The characteristic blue spectra of accretion disks in quasars as uncovered in the infrared

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Quasars are thought to be powered by supermassive black holes accreting surrounding gas$^{1-3}$. Central to this picture is a putative accretion disk which is believed to be the source of the majority of the radiative output$^{3-4}$. It is well known, however, that the most extensively studied disk model$^5$ — an optically thick disk which is heated locally by the dissipation of gravitational binding energy — is apparently contradicted by observations in a few major respects$^6,7$. In particular, the model predicts a specific blue spectral shape asymptotically from the visible to the near-infrared$^5,8$, but this is not generally seen in the visible wavelength region where the disk spectrum is observable$^9-13$. A crucial difficulty was that, toward the infrared, the disk spectrum starts to be hidden under strong hot dust emission from much larger but hitherto unresolved scales, and thus has essentially been impossible to observe. Here we report observations of polarized light interior to the dust-emitting region that enable us to uncover this near-infrared disk spectrum in several quasars. The revealed spectra show that the near-infrared disk spectrum is indeed as blue as predicted. This indicates that, at least for the outer near-infrared-emitting radii, the standard picture of the locally heated disk is approximately correct.

A success of the most extensively studied disk model is that it gives the radiative output peak approximately correctly in the ultraviolet (UV; $\sim 0.01-0.4 \mu$m) wavelengths for the case of a supermassive black hole. This is observed for a generic spectral energy distribution of quasars, the most luminous example of active galactic nuclei (AGN). However, it has long been known that the model apparently shows a few major contradictions with observations$^{6,7}$. One of the disagreements, and perhaps the most easily comprehensible one, is the spectral shape of the radiation. From the basic hypothesis of the model (an optically thick disk heated locally), the effective disk temperature $T$ is fixed as a function of radius $r$ as $T \propto r^{-3/4}$ over a broad range of radii. This leads to a well-known blue spectral shape limit, $F_\nu \propto \nu^{+1/3}$, being asymptotically reached at long wavelengths from the visible (also called the optical; $\sim 0.4-1 \mu$m) to the near-infrared ($\sim 1-2 \mu$m) for AGN disks. In contrast, many studies have shown that the general AGN spectral shape observed at optical/UV wavelengths is much redder, spectral slope $\alpha$ being from $-0.2$ to $-1$ ($F_\nu \propto \nu^\alpha$), and never as blue as this spectral shape$^9-13$.

The predicted blue shape limit is strictly true in the simplest assumption of local black-body emission. In more sophisticated disk atmosphere models$^3$, the spectrum generally becomes slightly redder at optical wavelengths, owing to various opacity and non-LTE effects, but discrepancies between the model and observed spectra still remain$^1$. However, the redder model slopes at optical wavelengths form a wider concave spectrum that shifts the bluer limit above to longer wavelengths, into the near-IR. The observed spectra certainly appear to become bluer from the short UV wavelengths to the optical. The crucial observational difficulty here has been that the disk spectrum starts to be hidden under the hot dust thermal emission which begins at wavelengths greater than $\sim 1 \mu$m, a limit set by the sublimation temperature of dust grains ($\sim 1500$ K). These dust grains exist at larger spatial scales, in a configuration often thought to have a torus-like geometry but which is generally not yet spatially resolvable. Therefore, it has been virtually impossible to observe the underlying near-IR disk spectrum$^9$. We note that, contrary to early spectral fitting studies$^3,4,6,16,17$, the IR component is no longer thought to be non-thermal, and thus cannot be extrapolated to underlie the optical spectrum — an extrapolated non-thermal spectrum had effectively made the inferred disk spectrum on top of the non-thermal spectrum bluer.

We argue here that this buried part of the disk spectrum can be revealed by observing the near-IR polarized light. Optical continua of many directly-visible AGNs called Type 1s (Seyfert 1 galaxies and quasars) are known to be linearly polarized at a level $\leq 1\%$. The polarization position angle (PA) in these Type 1 cases is mostly parallel to the rotation axis of the putative accretion disk, where the axis can be probed by the linear jet-like structure of radio emission$^{18-20}$. (This is in contrast to the cases in hidden AGNs or Type 2s, which show high polarization at perpendicular PAs and strong broad lines in polarized light, and which are not the subject of the present paper.) This polarization in Type 1s is interpreted as an indication of an equatorial scattering region, which is optically thin and surrounds the disk. In many Seyfert 1 galaxies, broad emission lines are polarized at a much lower level than the continuum polarization and at different PAs$^{19,20}$, indicating that the scatterers reside roughly at the same spatial scales as the broad-line-emitting clouds.

At least in several quasars, the emission line polarization even vanishes — the optical polarized light spectrum shows no
or very little emission line flux. This is very likely to indicate that the scatterers reside interior to the broad-line clouds. In these Type 1 cases, the scatterers are thought to be electrons and not dust grains, since the scattering region is interior to the dust sublimation radius. Because electron scattering is wavelength independent, the polarized light therefore produces a copy of the spectrum originating interior to the scattering region. (We note that this electron scattering is conceptually different from the one in previous works, which was assumed to be intrinsic to the accretion disk atmosphere and gave rise to the prediction of perpendicular PAs.) In the optical polarized light from these quasars, which excludes the emission from the broad-line region, we actually found a hydrogen Balmer-edge feature in absorption for the first time, which we believe originates in the disk and is a very specific indication of the thermal and optically-thick nature of the emission.

