OCCULTATION MAPPING OF THE CENTRAL ENGINE IN THE ACTIVE GALAXY MCG –6-30-15

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ABSTRACT

The colossal power output of active galactic nuclei (AGNs) is believed to be fueled by the accretion of matter onto a supermassive black hole. This central accreting region of AGNs has hitherto been spatially unresolved, and its structure therefore unknown. Here we propose that a previously reported “deep minimum” in the X-ray intensity of the AGN MCG –6-30-15 was due to a unique X-ray occultation event and that it probes structure of the central engine on scales smaller than $10^{14}$ cm, or $1.4 \times 10^{-7}$ arcsec. This resolution is more than a factor of $\sim 3 \times 10^6$ greater than is possible with current X-ray optics. The data are consistent with a bright central source surrounded by a less intense ring, which we identify with the inner edge of an accretion disk. These may be the first direct measurements of the spatial structure and geometry of the accreting black hole system in an active galaxy. We estimate a mass lower limit for sub-Eddington accretion of $3.1 \times 10^5 M_\odot$. If the ring of X-ray emission is identified with the inner edge of an accretion disk, we get mass upper limits of $1.9 \times 10^6$ and $9.1 \times 10^4 M_\odot$ for a nonrotating and maximally rotating black hole, respectively. We point out that our occultation interpretation is controversial in the sense that X-ray variability in AGNs is normally attributed to intrinsic physical changes in the X-ray emission region, such as disk or coronal instabilities.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: individual (MCG –6-30-15) — X-rays: galaxies

1.INTRODUCTION

The accretion of matter onto a supermassive black hole as a mechanism for fueling the output of active galactic nuclei (AGNs) is a paradigm strongly supported by recent spectroscopic observations of the iron Kα X-ray emission line (Tanaka et al. 1995; Yaqoob et al. 1995; Nandra et al. 1997b and references therein). The extreme Doppler and gravitational energy shifts of the line photons, together with the shape of the line, are consistent with an origin in a disk rotating about a black hole (Fabian et al. 1989; Laor 1991). Strong gravitational redshifts, in which photon energies are changed by more than 10%, occur only when matter approaches closer than $\sim 20$ gravitational radii ($\sim 20 r_g$; $r_g = GM/c^2$) from a compact object. However, it is not possible to directly map the physical structure of the system, since the highest spatial resolution of X-ray optics technology is a factor $\sim 10^6$ too poor for even the closest AGN. Optical and radio observations provide greater resolution, but the bulk of the emission at these wavelengths is not generated close enough to the central engine. So far, the highest spatial resolution observations, at radio wavelengths, have revealed a Keplerian disk in the AGN NGC 4258 down to only $\sim 60,000 r_g$ (Miyoshi et al. 1995; Maoz 1995). This still falls short by a factor $\sim 3000$ of mapping the black hole region.

The AGN MCG –6-30-15 ($z = 0.008$) was observed by the X-ray astronomy satellite Advanced Satellite for Astrophysics and Cosmology (ASCA) (Tanaka, Inoue, & Holt 1994) for $\sim 4.2$ days on 1994 July 23. Results from this observation have already appeared in the literature, including the 0.5–10 keV light curve (Iwasawa et al. 1996, hereafter I96; Reynolds 1997; Yaqoob et al. 1997; see Fig. 1) and a broad, asymmetric, variable iron K-line with a strong red wing, consistent with a disk inclined at $\sim 30^\circ$ rotating about a black hole (Tanaka et al. 1995; I96). The X-ray luminosity exhibits erratic variability on all timescales down to less than 50 s (Matsuoka et al. 1990; Green, McHardy, & Lehto 1995; Reynolds et al. 1995; Nandra et al. 1997a). Causality arguments alone cannot put constraints on the size of the X-ray emission region, since the high-frequency, lower amplitude variability may occur at localized regions of the source. Figure 1 shows an extended intensity dip at the end of the observation, from $\sim 3.3 \times 10^5$ to $\sim 3.6 \times 10^5$ s. This feature has previously been dubbed the “deep minimum” (I96).

A closer inspection (Fig. 2a) reveals a remarkable (albeit approximate) symmetry about the minimum luminosity.

