DISK MODELS FOR MCG \(-06-30-15\): THE VARIABILITY CHALLENGE

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ABSTRACT

Recent observations have shown that the Fe K\(\alpha\) line profile of the Seyfert 1 galaxy MCG \(-06-30-15\) is strongly variable. We attempt accretion disk model fits to the Fe K\(\alpha\) line profiles in high, low, and medium continuum luminosity phases of this source. During the monitoring by Iwasawa et al., a broad redshifted component remained reasonably constant, while a narrower component at \(\approx 6.4\) keV responded strongly to continuum changes. Physically consistent fits are possible if the index \(\xi\) of the power-law emissivity changes from 0.7 (high phase) to 3.0 (low phase).

The shape of the redshifted component at the low phase is crucial to the disk model interpretation. We suggest that the actual shape may be a broad redshifted Gaussian. Three lines of evidence support the interpretation of the Fe K\(\alpha\) line as consisting of multiple components, beyond the lack of correlation in the response to continuum changes of the red and blue components in MCG \(-06-30-15\): (1) We show that the strong concentration of narrow-peak centroids at 6.4 keV is inconsistent with expectations of a random distribution of disk orientations. (2) The average Fe K\(\alpha\) profile for a sample of 16 mostly Seyfert 1 galaxies suggests a natural decomposition into two Gaussians: one is unshifted/narrow, and the other is redshifted/broad. (3) Evidence for emission in excess of the expectation of disk models on the high-energy side of the Fe K\(\alpha\) profile is both a challenge for low-inclination disk models and support for the two-component decomposition.

Subject headings: galaxies: Seyfert — line: formation — line: profiles — quasars: emission lines — X-rays: galaxies

1. INTRODUCTION

In a related paper (Sulentic et al. 1998, hereafter S98), we considered the problems associated with models that see the X-ray Fe K\(\alpha\) line emission at \(\approx 6.4\) keV in Seyfert 1 galaxies as arising from fluorescence reflection (or emission) from an accretion disk. A broad and redshifted Fe K\(\alpha\) emission feature is observed in the spectra of many Seyfert 1 galaxies. The situation for other active galactic nucleus classes is less well defined and will not be considered here. Seyfert 1 emission profiles with a narrow unshifted peak at a rest energy \(\approx 6.4\) keV and a broad redshifted wing extending down to \(\approx 4.5\) keV are most suggestive of an accretion disk line profile (see, e.g., Tanaka et al. 1995). A great deal of effort has been expended toward observing them and fitting their spectra with disk models (see S98 for references).

In S98 we attempted to build a disk illumination model that could simultaneously produce both Fe K\(\alpha\) and optical Balmer lines. The motivation was to somehow constrain the wide dispersion in disk model fits that have been published for Seyfert 1 galaxies.

While we could reproduce the profile widths and approximate emitting radii consistent with the observations, our model fits to the observed Balmer line profiles were especially poor. In addition, there were cases of severe disagreement between inclinations derived for H \(\alpha\) and Fe K\(\alpha\). The diversity in Seyfert 1 line profiles does not allow us to obtain a convergence in disk model parameter space. Nandra et al. (1997a, 1997b) also found empirically that no single emissivity law could account for the diversity in line profiles among their sample of 16 mostly Seyfert 1 galaxies. These problems may be more easily overcome if one is prepared to consider a significant flux contribution from a second, nondisk, source.

Recently, a challenge to disk models has arisen from the most studied Seyfert 1 galaxy, MCG \(-06-30-15\) (Iwasawa et al. 1996, hereafter I96). The Fe K\(\alpha\) line profile appears to change dramatically in response to continuum variations. In § 2 we summarize the variability data and the challenge to the line-emitting accretion disk interpretation for Fe K\(\alpha\) posed by MCG \(-06-30-15\). We attempt a solution to all variability phases in § 3. In § 4 we consider the evidence for the composite nature of the Fe K\(\alpha\) profile, and in § 5 we briefly discuss the implications for disk models.

2. INTERPRETATION OF VARIABILITY DATA FOR MCG \(-06-30-15\)

I96 report extensive observations of MCG \(-06-30-15\). This source underwent considerable variations in line and continuum intensity during a period of a few days. I96 divide the data and generate Fe K\(\alpha\) profiles for high, medium, and low continuum phases (see Fig. 1). We consider each of the phases, beginning with the medium one, when the profile showed its most typical structure. In that phase, the line is very similar to the Fe K\(\alpha\) profiles for (1) MCG \(-06-30-15\), as shown by Tanaka et al. (1995), and (2) the average of 16 sources (mostly Seyfert 1 galaxies) presented by Nandra et al. (1997b).

