12-1-2006

The Origin of Wavelength-Dependent Continuum Delays in AGNs – a New Model

C. Martin Gaskell

University of Nebraska-Lincoln, mgaskell@ucsc.edu

Gaskell, C. Martin, "The Origin of Wavelength-Dependent Continuum Delays in AGNs – a New Model" (2006). *Martin Gaskell Publications*. 23.
https://digitalcommons.unl.edu/physicsgaskell/23

The Central Engine of Active Galactic Nuclei
ASP Conference Series, Vol. 000, 2007
L. C. Ho and J.-M. Wang (eds.)

The Origin of Wavelength-Dependent Continuum Delays in AGNs – a New Model

C. Martin Gaskell

Department of Physics and Astronomy, University of Nebraska, Lincoln, NE 68588, USA

Abstract. A model of wavelength-dependent lags in optical continuum variability of AGNs is proposed which avoids the problems of the popular "lamp-post" model. Rather than being due to reprocessing of high-energy radiation from a hypothetical source above the accretion disk, the wavelength-dependent delays observed from the B to I bands are instead due to contamination of an intrinsically coherently variable continuum with the Wien tail of the thermal emission from the hot dust in the surrounding torus. The new model correctly gives the size, wavelength dependence, and luminosity dependence of the lags, and quantitatively predicts observed color hysteresis. The model also explains how the measured delays vary with epoch of observation. There must also be contamination by scattered light and this can be detected by a lag in the polarized flux.

1. Introduction

The timescale of wavelength-dependent lags in AGNs has long been problematic since the delays are much longer than a dynamical timescale. When delays were first convincingly established in NGC 7469 (Wanders et al. 1997; Collier et al. 1998) we interpreted them as a consequence of light-travel time in the external illumination of a disk with a $T \propto R^{-3/4}$ radial temperature structure. This gives delays, $\tau \propto \lambda^{4/3}$ (Collier et al. 1998; Kriss et al. 2000). From broad-band optical photometry, Sergeev et al. (2005) have found many more wavelength-dependent lags and made the important discovery that the lags are luminosity-dependent with $\tau \propto L^{1/2}$. To explain this they postulate that the height of the external illumination source depends on the square-root of the luminosity.

2. Problems with Lamp Posts

Although the external-illumination ("lamp-post") model can readily reproduce the wavelength dependence of the lags in NGC 7469, I believe it has enormous problems. The first major problem is that the "lamp" is not seen at *any* wavelength. It shines on the disk but never in the direction of the observer. In the terminology of the *International Dark Sky Association* the lamp is a "fully-shielded" fixture! While observational optical astronomers consider this to be highly desirable for all fixtures on terrestrial lamp posts, this is impossible for the putative external sources of illumination above AGN accretion disks – no shield could survive in the harsh conditions near the hypothetical energy source.

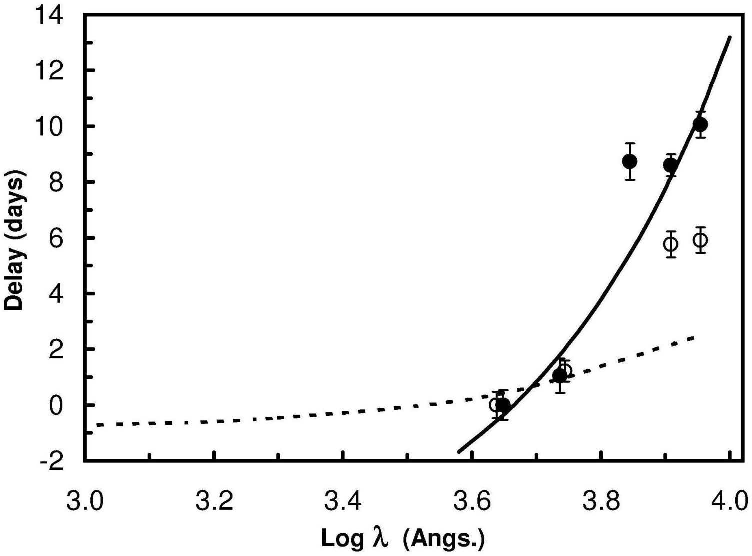

Figure 1. Normalized wavelength dependent delays scaled to the size of NGC 5548. Filled circles are from the centroids of the cross-correlation functions; open circles are from the peaks of the cross-correlation functions. The solid line is a fit of $\tau \propto \lambda^{4/3}$ through the mean centroid delays observed at $\lambda\lambda$ 4400, 5500, 8000, and 9000. The dotted line is a $\tau \propto \lambda^{4/3}$ relationship fit to the observed delay between λ1350 and λ5100 in NGC 5548.