We propose that the dip was caused by an occultation of the X-ray source by optically thick matter. This interpretation is controversial and “nonstandard,” since X-ray variability in AGNs is normally attributed to intrinsic properties of the X-ray emission region, such as disk or coronal instabilities. However, so little is known about the structure of the central engine in AGNs that the occultation scenario should be explored. The obscurer must be optically thick because the dip continuum spectrum only shows evidence for weak absorption—nowhere near enough to explain the observed intensity variation over the whole ASCA bandpass (see Weaver & Yaqoob 1998, hereafter WY98). The luminosity at the absolute minimum of the dip is $\sim 0.4$ of the predip value and must represent persistent emission, which has much smaller surface brightness than the primary source. Hereafter, we will refer only to the primary X-ray emission unless explicitly referring to the persistent emission. The proposed obscurer very likely hides the most compact and variable part of the X-ray source, since the usual rapid variability outside the dip is absent during the obscuration.

Of course, it is possible that the dip is due to intrinsic variation of the X-ray source. However, the origin of X-ray variability in AGNs is not understood. Models that come close to successfully reproducing the observable quantities obtained

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from AGN light curves are of the shot-noise or “rotating hot-spot” variety (e.g., Green et al. 1993; Bao & Abramowicz 1996 and references therein). However, the parameters of such models must be highly tuned in order to reproduce AGN power spectra. On the other hand, we show in this paper that a very simple-minded model can account for the temporal profile of the intensity dip in MCG −6-30-15, and we briefly discuss the implications for AGN X-ray variability in general.

2. A SIMPLE MODEL FOR THE DIP TEMPORAL PROFILE

Here we present a simple occultation model of the intensity dip (Fig. 2). The dip is clearly divisible into several distinct time intervals. The turning points are labeled $t_i$–$t_f$ in Figure 2, and the values shown for $t_i$–$t_f$ are the nearest centers of the 512 s bins. The values for $t_i$ and $t_f$ are obtained from a model described below. Without any further analysis, one can make some immediate deductions, since the obscuring cannot travel faster than the speed of light. The duration of the observed dip ($\sim 3 \times 10^4$ s) implies a source size less than $9 \times 10^{15}$ cm, and the duration of the absolute minimum, $\sim 3000$ s, implies that distance scales smaller than $9 \times 10^{13}$ cm are resolved.

The fact that there are two ingresses and egresses in the dip implies that either the obscuring or the X-ray emission must be spatially nonuniform. A nonuniform obscuring must have an extremely contrived shape and size relative to the X-ray source. For a nonuniform source, we can deduce a one-dimensional intensity profile. This profile must peak in three places to produce the nearly symmetric occultation profile observed. Two of the peaks must have similar intensity and be approximately equidistant from the central peak to preserve approximate symmetry. The obscuring must be larger than the distance spanned by the three peaks to avoid local maxima in the occultation profile. As the obscuring moves over the three peaks, if the first and last peaks are the more intense, then the size of the obscuring must be fine-tuned so that the last peak is covered at the same rate as the first peak is uncovered in order to avoid a large, sharp rise after the absolute minimum. Moreover, the duration of the absolute minimum must be significantly greater than the duration of the inflexions in the dip ($t_f - t_i$), which is not observed. Therefore, the central peak must have the greatest intensity. Thus, the one-dimensional intensity profile must have the general (but not necessarily exact) form shown in Figure 2b. In this case, the first drop in intensity ($t < t_1$) is small and not observable since most of the X-ray emission is still unobscured. The large drop over $t_1 - t_2$ is then due to the central source being covered. Note that the high data point when the source has just come out of the dip is not required to be ex-
plained by the model. This is because the central source, which we know exhibits rapid and erratic variability, is then completely uncovered.

