Emission Lines in Active Galaxies: New Methods and Techniques
ASP Conference Series, Vol. 113, 1997
B.M. Peterson, F.-Z. Cheng, and A.S. Wilson (eds.)

Relativistic Iron Kα Emission in Seyfert Galaxies

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Abstract. Evidence is presented for widespread relativistic effects in the central regions of active galactic nuclei (AGN). A sample of 18 Seyfert 1 galaxies observed by *ASCA* show iron Kα emission which is resolved, with mean full width at half maximum (FWHM) $\sim 50,000\,\mathrm{km\,s^{-1}}$ for a Gaussian profile. However, many of the line profiles are asymmetric. A strong red wing is indicative of gravitational redshifts close to a central black hole, and accretion-disk models provide an excellent description of the data. Such observations probe the innermost regions of AGN, and arguably provide the best evidence yet obtained for the existence of supermassive black holes in the centers of active galaxies.

1. Introduction

Iron Kα emission is extremely common in the X-ray spectra of Seyfert galaxies. The mean energy of 6.4 keV and equivalent width of 100–300 eV indicate an origin for the line via fluorescence in near-neutral, optically thick material out of the line of sight (Nandra & Pounds 1994 and references therein). Given the implied covering fraction of $\sim 50\%$, it is most obvious to identify the reprocessing site with an accretion disk illuminated by the X-ray source.

Further impetus for the study of iron Kα lines in Seyfert galaxies has come from more recent *ASCA* data, which have indicated that the line may be a key element in our understanding of AGN. The earliest data showed good evidence that the emission lines were resolved (Fabian et al. 1994; Mushotzky et al. 1995), and high signal-to-noise ratio data for two sources have shown characteristic line profiles (MCG–6–30–15, Tanaka et al. 1995; NGC 4151, Yaqoob et al. 1995). They are extremely broad, indicating relativistic velocities of order $0.2c$. Furthermore, there is a strong asymmetry to the red, which is indicative of the gravitational redshifts associated with the inner regions of an accretion disk surrounding the black hole. Fabian et al. (1995) concluded that this was the most plausible explanation for such profiles, rejecting other interpretations such as Comptonization. Whilst it is tempting to extrapolate such a model and apply it to all AGN, it must be borne in mind that these extraordinary profiles are relatively rare in the literature. Further reinforcement of the black-hole/accretion-disk paradigm requires confirmation of that model for further sources.

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https://doi.org/10.1017/S0252921100039580 Published online by Cambridge University Press

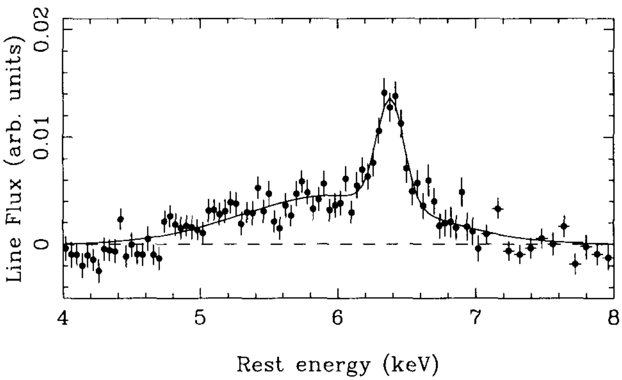

Figure 1. Mean line profile for the sample, determined by interpolating the continuum below 5 keV and above 7 keV for each source and summing these individual profiles in the rest frame. The solid line is a double-Gaussian fit. The narrower component peaks at 6.4 keV with a width of $\sigma \approx 0.1$ keV. The broader component is strongly redshifted, with a centroid energy of 6.1 keV and a width of 0.7 keV and carries most ($\sim 75\%$) of the flux.

2. Sample Analysis

Here a sample of Seyfert 1 galaxies is considered, consisting of 23 observations of 18 Seyfert 1 galaxies available in the *ASCA* archive (see Nandra et al. 1996 for further details). Optical classifications ranged from Sy 1–1.5 and the redshift was restricted to $z < 0.05$. Most of the sources are bright, X-ray selected Seyferts although the sample is complete in no conventional sense. In the following, the X-ray spectra in the 3-10 keV range are considered. This band avoids the effects of the 'warm absorber' (e.g., George, these proceedings) which could otherwise complicate the analysis of the iron Kα line.