1. Medium phase.—The line profile shows a strong and narrow (unresolved at ASCA resolution) peak centered at 6.4 keV, along with a broad (\(\sigma = 0.6\) keV) red wing extending down to \(\sim 4\) keV. The EW of the broad wing (\(\sim 200–400\) eV) is approximately double that of the unresolved peak in this phase. Tanaka et al. (1995) found a Kerr metric solution for the profile with an accretion disk inner radius \(R_{\text{in}} = 4.7R_g\) (\(R_g = GM/c^2\)), inclination \(i = 27^\circ\), and \(\xi = 4.5\) [where the em-
issivity is described by a power law $\epsilon(r) \propto r^\xi$. I96 derive $7.6$, $30^\circ$, and $3.0$, respectively.

2. **High phase.**—The narrow blue peak is considerably stronger when the continuum is at its highest level. In principle, the red wing becomes weaker or, even, disappears. The confidence contours around the best solution are marginally consistent with both zero and unchanged flux. I96 fitted a disk model to the narrow peak, which requires a very flat emissivity law $\xi = 1$ and emission out to $1000R_g$. This fit would be physically inconsistent with the adopted medium-phase fits. A solution more consistent with the medium-phase (and low-phase) fits can be found if we assume that the red wing is still present.

3. **Low phase.**—The narrow peak disappears when the continuum is at its lowest level. Either there is a weak residual peak blended with the broad red feature or else the broad red-shifted component is all that remains. I96 found a Kerr metric solution for this phase with $R_m = 1.24R_g$ and $\xi \sim 2.7$. The shape of this low-phase profile is not well defined. Taken at face value, it is reasonably flat over the 4–6.5 keV interval, with a red shoulder extending down to 3 keV or below. The low phase is very poorly sampled blueward of 6.5 keV.

The variations therefore suggest (a) a positive correlation between continuum and blue peak changes as well as (b) marginal evidence for a red wing–continuum anticorrelation.

3. MODELING THE CHANGING Fe Kα PROFILE IN MCG −06-30-15

An important aspect of the model fits to MCG −06-30-15 is that they apparently require Kerr metric solutions, while most previous fits used a Schwarzschild metric (they are indistinguishable beyond $20R_g$). In other words, the best data are driving us toward an extreme disk solution. Two challenges arise immediately for models fits to MCG −06-30-15: (1) producing a model that accounts for all three phases with derived parameters that are physically consistent/plausible, and (2) accounting for the lack of correlation between the blue and red components during continuum changes.

Actually, one must deal with two possible interpretations of the bright phase, a strong blue peak with and without a weak red wing. In other words, the most unambiguous correlation is a positive one between the blue peak and the continuum flux. The main confusion connected with the low phase involves the real shape of the redshifted profile. We consider that in the next section. A possible third challenge involves fitting the smooth high-energy wing of the profile with a disk model, but this also relates to the discussion in the next section. Most models produce a very sharp drop on the high-energy side, a product of the effects of gravitational redshift and Doppler boosting. We considered the evidence for a high-energy smooth wing in S98.

In S98, we computed the H $\alpha$ Fe Kα line profiles produced by an illuminated accretion disk (Fe Kα and H $\alpha$). The basic assumption of the model is that a halo of free electrons scatters part of the continuum toward the disk. We computed the scattered flux without taking into account relativistic effects (such as returning radiation). Apart from this approximation, and for approximations on the vertical structure of the disk, the correct relativistic treatment was used for all other computations in the model: the radial structure of the disk was appropriate for the Kerr metric with specific angular momentum $a/M = 0.998$ ($c = G = 1$). The resulting cold Fe Kα surface emissivity (a power law with radial emissivity index $\xi = 1.8$) was then used to compute the line profile. We included all effects of relevance in the Kerr metric, using the code developed by Fanton et al. (1997) to compute the Fe Kα line profile.

In this Letter, we attempt to reproduce the different Fe Kα profiles corresponding to different continuum luminosities. I96 isolated three different profiles, typical of “low,” “medium,” and “high” continuum luminosity. In Figure 1, we show the I96 data with superposed model profiles (we assume $i = 30^\circ$). The fits to all three luminosity phases are statistically satisfactory, with normalized $x^2 \approx 1$. Model and disk fit parameters are presented in Table 1. For each luminosity phase (listed in the first column), we report $x^2$, the number of degrees of freedom, $\chi^2$, the radial emissivity index $\xi$, and the disk inner and outer radii, $R_{in}$ and $R_{out}$. Dabrowski et al. (1997) obtained a very similar emissivity law (with $\xi = 3.5$) by inverting the line profile to obtain the disk emissivity profile.

