A new direct method for measuring the Hubble constant from reverberating accretion discs in active galaxies

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ABSTRACT

We show how wavelength-dependent time delays between continuum flux variations of AGN can be used to test the standard black hole-accretion disc paradigm, by measuring the temperature structure $T(R)$ of the gaseous material surrounding the purported black hole. Reprocessing of high energy radiation in a steady-state blackbody accretion disc with $T \propto R^{-3/4}$ incurs a wavelength-dependent light travel time delay $\tau \propto \lambda^{4/3}$. The International AGN Watch multiwavelength monitoring campaign on NGC 7469 showed optical continuum variations lagging behind those in the UV by about 1 day at 4800 Å and about 2 days at 7500 Å. These UV/optical continuum lags imply a radial temperature structure $T \propto R^{-3/4}$, consistent with the classical accretion disc model, and hence strongly supports the existence of a disc in this system. We assume that the observed time delays are indeed due to a classical accretion-disc structure, and derive a redshift independent luminosity distance to NGC 7469. The luminosity distance allows us to estimate a Hubble constant of $H_0 (\cos \theta / 0.7)^{1/2} = 42 \pm 9 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The interpretation of the observed time delays and spectral energy distribution in the context of an accretion disc structure requires further validation. At the same time, efforts to minimize the systematic uncertainties in our method to derive a more accurate measurement of $H_0$, e.g. by obtaining an independent accurate determination of the disc inclination $\theta$ or statistical average of a moderate sample of active galaxies, are required. However, this remains a promising new method of determining redshift-independent distances to AGNs.

Key words: accretion disc – cosmology – AGN.

1 INTRODUCTION

The Hubble constant $H_0$ and deceleration parameter $q_0$ are fundamental parameters in standard cosmology, measuring respectively the rate at which the Universe is expanding and the rate at which that expansion is impeded by the attractive force of gravity. Moreover, $H_0$ determines a size scale and age of the Universe, constrains the baryonic density produced in the Big Bang, the amount of dark matter in the Universe, and the epoch for galaxy and quasar formation in the early Universe. A measurement of the deceleration parameter constrains the geometry of the Universe.

The value of the Hubble constant remains in dispute after over half a century of intensive studies (Rowan-Robinson 1988, van den Bergh 1992, and de Vaucouleurs 1993). Broadly speaking there are two distinct methods of calibrating distances to galaxies. The first group of methods relies on accurate distances (parallaxes) to nearby objects to calibrate a ‘distance ladder’ extending to objects further away. A recent successful example of this is the HST Key project (Freedman et al. 1994 and Freedman et al 1997) that aims to measure the Hubble constant with an accuracy of 10% by using Cepheid variables as standard candles to measure distances to the Virgo Cluster. Current estimates of $H_0$ using this and similar methods (Tanvir et al. 1995) are in the range $\approx 60-90 \text{ km s}^{-1} \text{ Mpc}^{-1}$. By accurately calibrating distances to the Virgo cluster galaxies the ‘distance ladder’ will be extended via numerous secondary methods, including the D-$\sigma$ relation (Faber et al. 1989), Tully-Fisher relationship (Tully & Fisher 1977), surface-brightness fluctuation method (Tonry & Schneider 1988), and supernova (Sandage et al. 1996 and Perlmutter et al. 1997) method.

The second group of methods does not require any calibration or progression along a ‘distance ladder’ but applies directly to the object concerned. Examples include the use of gravitational lens systems (Refsdal 1964 and Kundic et al. 1997) and the Sunyaev-Zel’dovich effect (Sunyaev &
Zel’dovich 1980 and McHardy et al. 1990). Current early estimates of $H_0$ using these two methods are in the range $\approx 30–80 \text{ km s}^{-1} \text{ Mpc}^{-1}$. These direct methods, whilst generally more model dependent, give an important check on ‘distance ladder’ methods.

AGNs are potentially important cosmological probes because their high luminosity allows them to be observed at large redshifts. Correlations between the luminosity and various emission line strengths and ratios (Baldwin 1977 and Kinney et al. 1990) have been investigated for many years, but have not yet allowed a consistently accurate inference of the distances of AGNs independently of their redshifts. A promising geometrical method that uses proper motions and line-of-sight accelerations of water maser emission in NGC 4258 yields an accurate distance of 6.4 ± 0.9 Mpc (Miyoshi et al. 1995). In principle, a similar method may be employed to infer distances to maser sources but not to much higher redshifts where proper motions become too small.