Although any two-dimensional model that gives the profile in Figure 2b is valid, it appears that an obvious and the least contrived realization of the inferred intensity profile is an X-ray source consisting of a high-luminosity central part, surrounded by a ring of dimmer emission. The gap between the central source and the ring is required in order to fit the intensity profile between $t_2-t_3$ and $r_t$-$t_5$. We construct a simple two-dimensional model that can explain the data (Fig. 2b). The central source is represented by a circle of radius $r_c$, and the obscurer is represented by a circle of radius $r_o$. In reality, the latter may be more elongated in the direction of travel, but the important quantity is its length, $2r_o$. The inner and outer ring radii are $r_1$ and $r_2$, respectively. To account for the slight asymmetry in the dip (luminosity during $t_1$-$t_2$ higher than $t_2$-$t_3$), the half-ring uncovered last is made more luminous. Let the intensities per unit area of the central source and the first and last covered halves of the disk be $I_1$, $I_2$, and $I_3$, respectively, and let $v$ be the transverse velocity of the obscurer. We find a fiducial model of the dip profile by adjusting $r/v$, $l/\alpha$, and $I/\beta$. The other parameters are fixed by the relations $(r_1 - r_2)v = t_3 - t_2$, $(r_c - r_2)v = t_2 - t_1$, and $(2r_2 - r_3)v = t_4 - t_5$. A good fit (solid line, Fig. 2a) is obtained with $r/v = 1536$ s, $r/v = 3.66$, $r_2$/$r_t = 7.32$, $r_o/r_c = 8.32$, $I/\alpha = 0.024$, and $I/I_c = 0.012$. The dip slope between $t_1$ and $t_2$ strongly constrains the uncertainty in $r/v$ to less than 20% of the fiducial value. The ranges on $r_1$, $r_2$, and $r_o$ depend on the uncertainties in $r$ and the turning points, and again are less than 20%, assuming a tolerance of 512 s (i.e., the bin width) for the turning points. The tolerances on $I/I_c$ and $I/I_c$ are also less than 20%.

One interpretation is to identify the emission ring with the inner edge of an accretion disk. An inclined disk would explain the asymmetry in the occultation, since Doppler effects due to rotation would give intensity enhancement or reduction from blueshifts or redshifts, respectively. $I/I_c \sim 2$ can easily be obtained for velocities of only 0.17c (Reynolds & Fabian 1997). In practice, one must integrate Keplerian velocities over the disk (note that at $6r_o$, $v = 0.4c$). The persistent continuum emission during the dip is likely to be due to any uncovered part of the accretion ring plus emission from the rest of the accretion disk (which must have much lower surface emissivity than the inner ring).

3. THE X-RAY CONTINUUM AND Fe-K EMISSION LINE DURING THE DIP

We have shown that a simple-minded occultation model successfully reproduces the observed intensity dip in MCG –6-30-15. WY98 showed that the same model successfully explains the shape of the Fe-K line during the dip. The peculiar shape during the dip (bowed red wing and diminished blue-side emission) has been interpreted by a number of authors as evidence for line emission from within $6r_o$ of a black hole (I96; Reynolds & Begelman 1997; Fabian et al. 1997). In the occultation model, the shape is due to obscuration of the most blueshifted and redshifted part of the line emission from the putative accretion disk, leaving only redshifted emission. Line emission from within $6r_o$ is not required. Moreover, WY98 find, in contrast to I96, that a huge Fe-K line equivalent width (EW > 1000 eV) during the dip is not required but is of the same order as the EW from the 4.2 day time-averaged value (~400 eV). Further, the Fe-K line intensity is not required to increase during the dip, compared to the time-averaged or flaring-state value (in contrast to the I96 analysis). In the analysis of WY98, the data are consistent with the line intensity decreasing during the dip.

WY98 also reanalyzed the X-ray continuum spectrum during the dip. I96 interpreted the change in the 3–10 keV continuum power-law photon index $\Gamma$ from ~2 (time-averaged “normal” value) to ~1.7 (dip value) as an intrinsic continuum change. WY98 found that the dip data are consistent with $\Gamma$ fixed at the normal value of 1.98 but allowing for extra absorption (equivalent neutral hydrogen column density of ~$2 \times 10^{22}$ cm$^{-2}$). WY98 interpreted this as the increase in opacity of the photoionized absorber in MCG –6-30-15 (e.g., Reynolds et al. 1995; Otani et al. 1996) due to the central ionizing source being blocked by the putative optically thick obscurer. Thus the occultation model for the dip temporal profile is entirely consistent with the observed Fe-K line and X-ray continuum during the dip.

