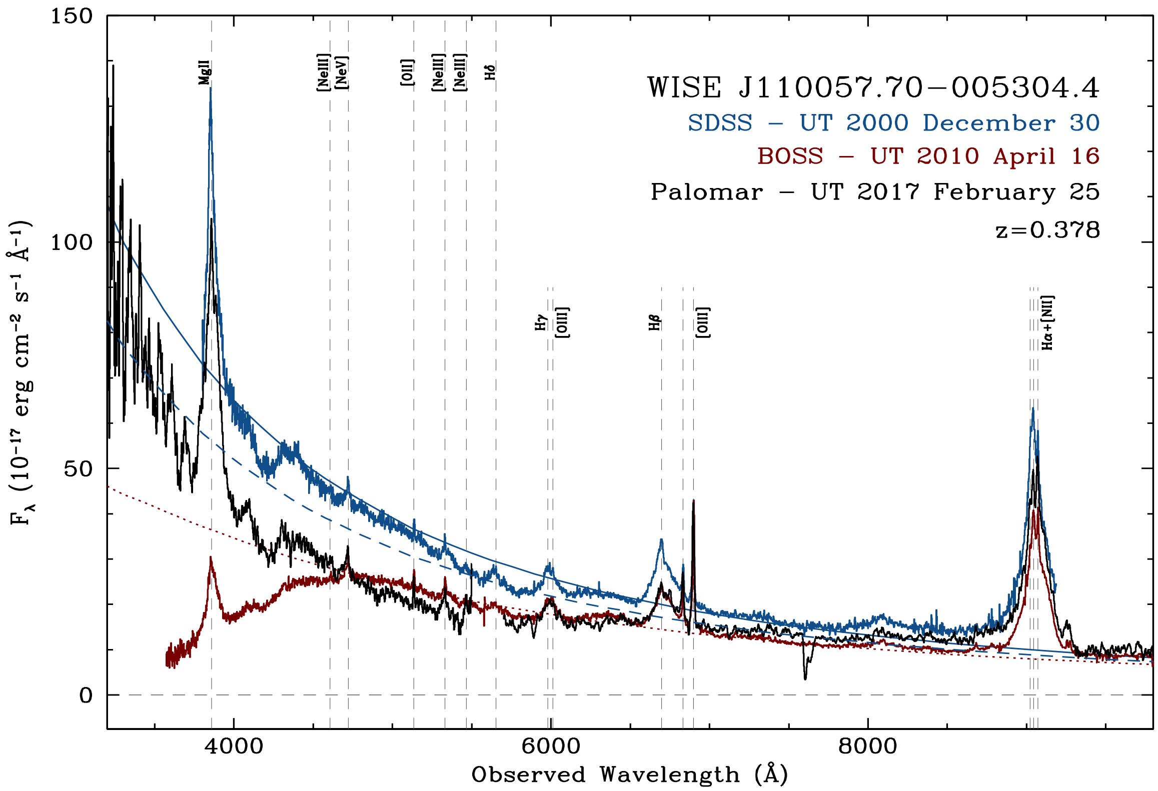

Figure 2 Optical spectra of J1100-0053 obtained on MJD 51908 (blue; SDSS), 55302 (red; BOSS) and 57809 (black; Palomar). Spectra have been renormalized to maintain a constant [O III] luminosity. Over the past two decades, the UV continuum and broad lines have changed significantly for this quasar. In 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., 27], 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.

later, albeit at a diminished flux from the initial spectrum. The Supplemental Material gives further observation details including an achival ROSAT detection.

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.

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 $r \sim 100r_\mathrm{g}$. 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., 36, 37]. 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_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_ion), which will cause: 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.

If the inner accretion disk is usually inflated [see e.g., 27, 38, 39], 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 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., 40].