We propose a new method that utilizes the relatively simple physics of light-travel time and blackbody radiation to measure directly redshift-independent luminosity distances to AGNs, and hence determine $H_0$. In §2 we discuss the theory of the method, and show how wavelength-dependent time delays determine $T(R)$, and measure $H_0$. Therefore, wavelength-dependent time delays can be used to a) provide ‘smoking gun’ evidence of accretion disc structures in AGNs and b) determine cosmological parameters, e.g. $H_0$. The first application of our method uses data from the International AGN Watch monitoring campaign on NGC 7469, and is discussed in §3. The systematic errors in our method are presented in §4, and §5 summarizes the main results of the paper.

2 THEORY

A blackbody accretion disc illuminated by a central source has a radial temperature profile $T(R)$ that is a non-linear combination of the surface temperature due to viscous heat dissipation $T_{\nu,v}$ and that due to irradiation $T_{\nu,i}$ of the disc, $T^4 = T^4_{\nu,v} + T^4_{\nu,i}$. Therefore $T(R)$ depends on both the geometry of the accretion disc and the relative prominence of viscous heat dissipation and irradiation effects. For example, when $T(R)$ is determined by viscous dissipation alone, a $T \propto (M M \dot{M})^{1/4} R^{-3/4}$ structure exists where $M$ is the mass of the black hole and $M$ is the mass accretion rate. An irradiating source, luminosity $L$, situated a height $H_x$ above the disc plane incurs a similar $T \propto (L H_x)^{1/4} R^{-3/4}$ structure for $R \gg H_x$, provided the disc thickness $H \ll H_x$.

The reprocessing hypothesis assumes that the UV/optical continuum variations represent the response of gaseous material to variations in the higher-energy continuum. The stringent upper limits, $< 0.3$ day, on time delays between the X-ray and UV variations in NGC 4151 (Edelson et al. 1996) suggest that the variations in different wavebands must be radiatively coupled (i.e., any possible time delays are due to light-travel time effects), since, for example, viscous time scales are much too long. Furthermore, the equivalent width of Fe Kα at 6.4 KeV and the strength of Compton reflection observed at $> 10 \text{ KeV}$ suggest that the majority of X-rays generated by an isotropic source must be reprocessed by relatively cold ($< 10^6 \text{ K}$) optically thick gas, possibly that of an accretion disc (Pounds et al. 1990 and George & Fabian 1991). This has led to ‘ad hoc’ models where the higher-energy, e.g. X-ray, source illuminates the accretion disc from above.

We assume here that a similar mechanism must be operating, i.e. some variable source of high-energy radiation in the vicinity of the disc axis illuminates the disc and radiatively drives the UV/optical continuum variations. When high-energy radiation is emitted from the central regions of the disc, a wave of heating propagates out at a speed $c$ arriving at radius $R$ after a mean time $\tau = R/c$. At this radius $R$ the temperature $T(R)$ rises slightly, thereby emitting more photons near wavelength $\lambda = h c / k T X$ (where $X \approx 3–4$ for blackbody radiation). When we observe a time delay $\tau$ at wavelength $\lambda$ that in effect measures the radius $R = \tau c$ at which the disc has temperature $T = h c / k \lambda X$.

Assuming a temperature profile of the disc, $T = T_0 (R/R_0)^{-3/4}$, the wavelength-dependent time delay is

$$
\tau(\lambda) = 3.9 d \left( \frac{\nu}{10^{-9} \text{ MHz}} \right)^{4/3} \left( \frac{L}{10^{44} \text{ erg s}^{-1}} \right)^{4/3} \left( \frac{M}{10^5 \text{ M}_\odot} \right)^{1/3},
$$

where $T_0$ is the temperature of the disc at radius $R_0 = 1$ light day. Note that with $T \propto R^{-3/4}$ predicts a $\tau \propto \lambda^{1/3}$ wavelength-dependent time delay, and an annulus of fixed $R$ in the disc responds with a range of time delays $\tau = (R/c)(1 \pm \sin i)$, with $i$ the disc inclination. Hence, in principle, the width of the time delay distribution at each wavelength determines $i$. The explicit inclusion of $X$ in the above and following equations is for heuristic purposes, since $X$ is not a free parameter or variable but is determined by the blackbody model.