4. DISCUSSION

If accreting matter is exposed to the same UV/X-ray luminosity that we observe ($L \sim 4 \times 10^{43}$ ergs s$^{-1}$), then for gravitational infall to overcome outward radiation pressure requires the mass of the central black hole, $M_{BH}$, to exceed $3 \times 10^8 M_{\odot}$. Thus, if $r_1$ is the radius of the inner edge of the accretion disk, identified with the last stable orbit of matter, and $\Delta t$ is the time taken for the obscurer to traverse $r_1$ (i.e., $t_5 - 0.5(t_2 - t_1)$), then $2(r_2 - r_3)v = t_4 - t_5$, where $\kappa = 6$ or 1.24 for Schwarzschild or maximally rotating Kerr metrics, respectively. But $r_1 < c\Delta t$, and $r_2 > 1.48 \times 10^{13} (M_{BH}/M_{\odot})$ cm, so $M_{BH} < 1.9 \times 10^8 M_{\odot}$ or less than 9.1 $\times 10^8 M_{\odot}$, for a Schwarzschild or Kerr black hole, respectively. Assuming instead the Keplerian velocity at the inner disk edge as the maximum velocity of the obscurer $v/c = (\kappa/r_c)^{1/2} = (1/v)^{1/2}$ yields smaller mass upper limits of $M_{BH} < 7.7 \times 10^7$ and $M_{BH} < 8.2 \times 10^8 M_{\odot}$ for a Schwarzschild and extremal Kerr metric, respectively. If the obscurer is at a distance $d$ from the central source, $r_1 = d\Delta t = c(r_2d)^{1/2}$, gives $d = c^2[\Delta t]^2/[r_c^2 \times (M_{BH}/M_{\odot})]$ cm. Thus, $M_{BH} > 3 \times 10^8 M_{\odot}$ implies $d < 1.8 \times 10^{16}$ and $d < 4.2 \times 10^{16}$ cm for Schwarzschild and Kerr metrics, respectively. The origin of the optically thick blobs is unspecified, but Guillet & Rees (1988) presented some simple arguments for the existence of dense ($n > 10^{15}$ cm$^{-3}$), optically thick material residing at the heart of accreting sources. The only independent estimate of the size of the “blobs” is that they should be much thicker than $10^6 n_{15}^{-1}$ cm ($n_{15}$ in units of $10^{15}$ cm$^{-3}$). The blobs must be optically thick even near their physical boundaries (i.e., they must have fairly sharp edges), otherwise the dip profile would not be so well defined. Also, the blobs must be fairly stable, especially if they are created in the central region itself and “propelled” up to high altitudes.

The nature of the bright central X-ray source is intriguing. An inclined jet is unlikely, since even at 30° the inflexions in the dip profile ($t_1-t_2$ and $t_5-t_3$) would have different durations. If the central X-ray source extracts its energy directly from the black hole, then the metric is likely to be Kerr since energy cannot be extracted from a nonrotating black hole (Blandford & Znajek 1977; see also Ghosh & Abramowicz 1997). Occultations such as the one described here may occur frequently in AGNs, but the relative sizes of the obscurer and source must be just right in order to observe such a clear event. Indeed, the usual rapid variability or flicker may be partly caused by the transit of optically thick bodies smaller than the source.
tested this hypothesis, again using a simple-minded model. Representing the bright central source as a circular disk with uniform emissivity (ignoring the ring due to its weaker emission), optically thick blobs with ranges in radii (relative to the source) and velocities taken from Gaussian distributions were passed over the source. An additional parameter is required to specify the “blob birthrate” (i.e., the rate at which new blob trajectories are started). Such a model was used to produce predicted light curves for different model parameters. The power spectrum of each light curve was computed using the method of Papadakis & Lawrence (1993), omitting Poisson noise. In the range \( \sim 10^{-2} \) to \( \sim 10^{-2} \) Hz, no preferred or “universal” power-law spectral slope was found. It is possible to produce power-law spectra with slopes similar to those typically measured (\( \sim -1 \) to \( -2 \)), but for most parameter values the slopes are too steep. Thus, fine-tuning would be necessary to explain the “universal” power-law slopes found in the handful of AGNs in which it can be measured (e.g., Lawrence & Papadakis 1993; Green et al. 1993). This is essentially because if the product of blob crossing time and birthrate is too large or too small, there will be no variability. The direct simulated light curves assume, of course, that the intrinsic source intensity is constant, which almost certainly is not the case. Thus, our model does not explain AGN variability in general, but its effects are potentially important to consider in any model of AGN variability.

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