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., 41]. 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 wll be asymmetric in time, as observed, and

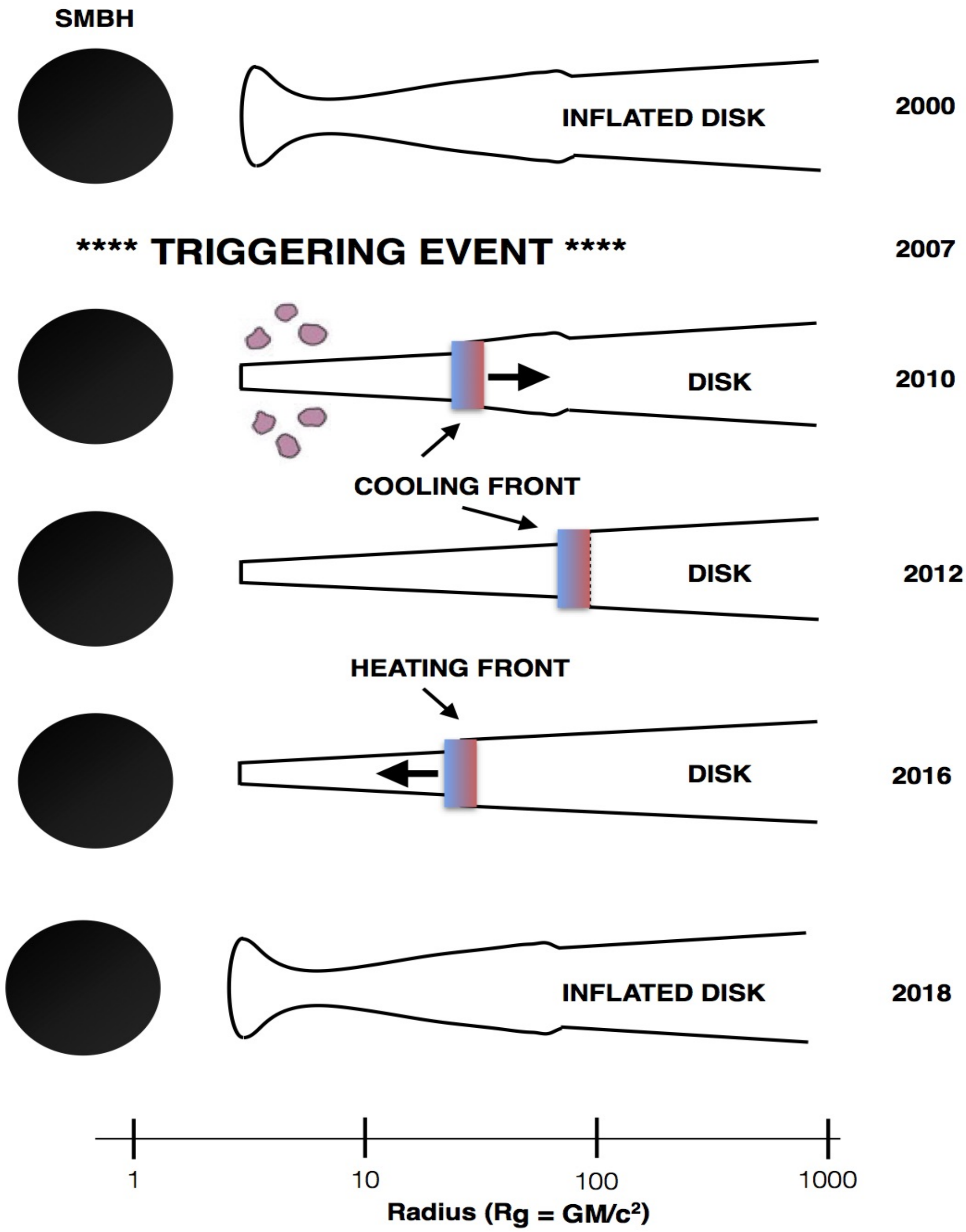

Figure 3 Cartoon illustration of our model explaining the unusual spectral evolution of J1100-0053. In 2000, corresponding to the SDSS spectral epoch, the quasar has a standard inflated accretion disk, i.e., where non-zero torque at the ISCO heats the inner radii of the accretion disk, causing it to puff up **?**]. 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 propogate outwards in the accretion disk, traveling on the $t_{\rm front}$ time-scale. Circa 2012, the cooling front reaches a predicted kink in the accretion disk profile at 100 Rg, associated with a shift in the accretion disk opacity **?**]. 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 g-band bottoms out first, because that wavelength is dominated by emission coming from $r \sim 100 r_g$ (see discussion inthe Supplemental Material).

Using [42] and [27], 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 $6 r_{\rm g}$ and outer disk radius of $10,000 r_g$. 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.

[43] 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 [43] result further in the Supplemental Material.

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.

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