With $T(R)$ determined from the observed $\tau(\lambda)$, the predicted spectrum of the disc can be calculated straightforwardly by summing up the blackbody contributions from various disc annuli (Shakura and Sunyaev 1973). The disc spectrum is given by

$$
f_\nu = 11.2 \text{ Jy} \left( \frac{\nu}{\text{ MHz}} \right)^2 \left( \frac{D}{10^2 \text{ Mpc}} \right)^{-2} \left( \frac{\lambda}{10^4 \text{ A}} \right)^{-3} \left( \frac{X}{4} \right)^{-8/3} \cos i,
$$

where $D$ is the distance to the AGN and $i$ is the inclination of the disc. Note that the classical thin disc spectrum, $f_\nu \propto \lambda^{-1/3}$, is recovered since $\tau \propto \lambda^{1/3}$, hence $f_\nu \propto \tau^2 \lambda^{-3} \propto \lambda^{-1/3}$. We note that $f_\nu$ is the distribution of flux with frequency $\nu$.

The redshift-independent distance to the AGN is then derived to be

$$
D = 3.3 \text{ Mpc} \left( \frac{\nu}{\text{ MHz}} \right)^{-3/2} \left( \frac{M}{10^5 \text{ M}_\odot} \right)^{-1/2} \left( \frac{\nu}{\text{ MHz}} \right)^{-4/3},
$$

By inserting observed values of $\tau(\lambda)$ and $f_\nu$ into the above equation, we determine a redshift-independent distance to the object. Hubble’s constant, $H_0 = c z / D$, is then

$$
H_0 = 89.6 \text{ km s}^{-1} \text{ Mpc}^{-1} \left( \frac{\nu}{10^4 \text{ A}} \right)^{3/2} \left( \frac{\tau}{\text{ day}} \right)^{-1} \left( \frac{f_\nu}{\text{ Jy}} \right)^{1/2} \left( \frac{X}{4} \right)^{4/3},
$$

where $z \ll 1$ is the redshift of the AGN.
Figure 1. Top Panel: The predicted time delays for the irradiated accretion disc model are compared with the observed time delays, measured relative to 1315 Å. The time delay increases above the overall trend near the emission lines because here there is a mix of continuum and line flux. The lines respond with longer time delays and this results in a larger net delay. Bottom panel: Model spectra for an irradiated accretion disc (assuming $H_0 = 42\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ and $i = 45^\circ$) are compared with observed spectra of NGC 7469 from the 1996 AGN Watch multiwavelength monitoring campaign. See text for full details.

3 APPLICATION OF METHOD TO NGC 7469 MONITORING DATA

To apply our new method we use data from a seven-week International AGN Watch (Alloin et al. 1994) multiwavelength monitoring campaign on NGC 7469, $z = 0.0164$, which showed optical continuum variations lagging behind those in the UV by about 1 day at 4800 Å and about 2 days at 7500 Å (Wanders et al. 1997 and Collier et al. 1998). These UV/optical continuum lags have been shown to be statistically significant at no less than 97% confidence (Peterson et al. 1998). The measured time delay between the flux variations at wavelength $\lambda$ and those at wavelength $1315\,\text{Å}$ is shown in the top panel of Figure 1. The observed delays increase above the overall trend at wavelengths near emission lines. Here there is a mix of continuum and line flux, the lines responding with larger delays than the continuum light. The horizontal axes in Fig. 1 give for each wavelength $\lambda$ the corresponding temperature $T$ in the disc. The temperature is calculated assuming $T = \frac{hc}{k\lambda X}$, with $X = 3.89$ being appropriate for blackbody discs with $T \propto R^{-3/4}$ as indicated by numerical simulations.

The bottom panel of Fig. 1 compares the de-reddened UV/optical maximum, minimum and difference spectra of the NGC 7469 monitoring campaign with predicted spectra for $H_0 = 42\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ ($D \approx 117\,\text{Mpc}$) based on the irradiated accretion disc model inclined at $i = 45^\circ$ to the observer’s line-of-sight. The dotted and dashed lines represent model spectra for bright and faint states of the irradiated accretion disc, and define maximum and minimum temperatures, $T_{\text{max}}^0 \approx 7700\,\text{K}$ and $T_{\text{min}}^0 \approx 6500\,\text{K}$, at radius $R_0 = 1\,\text{light day}$ respectively. The brightest and faintest spectra seen during the NGC 7469 campaign are both much redder than the predicted disc spectra. This is caused by contamination of the observed spectra by a red starlight component from the host galaxy. We therefore consider these spectra to be upper limits to the spectrum of the active nucleus. The solid line represents the predicted difference spectrum between the bright and faint states of the disc. This agrees approximately with the difference spectrum between the brightest and faintest spectra recorded in the NGC 7469 AGN Watch campaign. The difference spectrum, which cancels any starlight contamination, gives a lower limit to the nuclear spectrum.

