Notes for Nature letter "A dust-parallax distance of 19 megaparsecs to the supermassive black hole in NGC 4151"

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1. Letter

The accretion disk emits primarily in the UV and optical. For temps lower than 1500 K dust can survive and we have the dusty torus where the emission is absorbed and reemitted in the IR which means we should see any variability from the disk in the torus with a time delay. infrared interferometry at the same wavelength the torus emits measures the angular size, ρ, of the same emission region. The physical R_τ and angular size ρ are related by

$$sin(\rho) = \frac{R_\tau}{D_A}$$

where D_A is the angular-diameter distance to the object. taking into account cosmic time dilation and that for small angles $sin(\rho) \approx \rho$ we have $D_A(Mpc) = \frac{0.173\tau(days)}{(\rho(mas)(1+z))}$. The idea was to use the BLR originally but its angular size is too small to be spatially resolved with todays equipment. The dust continuum emission from the dusty torus is 4X larger and it requires only photometric reverberation mapping.

When the physical size and angular size are compared it is paramount that the measurements refer to the same region of the AGN, One way to account for this is to make the dust observation in the same waveband (K-band). The dust distribution also has an effect on the measured size such that a homogeneous distribution of dust will give a larger radius than a compact one (see figure 1).
Using a disk model, where the dust is heated by AGN radiation and the projected brightness distribution is represented by the power law account for this distribution effect. the shallower brightness distribution have a smearing effect that can then be accounted for and the inner radius of the brightness distribution can be found. The determination of the physical and angular size of the inner boundary of the brightness distribution is also affected by the disk geometry and dust properties. for constraints on the disk inclination/orientation the emission line region and polarimetry is considered, whereas dust properties are included in the parameterization of the brightness distribution.
It is important to note that the reference time lag or the reference angular size individually is quite uncertain, but both parameters are strongly correlated with the dust brightness distribution, so their ratio D_A can be determined with much higher precision given they are calculated at the same time for a given power law parameterization.

2. Methods

The radius-dependent brightness distribution F(r) in any infrared band can be approximated by a power law

$$F(r) = F(r_{in}) \left(\frac{r}{r_{in}}\right)^{\frac{\alpha'-2}{4+\gamma}} = F(r_{in}) \left(\frac{r}{r_{in}}\right)^{\alpha}$$

where the power-law index γ describes the change of absorption efficiency in the infrared with respect to the optical and the equation of local thermal equilibrium was used. values for $\gamma \approx 1.6 - 1.8$. $F(r_{in})$ is the emission at the innermost radius, which is at the dust sublimation temperature. The dust opacity of the emitting medium is thus implicitly accounted for because γ is part of α, so no particular dust composition needs to be assumed, but instead solve self-consistently for the effect of dust absorption efficiencies.

Since $\tau = \frac{r}{c}$ and $\rho = \frac{r}{D_A}$ for small ρ we can switch out r for these variables instead in the above equation. The power law index α also needs to be constrained which may be done from both interferometry and reverberation measurements or from fitting the light curves to determine ρ_{in}. τ_{in} and ρ_{in} both depends on the dust sublimation temperature but in the same way so their ratio does not.

In the future the orientation and inclination angle can both be obtained with multi-baseline infrared interferometry as they will be self-consistently inferred from the data without the need for extra information. The position

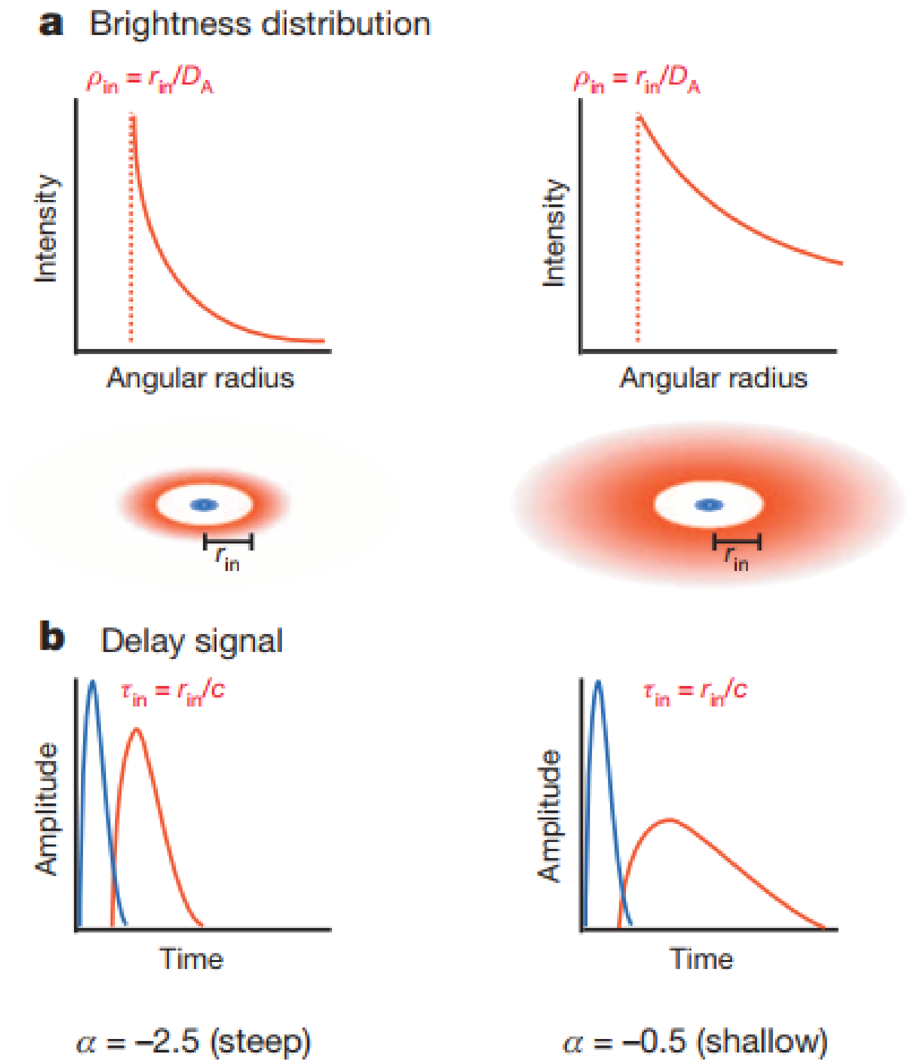

Figure 1 | Effect of the brightness distribution on the observed sizes and time lags. The bottom row (**b**) illustrates effects on the time lag signal of varying the brightness distribution (blue, optical; red, near-infrared), and the upper row (**a**) outlines the corresponding (interferometric) brightness distribution in the near-infrared. Compact distributions lead to shorter time lags and smaller interferometric radii than do shallow profiles. This information is encoded in the shape (width, amplitude) of the light curve. With a simple power-law parameterization, this smearing effect can be accounted for to determine the time lag and angular size of the innermost radius of the brightness distribution. The simultaneous modelling of light curves and interferometry results in a very precise angular distance measurement.

angle of the AGN has been inferred from kinematic modelling of emission lines and optical polarimetry, whereas the priors for the inclination of the disk come from the kinematic modelling of the emission lines in the outflow cone.

The dust covering factor cancels out for relative light curves but is assumed small for the K band. for the disk model the brightness distribution is a projected disk and, thus, geometrically thin. This simplifies the convolution of the light curves with the transfer function to a two-dimensional problem. Significant emission above the disk would give a contribution to the transfer function from 3D space. It seems that the assumption is fine as the observed K-band covering factor is $c_K < 0.2$ as estimated from the mean fluxes of the V- and K-band light curves.