A new 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 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 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 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).

Developed in the early 1970s, the Shakura-Sunyaev $\alpha-$disk model [10] of AGN accretion disk explains the strong, blue continuum observed from AGN as thermal emission from an optically thick, geometrically thin accretion disk ($h/r \ll 1$, where h is the vertical scale height of the disk and r is the radius from the disk center). However, the [10] α-disk thermal model is also known to have serious short-comings e.g. [11, 12, 13]. For example, AGN seem to be cooler than they ought to be [e.g., 13] with the spectral energy distributions (SEDs) of AGN showing a universal near-UV shape, reaching a maximum energy flux around 1100Å. Such a peak suggests a characteristic turnover temperature of T$\sim$30,000K, whereas for a thermal model, the characteristic temperature should be roughly T$\sim$100,000K. Moreover, constraints from microlensing observations for the size of the optical emission region [e.g., 14, 15, 16, 17] suggest this region is a factor of $\sim$4 times larger than the one predicted by the standard Shakura-Sunyaev disk.

Changing-look quasars have traditionally been discovered by looking for large, $|\Delta m| > 1$ magnitude changes in optical light curves of quasars or galaxies (e.g. across 3720Å $< \lambda <$ 5680Å, in the g-band). However, we have taken advantage of the ongoing Near-Earth Object WISE Reactivation mission [NEOWISE-R; 18, 19, 20], as well as

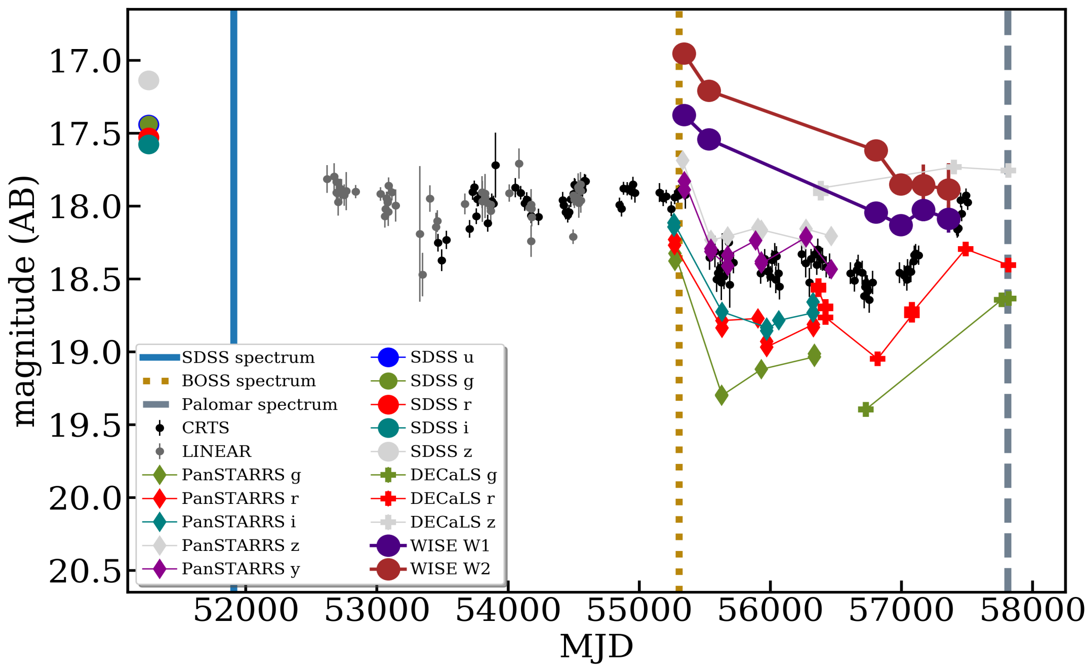

Figure 1 The light curve of J1100-0053. SDSS, DECaLS and PanSTARRS give the optical photometery. The WISE IR light curves are shown and their dramatic decrease led to the identification of J1100-0053. The three spectral epochs are shown by the vertical lines.

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 [21, 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 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.

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.