A second major problem is that after the correct subtraction of the host galaxy light, the UV and optical variability amplitude is large – an order of magnitude is not unusual. To explain the lags with external illumination requires that this order-of-magnitude variability be due to the external illumination. If this is so, the luminosity of the "lamp" exceeds that of the accretion disk, the disk is irrelevant, and the lamp-post model is inconsistent, since it requires the disk radial temperature dependence to be determined by the accretion disk.

In Fig. 1 I show the mean lags relative to the B band (λ4400) for the 14 AGNs measured by Sergeev et al. (2005). The lags were determined with the cross-correlation function (CCF) technique of Gaskell & Sparke (1986). Since the lags are luminosity dependent, I have normalized the lags from the centroids of the CCFs of the λ8000 and λ9000 bands to the corresponding Sergeev et al. (2005) centroid lags for NGC 5548. The error bars give errors in the means. It can be seen that there is a clear wavelength dependence and that this can easily be fit by $\tau \propto \lambda^{4/3}$. However, this fit (the solid line in Fig. 1) predicts a far larger UV-to-optical lag than is observed. The dotted line shows a $\tau \propto \lambda^{4/3}$ fit to the actual λ1350–λ5100 delay we reported for NGC 5548 (Korista et al. 1995).

3. The Effect of Optical Emission from the Dusty Torus

The sharp increase in lag at long optical wavelengths in Fig. 1 has no explanation in the lamp-post model. I propose instead that it is due to contamination from

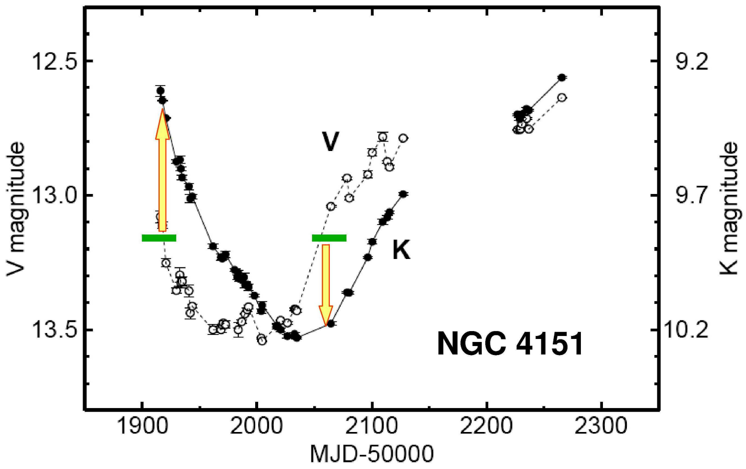

Figure 2. The K-band flux lagging the V-band flux in NGC 4151. The vertical arrows show how the (V-K) colors are substantially different at different epochs because of the lag of the K-band flux. Adapted from Minezaki et al. (2006)

optical emission from the hot dust in the inner torus. Although the dust emission peaks in the IR, the high dust sublimation temperature ($\sim 1500\,\mathrm{K}$) means that there is substantial *optical* emission as well[1].

It is well known that the variability of the IR dust emission lags the optical variability (see Fig. 2), and IR lags have been determined for many objects (Suganuma et al. 2006, see also these proceedings). The contaminating dust emission flux at shorter wavelengths will thus also lag the direct emission from the AGN. If two time series are cross correlated, the effect of contaminating one series with a third series with a different lag is to shift the peak in the CCF. This was modeled in a different context by Gaskell & Peterson (1986). In the model proposed here, the flux in the R band, say, is the sum of the intrinsically-varying continuum (assumed to be varying coherently) and a small, much delayed contribution from the Wien tail of the hot dust.