The results shown in Fig. 1 demonstrate that the observed variability in the continuum spectrum of NGC 7469 is in approximate agreement with a blackbody disc, $T \propto R^{-0.75}$, and $H_0 (\cos i)^{1/2} = 35 \pm 6\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. The error-bars reflect statistical uncertainties in the measured fluxes $f_\nu$, time delays $\tau$ and redshift $z$, e.g. equation (4). The point-to-point scatter in the continuum time delays allows us to as-
sign a 10% uncertainty to the time delay measurements. The lower limit to the flux of the nucleus, is \( \Delta f_\text{H} = 3.5 \pm 1.0 \text{ mJy at } \lambda = 1315\text{Å} \). The uncertainty in the redshift of NGC 7469 (\( z = 0.0164 \)), induced by assuming \( \pm 300 \text{ km s}^{-1} \) peculiar velocities (Lynden-Bell et al. 1988), is 6%. Our 10% uncertainty in \( \tau \), 20% and 6% uncertainties in \( \Delta f_\text{H} \) and \( z \) respectively, result in a 18% uncertainty in \( H_0 (\cos i)^{1/2} \).

### 4 SYSTEMATIC ERRORS

Our estimate of \( H_0 \) is subject to several systematic errors. The AGN spectrum is diminished and reddened by intervening dust. Reddening estimates derived from pointed 21cm observations give \( E(B-V) \approx 0.074-0.096 \) (Elvis et al. 1989 and Lockman & Savage 1995). Other estimates based on using the 2200Å dust absorption feature give \( E(B-V) \approx 0.14 \) (Westin 1985). We have corrected our spectra using \( E(B-V) = 0.14 \). The host-galaxy contamination can be estimated from off-nuclear observations of the host galaxy, e.g. using HST or ground based adaptive optics. In the difference spectra the host-galaxy contamination is negligible. The red slope of the mean spectrum is due to contamination by starlight from the host galaxy, which contributes at least 40% at 5400 Å by starlight from the host galaxy, which contributes at least 40% at 5400 Å (Malkan & Filippenko 1983). Welsh et al. 1998 present contemporaneous HST observations of NGC 7469 and estimate a percentage host galaxy contamination at 7400Å of \( \approx 80\% \) in a 10′′ × 16′′ aperture.

A systematic error arises from uncertainty in \( (\cos i)^{1/2} \). However, the inclination uncertainty is not a major obstacle. According to unified schemes (Antonucci 1985 and Hes et al. 1993), Seyfert 1 galaxies, in which we see the broad emission line region (BLR), have \( i < 60\deg \), while Seyfert 2 galaxies, in which the BLR is obscured by a dusty torus, have \( i > 60\deg \). For \( i < 60\deg \), \( (\cos i)^{1/2} > 0.7 \). By adopting \( i = 45\deg \), \( (\cos i)^{1/2} = 0.84 \), we commit a maximum error of \( \pm 17\% \), and an RMS error of \( \pm 11\% \). Averaging over 10 objects could reduce this by a factor \( \sqrt{10} \approx \pm 3.5\% \). With \( (\cos i)^{1/2} = 0.84 \pm 0.1 \) we find \( H_0 = 42 \pm 9 \text{ km s}^{-1} \text{ Mpc}^{-1} \). We may be able to reduce the uncertainty in \( (\cos i)^{1/2} \) if we can measure \( i \) independently rather than averaging over the full range of \( i \). Our echo mapping method in principle allows us to derive the inclination \( i \), because the width of the time delay distribution at each wavelength is a function of \( i \). This method may be applied, in future, to NGC 7469 and other Seyfert 1 galaxies. However, it is likely to be a difficult task. Fits to the profile of the X-ray FeKα line in MCG-6-30-15 (Tanaka et al. 1995) yielded a disc inclination \( i \) of \( 30 \pm 3\deg \). Similar observations of an X-ray FeKα line in NGC 7469 could therefore measure \( i \) with about 10% accuracy. It may also be possible to determine \( i \) from polarization measurements. Therefore there are good prospects for measuring inclinations of individual AGNs.