[1] legacysurvey.org/decamls/

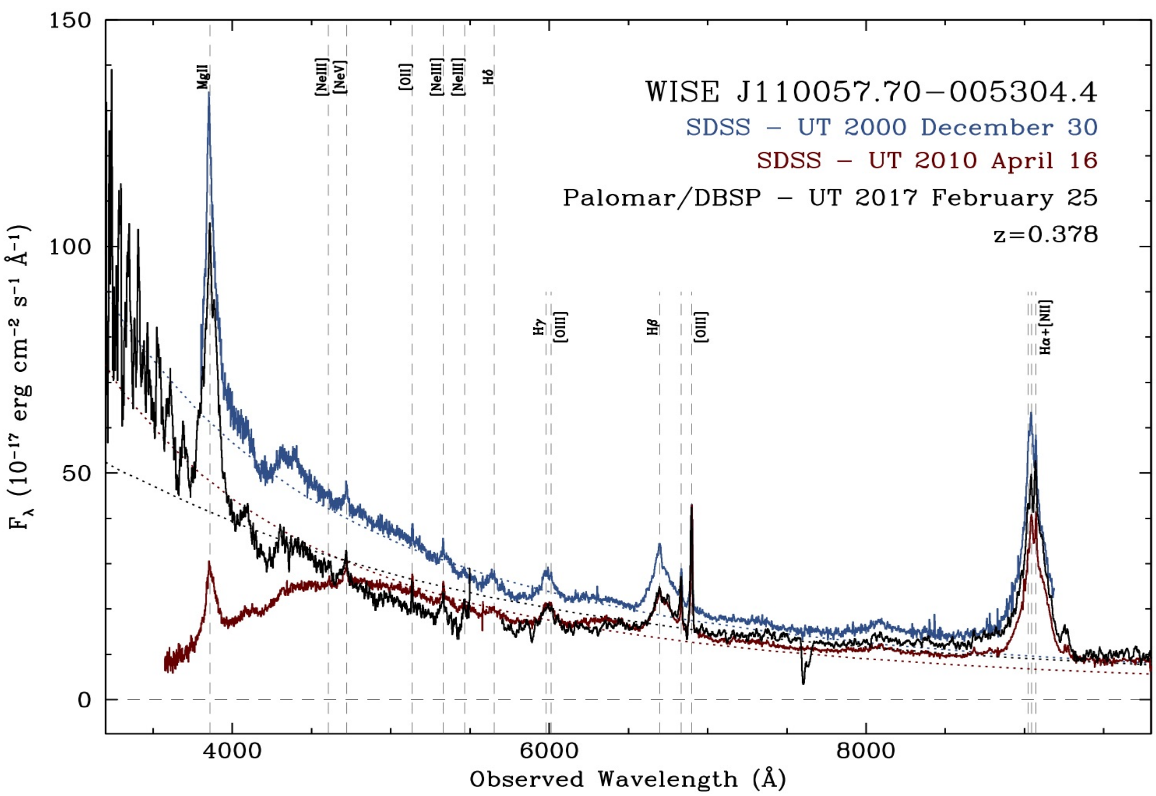

Figure 2 Optical spectra of J1100-0053 obtained on MJD 51908 (blue; SDSS), 55302, (red; BOSS) and 57809 (black; Palomar/DBSP). *Left::* The full optical spectra; *Right (top)::* Zoom in on the Hβ-[O III] complex; *Right (bottom)::* Zoom in on the Hα-N II complex.

1 Target Selection and Observations

We started by matching the SDSS-III BOSS Data Release 12 Quasar catalog [DR12Q; 22] 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 20, 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 $\approx$ 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; 23, 24], LINEAR [25] and PanSTARRS [26, 27, 28, 29] 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 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 disk, with non-zero torque at the ISCO, and $h/r \sim 0.2$ inside of $r \sim 100 r_{\mathrm{g}}$. This is the initial state circa 2000 ($\approx$ MJD 51900). Around 2007, there is a switch to a state of zero torque at the ISCO. This causes a cooling front to propagate out from the ISCO over the timescale, t_{front}. The drop in temperature leads to a drop in flux; regions behind the cooling front emit 10% of the flux compared to what they did prior to the passage of the cooling front and the temperature decrease leads to the height dropping by a factor of 2. L_{ion} starts decreasing due to the drop in ionizing photons, which in turn causes the Balmer lines to decrease in flux.