We can then use the same polarized light, but in the near-IR, to reveal the hidden spectrum of the disk, by stripping off the dust radiation from the torus exterior to the scattering region. In previous work, we suggested that this method appears to work in at least one quasar that has polarization data with high signal-to-noise-ratio at two wavelength bands in the near-IR. However, crucial information needed at the time was whether the near-IR polarized light behavior is consistent and systematic in different objects. If it is, this would critically argue against, for example, a possible secondary polarization component related to dust grains newly arising in the near-IR. Therefore we undertook the near-IR polarimetry of five other quasars. The targets were selected to be polarized in optical continua but essentially not in emission lines, to ensure the scattering to be interior to the broad-line region. These properties were either already known or were determined in our optical polarimetric survey and follow-up spectropolarimetry.

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![Diagram](image_url)

**Figure 1:** Overlay of the polarized- and total-light spectra observed in six different quasars. We plot scaled $\nu F_{\nu}$ data: Q0144-3938 (redshift $z=0.244$), green; 3C95 ($z=0.616$), blue; CTS A09.36 ($z=0.310$), light blue; 4C 09.72 ($z=0.433$), red; PKS 2310-322 ($z=0.337$), light green. Plotted in purple are the data for Ton 202 ($z=0.366$) from a previous paper. Total-light spectra, shown as bold traces in the optical and as squares in the near-infrared, are normalized at 1 $\mu$m in the rest frame, by interpolation (except for 3C95 for which we normalized by $\nu F_{\nu}$ observed at 1.3 $\mu$m in the rest frame). Polarized-light spectra, shown as light points in the optical and as bold points in the near-infrared both (vertical error bars, 1-$\sigma$), are separately normalized, also at 1 $\mu$m, by fitting a power-law to the near-IR polarized-light spectra. For both total-light and polarized-light data, horizontal bar lengths indicate bandwidth. The normalized polarized-light spectra are arbitrarily shifted downwards by a factor of three relative to the normalized total-light spectra, for clarity. The total-light spectra in $\nu F_{\nu}$ turn up at around or slightly longward of 1 $\mu$m. In contrast, the polarized-light spectra in $\nu F_{\nu}$ all consistently and systematically decrease towards long wavelengths, showing a blue shape of approximately power-law form.

The measurement of the spectral index $\alpha$ in $F_{\nu} \propto \nu^{\alpha}$ for each object is shown in Fig.2. The measured slopes are consistent with each other within their errors, and the individual slopes as well as their average clearly point to a shape much bluer than those observed in the UV/optical. Astonishingly, they are all consistent with the $F_{\nu} \propto \nu^{+1/3}$ shape. The weighted mean of the measured slopes is $\alpha = +0.44\pm0.11$. Although the sample size is small, there does not appear to be any luminosity dependence, as seen in Fig.2, and we did not find dependencies on black hole masses $M_{\text{BH}}$ or Eddington ratios $L/L_{\text{Edd}}$ derived from the width of the Hβ Balmer line. This is expected if the near-IR spectrum is in the long-wavelength limit of the disk model, which is independent of parameters such as black hole mass or Eddington ratio. In this case, by regarding each measurement as a measurement of the same quantity, the weighted mean over these measurements becomes physically meaningful.

We note that, if we formally convert the mean slope to the radial temperature distribution for the case of an optically-thick disk, we obtain $T \propto r^{-0.78\pm0.03}$, consistent with the predicted dependence $T \propto r^{-3/4}$.

The systematic behavior of the near-IR polarized light, as well as the constancy of the PAs over all wavelengths,
is not directly relevant except for some very specific cases
local internal heating in the outer radii considered here, and thus
tral shape at long wavelengths; but it would not dominate the
size. Therefore the near-IR polarized light spectra very likely
emission size becomes almost the same as the scattering region
Significant geometrical effects will not occur unless the disk
predicted shape
untruncated multi-temperature black-body disk for our quasars.
be affected if the corresponding spatial scale of the disk emis-
strongly argues against there being any secondary polarization
contamination. We might worry that the polarized light would
Spectral index of polarized light spectra. We plot \( \alpha \) (in
\( F_\nu \propto \nu^\alpha \)) against \( \nu L_\nu \) for total light at 0.51 \( \mu m \). The index was
measured by a power-law fit for each near-IR polarized-light spectrum (note the different wavelength range covered depending on the redshift) and is shown with 1-\( \sigma \) error bars. A weighted mean of the spectral index measurements is shown dashed; the shaded area represents its deduced 1-\( \sigma \) uncertainty. The mean or median slopes of the UV/optical total-light spectra derived in various studies\(^9-13\) are also shown.

The measured slopes, being as blue as the slope of the predicted shape \( F_\nu \propto \nu^{+1/3} \), strongly suggest that, at least in the outer near-IR emitting radii, the standard but hitherto unverified picture of the disk being optically thick and locally heated is approximately correct. In this case, an implication is that other model problems at shorter wavelengths are associated with, or originate from, our lack of understanding of the inner regions of the same disks. We note that disk irradiation in limiting cases can contribute to the heating without changing the \( \nu^{+1/3} \) spectral shape at long wavelengths; but it would not dominate the local internal heating in the outer radii considered here, and thus is not directly relevant except for some very specific cases\(^27,28\).

The standard disk is also well known to be gravitationally unstable at large radii\(^29\). These radii may well correspond to those emitting in the IR\(^30\) (\( \sim 800R_S \) for our quasars). In this case, if the disk is truncated at such a radius, the spectrum will show a break, becoming even bluer at the longest wavelengths\(^25\). Although statistically insignificant, our data do suggest that the near-IR slope is slightly bluer than the spectral shape \( F_\nu \propto \nu^{+1/3} \), with a hint of possibly becoming bluer at longer wavelengths. This can be followed up by extending the wavelength coverage with similar polarized Type-1 AGNs at lower redshifts. Such future measurements may pioneer the way to probe how and where the disk ends and how material is being supplied to the nucleus.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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