The size of the lag primarily depends linearly on two things: (a) the ratio of the contaminating flux to the intrinsic flux, and (b) the inner radius of the dusty torus. These dependencies give us two predictions: first, the optical lag will increase with increasing wavelength (because the flux from the dust increases with wavelength), as is shown to be the case in Fig. 1. The second prediction is that because the inner radius of the torus (which is determined by the dust sublimation radius) increases as $L^{1/2}$ (Suganuma et al. 2006), the relative lags will also increase as $L^{1/2}$, as has been observed already by Sergeev et al. (2005).

In Fig. 1 the R band ($\lambda7000$) lag lies significantly above the line fit to the other points. This is to be expected because the strong Hα emission line falls within the R passband and so introduces additional delayed contamination.

---

[1] A candle flame is at the graphite/PAH condensation temperature and a candle emits in the optical!

Korista & Goad (2001) have also pointed out that broad lines will produce diffuse continuum emission. This will be another source of lagged contamination.

Because the dust emission comes from an extended region, its variabilty is smeared out as well as delayed. Rapid variations are washed out. This gives two additional predictions. The first is that the CCF will be asymmetric and the centroid of the CCF, which is less sensitive to the variability power spectrum (see Koratkar & Gaskell 1991), will show a larger delay than the peak of the CCF. It can be seen in Fig. 1 that this indeed the case. The second prediction is that the lag given by the peak of the CCF will be smaller when the variability is more rapid. Thus different lags will be measured at different times.

A final prediction is that there will be *hysteresis* in the color-magnitude diagram. It is obvious in Fig. 2 that the (V-K) colors are substantially different at two different epochs with similar V flux levels. In the model I have proposed, optical to IR colors can be predicted from the V-band light curve alone. For example, the hysteresis found by Bachev & Strigachev (2004) in their (V-I) versus V diagram for Mrk 279 is quantitatively reproduced.

The contamination model proposed here can be applied to other wavelength regions (e.g., cross-correlation analyses of X-ray variability). Because of the effects of contamination on cross-correlation analyses it is important to note that the lag given by a CCF often does *not* correspond to a physical scale.

In AGNs there must also be substantial contamination from *scattered* radiation. This could be an explanation of the general smoothness of optical light curves. Since the albedo of scatterers is largely wavelength independent, this will not cause wavelength-dependent lags, but the contamination can be detected through lags in the polarized flux (Shoji, Gaskell, & Goosmann 2005).

Acknowledgments. This research has been supported by the National Science Foundation through grant AST 03-07912 and by the Space Telescope Science Institute through grant AR-09926.01.

References

Bachev, R. & Strigachev, A. 2004, Astron. Nachr., 325, 317

Collier, S. J., et al. 1998, ApJ, 500, 162

Gaskell, C. M. & Sparke, L. S. 1986, ApJ, 305, 175

Gaskell, C. M. & Peterson, B. M. 1987, ApJS, 65, 1

Koratkar, A. P. & Gaskell, C. M. 1991, ApJS, 75, 719

Korista, K.Ṫ. & Goad, M. R. 2001, ApJ, 553, 695

Korista, K. T., et al. 1995, ApJS, 97, 285

Kriss, G. A., Peterson, B. M., Crenshaw, D. M., & Zheng, W. 2000, ApJ, 535, 58

Minezaki, T. et al. 2006, in AGN Variability from X-rays to Radio Waves, ed. C. M. Gaskell, I. M. McHardy, B. M. Peterson, and S. G. Sergeev, ASP Conf., 360, 79

Sergeev, S. G., Doroshenko, V. T., Golubinskiy, Yu. V., Merkulova, N. I, & Sergeeva, E. A., ApJ, 622, 129

Shoji, M., Gaskell, C. M., Goosmann, R. W. 2005, BAAS, 37, 1420

Suganuma, M. et al. 2006, ApJ, 639, 46

Wanders, I., et al. 1997, ApJS, 113, 69