If the inner accretion disk is usually inflated [see e.g., 30, 31, 32], 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

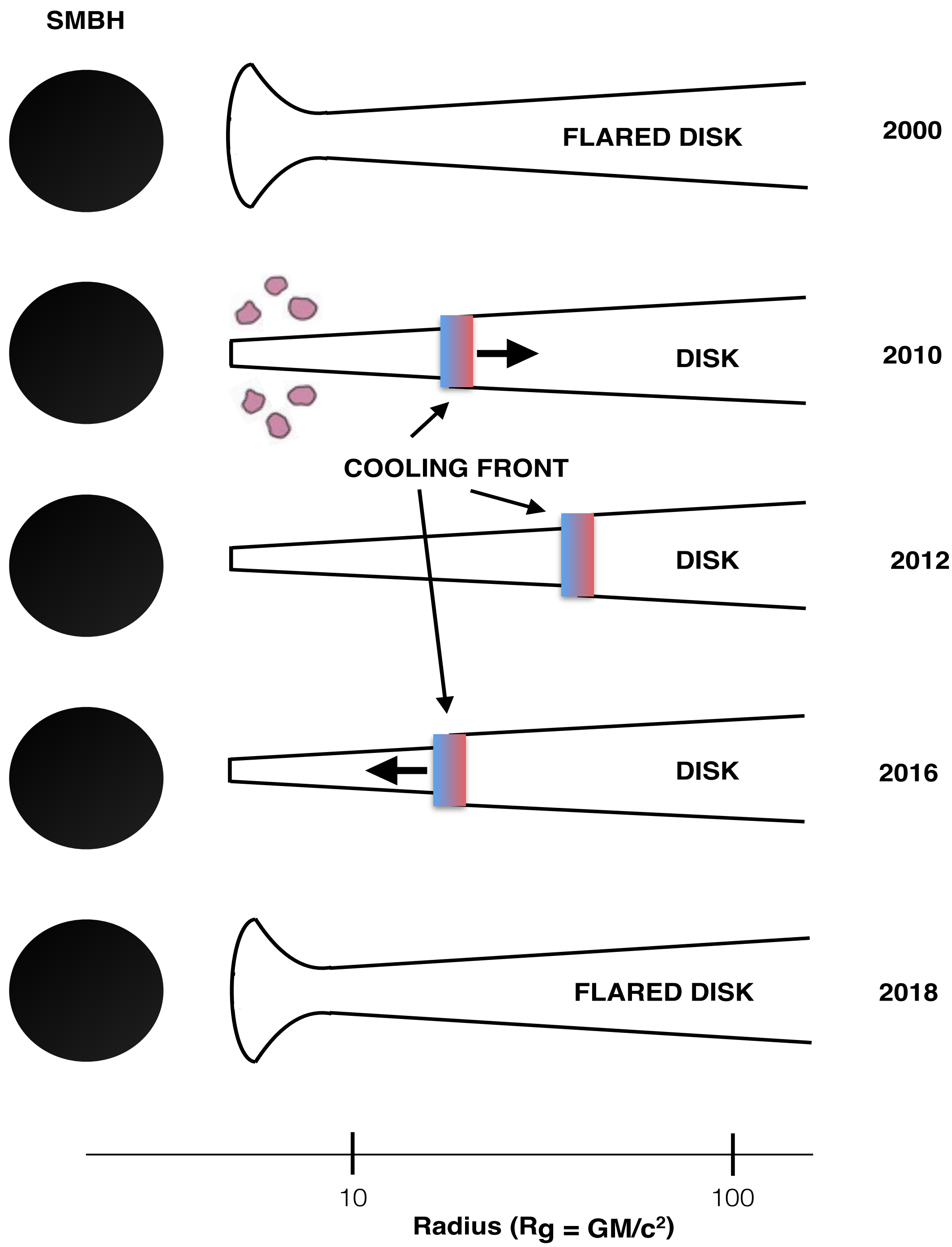

Figure 3 Our thermal model where an event at the ISCO causes a cooling front to initiate and propagate out away from the central black hole. We predict that the flared disk will return to close its original state in 2018.

delay due to light travel time as well [e.g., 33].

Since the disk starts puffed-up, the cooling front time is not long, and 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, which in turn causes Rayleigh scattering producing the blue downturn in the 2010 spectrum. The cooling front keeps going, until it hits the part of the disk where it is normally thin, around $r = 100r_g$, arriving around 2012. This sets up another (heating) front, which will travel *back in* towards the SMBH, and re-inflate the disk. This 'returning' front travels more slowly because the disk is thinner. This means the return to normal will be asymmetric in time, as observed, and the g-band bottoms out first because that is coming from $r \sim 100r_g$ (see discussion in the Supplemental Material).

Using [34] and [30], 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.

[35] 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 [35] result further in the Supplemental Material.

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