If a hot halo indeed scatters radiation toward a cold disk, the change of index in the radial emissivity law can be understood at least in qualitative terms. The emissivity change reflects a change in the distribution of the scattering matter: when the continuum is high, radiation pressure pushes the scattering matter outward; when the continuum luminosity is at a minimum, the scattering halo may not be fully supported against the massive black hole gravity, and the radial distribution of matter in the halo may follow a steeper power law.

The success of our model requires a significant red com-
ponent even during the high-variability phase. Fits to an isolated blue peak during this phase are physically incompatible with intermediate- and low-phase ones. Our fit to the red part of the high-phase profile is 30%–50% too high. This is reflected in the larger $\chi^2$. It is unclear how much of this discrepancy might be related to uncertainties in the continuum fit. The observational results are consistent with a rapid response to the continuum by the blue peak plus a weak (or zero, as favored by our model) anticorrelation by the red wing. This interpretation is apparently strongly driven by the response of the blue peak to large continuum fluctuations. When the largest flare and lowest minimum are excluded from the data set, I96 find almost the opposite result. The broad red wing correlates with more modest/frequent fluctuations in the continuum, while the data are consistent with a constant blue peak. In other words, the line response may depend on the amplitude of the continuum fluctuation. The data without the strongest continuum fluctuations included would require a model with two distinct emitting components, because disk models could not account for a constant blue (Doppler-boosted) component. We consider the observational evidence for a two-component profile in the next section.

4. A Composite Fe Kα Profile: The Variability Challenge

Our model fits to MCG $-06$-$30$-$15$ have followed the precedent set by other workers by modeling the entire profile. The underlying assumption is that most or all of the line flux arises from a single-component Fe Kα line (6.4, 6.7, or 6.9 keV) produced in a single emitting region (the accretion disk). In S98 we considered an alternative model for the production of the entire profile (infalling clouds in a biconical geometry).

The exact shape of the low-phase profile in MCG $-06$-$30$-$15$ is crucial to the success of the disk models. The assumption of a single emitting region is also fundamental. As it stands, the low-phase line profile could be fitted by a wide variety of shapes. The signal-to-noise ratio (S/N) is low, and the high-energy wing is undersampled. We propose that the actual shape may be Gaussian and that the red peak is independent of the blue one. Recently, several authors have followed an empirical approach to the Fe Kα line profile fitting, employing single or multiple Gaussian profiles (see Grandi et al. 1997; Weaver et al. 1997). There are several lines of evidence to support this interpretation for MCG $-06$-$30$-$15$. The first is the lack of correlation between the red and blue component responses to continuum changes. Our model discussion above suggests that this is not an insurmountable problem if our assumptions about the high- (red component present at approximately the same level as the medium phase), intermediate-, and low-phase (negligible/absent blue peak, non-Gaussian red profile) data are correct.

A more serious problem is illustrated in Figure 2, where we show the distribution of blue-peak centroid energy versus profile width (the blue peak is unresolved with ASCA). We see a strong concentration of blue-peak energies at 6.4 keV. Also plotted are the predictions of disk models similar to the ones implied by the MCG $-06$-$30$-$15$ fits. We show the model fits for the range of inclinations, $0°$–$45°$, expected for Seyfert 1 galaxies in a standard unification scheme. It is obvious that 6.4 keV has no special significance for the disk models: a range of blue-peak energies is expected if we are viewing line-emitting accretion disks at random inclinations. An energy of 6.4 keV has special significance only as the rest wavelength of fluorescence reflection Fe Kα. The only escape from this excess of 6.4 keV peaks is to argue that the current observational data are strongly biased toward a narrow range of disk models with blue-peak energy near 6.4 keV, for instance, because more inclined profiles are broader and hence less easy to detect at a high S/N. Similar results are obtained from a plot of narrow-peak energy versus centroid energy (measured on the broad base).

The remaining evidence brings us back to the exact shape of the low-phase profile (when the narrow peak is assumed absent). We suggest that the exact shape can be inferred from the composite spectrum presented in Nandra et al. (1997b). The shape of the average spectrum is robust to the exclusion of MCG $-06$-$30$-$15$. The simplest and most natural fit to the average spectrum involves two Gaussian components: (1) a narrow (FWHM $\approx 0.25$ keV) component centered at the Fe Kα rest energy ($\lambda_{\text{rest}} = 6.4 \pm 0.05$ keV) and (2) a broad (FWHM $= 1.6$ keV) redshifted ($\lambda_{\text{rest}} = 5.9 \pm 0.1$ keV) component.