The blackbody model is a source of systematic uncertainty. Our value \( X = 3.89 \) relies on the assumption that the changes in the UV/optical continuum can be modelled as irradiation of a blackbody disc. This is justified by the approximate agreement of the predicted \( f_\nu \propto \lambda^{-1.3} \) spectrum with the observed difference spectrum. This can be further investigated by considering models of the vertical structure and the emitted spectra of irradiated accretion disc atmospheres (Sincell & Krolik 1997). We expect that to first order our method of measuring distances should be insensitive to limb darkening (Hubeny et al. 1997). First, the irradiation of the disc will flatten the temperature versus optical depth relationship in the atmosphere and conspire to reduce the limb darkening effect. Second, the lower temperatures observed at high inclinations will change the apparent \( T(R) \) profile, but the same blackbody relationship will describe the surface brightness distribution. Hence, while our \( T(R) \) profile is sensitive to limb darkening the inferred surface brightness and subsequent distance is not.

Another source of systematic uncertainty is the source geometry and nature of the continuum variations. The preprocessing geometry we have considered might be completely ruled out by the recent X-ray observations of NGC 7469 (Nandra et al. 1998). The 2-10 KeV X-ray variations are poorly correlated or uncorrelated with the UV/optical variations described here. Either (a) the accretion disc sees different X-ray variations than we do, (b) the UV/optical variations are driven by another unobserved part of the spectrum, e.g. the extreme UV, or (c) the model geometry is completely wrong. However, observations of time delays between different wavebands and knowledge of the spectral energy distribution of sources will allow us to determine the importance or irrelevance of these various systematic effects.

### 5 SUMMARY

Our Hubble constant estimate of \( H_0 = 42 \pm 9 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is not consistent with the independent ‘distance ladder’ estimates of \( H_0 = 80 \pm 17 \text{ km s}^{-1} \text{ Mpc}^{-1} \) by Freedman et al. 1994, and \( H_0 = 69 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1} \) by Tanvir et al. 1995. However, the 22% accuracy of our Hubble constant estimate compares favourably with the 21% and 12% uncertainties of the Hubble constant estimates reported by Freedman and Tanvir respectively. For comparison, the direct method utilizing gravitational lenses give, for example, Hubble constant estimates of \( H_0 = 42 \pm 6 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Schechter et al. 1997), \( H_0 = 53^{+10}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Courbin et al. 1997), and \( H_0 = 64 \pm 13 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Kundic et al. 1997). The Sunyaev-Zel’dovich method gives \( H_0 = 47^{+22}_{-9} \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Hughes and Birkshaw 1998 and references therein). Any apparent discrepancy in the Hubble constant estimates from ‘distance ladder’ and direct methods will need investigation, which in turn requires statistically significant samples of the methods to be compared.

Our result based on observations not specifically designed to measure \( H_0 \) can be improved upon. A continuous 2-3 month multiwavelength, multi-telescope monitoring campaign on a sample of AGNs will make this method a serious competitor with the established methods of measuring \( H_0 \). Principally, the time delay measurements can be constrained to better than 5%. There are good prospects for measuring inclinations of individual AGNs with high accuracy. The starlight contamination can be estimated and corrected for as already described, allowing an accurate determination of the nuclear spectrum to better than 10%. Finally, a statistical average of individual \( H_0 \) measurements will reduce our final uncertainty, and we expect a future optimally designed experiment to determine the Hubble constant with \( \leq 10\% \) accuracy.

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To conclude, we identify the variable component of the de-reddened UV and optical continuum fluxes as a lower limit to the nuclear spectrum. For NGC 7469 we note that this agrees approximately with the $f_\nu \propto \lambda^{-1/3}$ spectrum predicted for a blackbody accretion disc with a $T \propto R^{-3/4}$ structure. At the same time the wavelength-dependence of the observed time delays, $\tau \propto \lambda^{4/3}$, is consistent with $T \propto R^{-3/4}$. The concurrence of these two independent lines of evidence strongly supports the notion of a standard blackbody accretion disc in NGC 7469, and strengthens the evidence (Shields 1978, Malkan et al. 1982, and Tanaka et al. 1995) for accretion discs in AGN. Using the variable component of the continuum fluxes we find $H_0 (\cos i/0.7)^{1/2} = 42 \pm 9 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$. The interpretation of the observed time delays and spectral energy distribution in the context of an accretion disc structure requires further validation. However, analysis of the observed variable spectrum and wavelength-dependent time delays along the lines outlined above yields redshift-independent luminosity distances to AGNs. This opens up a new route to $H_0$ and by extension to fainter objects at $z \sim 1$, $q_0$.

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