3. Iron Line Properties

Iron Kα emission is evident in all 18 sources and the initial parameterization of the line was with a Gaussian. A remarkable 14 of the 18 sources in the sample showed evidence for significant line broadening in these fits. The mean width is 0.43 ± 0.12 keV, corresponding to a FWHM of 47,000 km s^{-1}. This demonstrates that the relativistic motions deduced for the few individual objects described above are commonly observed in Seyfert 1 galaxies. The mean energy in these Gaussian fits was 6.34 ± 0.04 keV, confirming the suspicion from the *Ginga* data that the line arises via fluorescence in near-neutral material. Figure 1 shows the mean profile for the whole sample. This is very similar to those obtained for MCG–6–30–15 and NGC 4151, but is not biased by the inclusion of those sources, as a similar profile remains when they are removed. The profile is extremely broad with ~ 2 keV full width at zero intensity, which corresponds to

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velocities of order 0.3c. As in many of the individual sources, the profile consists of a relatively narrow core, with an underlying broad component. The core peaks at an energy remarkably close to 6.4 keV. The broadening is primarily to the red, with relatively little flux blue-ward of 6.4 keV and specifically no strong component due to helium-like or hydrogen-like iron (6.7–6.9 keV).

The dramatic redshifts and broadening expected due to special and general relativistic effects close to a black hole provide a plausible explanation for the observed line profiles. One class of models which has been successfully applied to *ASCA* observation of MCG–6–30–15 and NGC 4151 is that of an accretion disk (Tanaka et al. 1995; Yaqoob et al. 1995). The other sources apparently exhibit rather similar profiles and such models are now considered.

4. Accretion-Disk Models

The accretion-disk models of Fabian et al. (1989; Schwarzschild geometry) and Laor (1991; Kerr geometry) provide remarkably good fits to these data, improving upon the broad Gaussian model described above. The reason for this is the clear asymmetry in the profiles. However, the disk models have a large number of free parameters and it was necessary to fix the inner and outer radii of the disk at $R_{\rm i} = 6R_{\rm g}$ and $R_{\rm o} = 1000R_{\rm g}$ respectively. The inclination of the disk, i and the index of the emissivity function, q (the emissivity is assumed to vary as R^{-q}) were allowed to be free. Reasonable constraints were obtained for these parameters in a number of cases, and a histogram of their values is shown in Fig. 2 (for the Schwarzschild geometry). These parameters illustrate some of the important consequences of the results presented here and the diagnostic power of the iron Kα line in general.

Referring first to q, the mean value of $q = 2.5$ implies that the line emission is concentrated very strongly in the central regions. The average emissivity function implies that ~50% of the line emission originates within $20\,R_g$, and ~80% within $100\,R_g$. Interestingly, there is evidence that the q values are significantly dispersed. In other words, that the sources in the sample are not consistent with a "universal" profile, suggesting differences in the geometry of the X-ray source/accretion disk system in the individual cases. If these Seyfert 1 galaxies were viewed at all inclinations, a mean of 60° would be expected, with a flat distribution in $\cos i$. These fits imply that the disk in these Seyfert 1s tend to be observed at a more face-on inclination, on average at 30°. This may be reconciled with Seyfert 1/2 unification schemes (e.g. Antonucci & Miller 1985) where the edge-on lines-of-sight are obscured.

5. Conclusions

The iron Kα emission of Seyfert 1 galaxies lend strong support for the black-hole/accretion-disk paradigm. The profiles indicate that the emission is concentrated in the innermost regions of the disk, where strong Doppler and gravitational shifts apply. Derivation of the inclinations and emissivity profiles reveal the first clues towards the determination of the physical conditions in the near environment of the black hole. This impressive diagnostic power can be exploited further using variability observations. Current instrumentation is already pro-

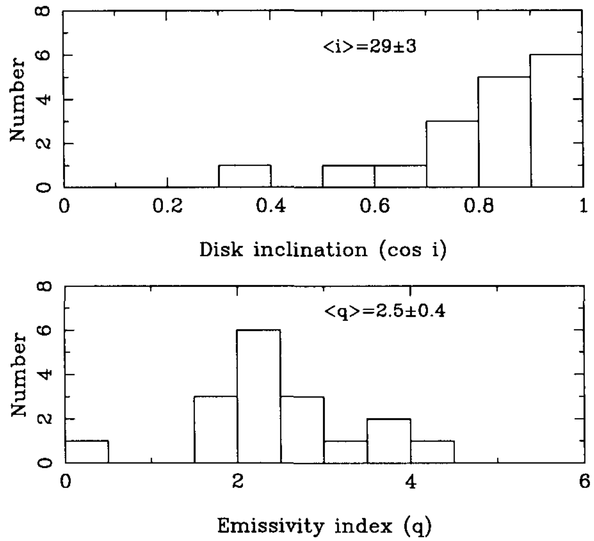

Figure 2. Histograms of the parameters from the disk line fits to the *ASCA* data. a) the inclinations $\cos i$, show a strong preference for low inclinations (i.e. face-on disks), and b) the emissivity indices q (see text) are steep, indicating that the emission is concentrated in the central regions.

viding important results (e.g., Otani et al. 1996), but future high-throughput missions, such as XMM, should prove even more satisfying.

Acknowledgments. My sincere thanks go to my collaborators on this project: Ian George, Richard Mushotzky, Jane Turner, and Tahir Yaqoob and to the *ASCA* team for performing the observations. The data were obtained from the HEASARC at NASA/GSFC.

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