Another piece of evidence that supports this interpretation and profile decomposition involves a smooth wing on the Fe Kα line high-energy side. The wing appears to grow in significance as the S/N of the MCG profile increases. Thus, it is best seen in the high and intermediate phases when the narrow peak is visible. Is the wing an independent high-energy component while the much broader red component arises in a disk?
The I96 data are ambiguous here: one plot shows a high-energy wing, while another shows a much steeper drop. Not surprisingly, the latter is used for the Dabrowski et al. (1997) fits because most Kerr models explored so far show a steep drop on the high-energy side. In the Nandra et al. (1997b) average spectrum, the high-energy wing can be fit as a natural extension of the broad red component under the blue peak. In S98 we show that a photoionized disk can produce enough hot Fe Kα to account for a blue wing. In that case, the blend of hot and cold Fe Kα emission must conspire to produce the observed smooth average profile.

Figure 1 shows a single Gaussian fit (dashed line) to the “low”-phase profile. The Gaussian parameters are quite similar to those found for this component in the average profile of Nandra et al. (1997b). We show that a fit as good as the one obtained with the disk model can be achieved, with $\chi^2 \approx 1.08$ obtained for a peak energy $\approx 5.2$ keV and a dispersion $\sigma \approx 0.75$ keV. If the redshifted component is (a) independent and (b) Gaussian in shape, then there is no obvious disk model that can account for it.

5. CONCLUSION

Accretion disk model fitting to the variable Fe Kα profile of MGC $-06-30-15$ requires a Kerr black hole: even if only the low continuum phase Fe Kα profile cannot be fitted by disk models around a Schwarzschild black hole, the angular momentum of a massive black hole obviously cannot change on timescales of $\approx 10^5$ s. Since the inner disk radius for a Kerr black hole with $a/M = 0.998$ is $\approx 1.23 R_g$ and since the region where the “Doppler-boosted peak” is formed occurs at $R \approx (5-20) R_g$, a different illumination of the disk following changes in the continuum luminosity explains the strong change observed in the narrow peak at 6.4 keV (Plate 1 of Fanton et al. 1997) shows that it is not so for a Schwarzschild black hole). On the other hand, without attempting a physical interpretation of the Fe Kα line profile, the strong variations of the narrow peak, along with the possibility of little or no variation in the redshifted broader line part, hint at two independent components. The two-component hypothesis is reinforced by the detection of the narrow peak at 6.4 keV in the wide majority of cases. This statistical difficulty for accretion disk models must be understood before accretion disk models can be accepted.

The formulation of a physical model for a multicomponent Fe Kα line goes beyond the aims of the present Letter. We can, however, speculate on several possibilities. One possibility, recently revived by Misra & Kembhavi (1998), is that broadening could occur by Compton-scattering the photons of an intrinsically narrower Fe Kα line in a corona of size $\approx 300 GM/c^2$, much larger than the size of the region of continuum formation. Another possibility is that the narrow peak could be associated with the broad-line region (BLR): with an intrinsic width of 30,000 km s$^{-1}$, Fe Kα emission from the classical BLR should appear as an unresolved peak. The maximum line shifts in the BLR are too small to be detected with ASCA, so the peak would always appear at about 6.4 keV (as expected for cold iron emission). Clearly, the detection of strong changes in the narrow peak with no apparent time delay (along with some difficulties raised by S98) challenges these interpretations, but a longer time coverage would be required to rule them out. The redshifted broader component may be, on the other hand, associated with the region of continuum production. Observations of a cutoff in the X-ray continuum of Seyfert galaxies at an energy $\approx 600$ keV suggests the presence of a thermal corona above the surface of the accretion disk (e.g., Zdziarski et al. 1995; Haardt & Maraschi 1993; see also S98). Fe Kα emission from highly ionized iron in the corona could be shifted to the observed rest energy by gravitational redshift.

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Note added in proof.—A recent study (T. J. Turner et al., ApJ, 493, 91 [1998]) reveals that Seyfert 2’s show the same Fe Kα profile shape as Seyfert 1’s like MCG $-06-30-15$ studied here. This is consistent with our assertion that accretion disk emission does not dominate the Fe Kα line emission (especially if unification ideas are correct).