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"A Robust Test of the Unified Model for Seyfert Galaxies with Implications for the Starburst Phenomenon"

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This report summarizes year 1 of a 5-year astrophysical research project.

1. Summary of Research

My research involves detailed analysis of X-ray emission from active galactic nuclei (AGN). For over a decade, the paradigm for AGN has rested soundly on the unified model hypothesis, which posits that the only difference between broad-line objects (e.g., Type 1 Seyfert galaxies) and narrow-line objects (e.g., Type 2 Seyferts) is that in the former case our line of sight evades toroidal obscuration surrounding the nucleus, while in the latter, our line of sight is blocked by the optically thick torus. It is well established that some Seyfert 2s contain Seyfert 1 nuclei (i.e., a hidden broad line region), but whether or not *all* Seyfert 2s contain obscured Seyfert 1 nuclei or whether some Seyfert 2s are *intrinsically* Seyfert 2s is not known. Optical, IR, and UV surveys are not appropriate to examine this hypothesis because such emissions are either anisotropic or subject to the effects of obscuration, and thus depend strongly on viewing angle. Hard X-rays, on the other hand, can penetrate gas with column densities as high as $10^{24.5}$ cm^{-2} and thus provide reliable, direct probes of the cores of heavily obscured AGN.

Combining NASA archival data from the Advanced Satellite of Cosmology and Astrophysics (*ASCA*), the Rossi X-ray Timing Explorer (*RXTE*), and *Rosat*, I am accumulating X-ray data between 0.1 and 60 keV to produce a catalog of the broad-band X-ray spectral properties of Seyfert galaxies. These data will be used to perform concrete tests of the unified model, and (compared with similar data on Starbursts) to examine a possible evolutionary connection between Seyfert and Starburst galaxies.

2. Status of Research after Year 1

The first year has been dedicated to collecting data and performing the spectral analysis necessary to establish a baseline for the scope of this investigation. I have accumulated and processed data for ~100 Seyfert and Starburst galaxies from the *ASCA* archive.

These data are used to infer the geometry and orientation of the central accretion disk and the molecular torus (i.e., the X-ray reprocessors), which are then compared with data at other wavelengths to address the important scientific question *"are the geometries and* *orientations of the central regions of AGN consistent with the current unified model hypothesis?"*. Observationally, the orientations of the disk and torus can be inferred by comparing the strength of the nuclear X-ray continuum (assumed to be an isotropic property) with the profile and strength of the Fe Kα emission line, the amount of reflected flux, and the amount of line-of-sight X-ray absorption, all inclination-dependent properties. I am currently examining the modeling uncertainties inherent in measuring physical properties from the Fe-K line profile (§3.1). A second project (§3.2) compares inclinations inferred from X-ray and radio data for a well-defined sample.

2.1. How Reliable is the Technique of Modeling the Fe Kα Profile to Determine the Inclination of the Accretion Disk?

The profile of the Fe Kα emission line, which is commonly very strong in Seyfert galaxies, can potentially yield important information about the orientation of the system relative to our line of sight, as well as the geometry and dynamics of the emitting matter. Some Fe Kα lines are significantly broadened, with FWHMs >20,000 km s^{-1} (e.g., Fabian et al. PASJ 46, L59 1994; Mushotzky et al. MNRAS 272, L9 1995; Nandra et al. 1997, ApJ, 477, 602). These are thought to arise in an accretion disk (e.g., George & Fabian MNRAS 249, 352 1991) Theoretical predictions of disk lines indicate that their centroid, breadth, and asymmetry all depend on viewing angle (Figure 1), in the sense that as our view moves from the axis towards the equatorial plane, the centroid moves from the red to the blue, the breadth increases, and the asymmetry decreases. On the other hand, some Fe Kα lines are unresolved, with FWHMs <6,000 km s^{-1} (e.g., Weaver et al. ApJ 458, 160 1996). These narrow lines could arise from fluorescence in the optical broad-line-region (BLR) clouds, or from the obscuring torus (Ghisellini, Haardt, & Matt MNRAS 267, 743 1994; Krolik, Madau, & Zycki ApJ 420, L57 1994). In the latter case, the equivalent width is a strong function of viewing angle, in addition to depending on the covering fraction and optical depth of the obscuration.

In the standard unified model picture, when looking along the axis we would expect the Kα line to be mostly due to disk emission. When looking in the equatorial plane, the prediction of the standard model depends on the column density of the obscuration. If the column density is small enough to let X-rays of energy greater than a few keV go through, we would see a very broad, but relatively weak, contribution from the disk, and a relatively strong, narrow component from the torus. For intermediate angles we expect comparable contributions from the disk and the obscuring torus (Figure 2, dot-dashed line profile). For data with medium to poor resolution, these can blend together into what appears to be a single broad line. A consequence of this blending is erroneous inferences of profile-dependent properties, such as the inclination angle of the disk. A broad line "contaminated" by a narrow component can mimic the predicted shape for emission from an approximately face-on accretion disk, which is highly peaked near the systemic velocity, (Figure 1).

A case where modeling a complex line incorrectly leads to misleading results is the Seyfert 1.9 galaxy MCG−5-23-16. Its optical classification suggests that it is viewed at an intermediate

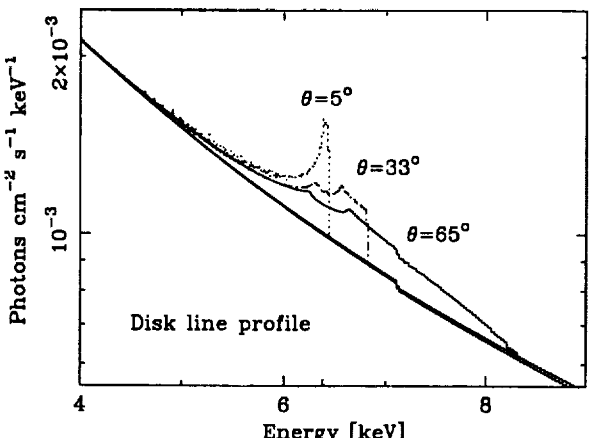

Fig. 1: Theoretical line profiles from a relativistic accretion disk (Fabian et al. 1989 MNRAS, 238, 729) for inclinations of the disk normal to our line of sight of 5° (dotted profile), 33° (dashed), and 65° (solid). Other line parameters are $E_{\rm peak}$=6.4 keV, disk emissivity index, $q = -2.5$ (r^q), inner radius, $r_i = 6r_g$, and outer radius, $r_o = 500r_g$.

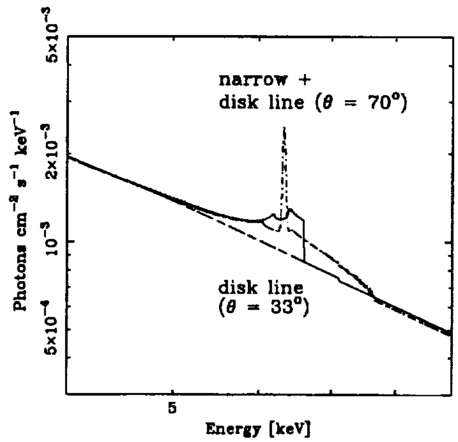

Fig. 2: Theoretical line profiles that represent the best fits of T98 (case 1) and W97 (case 2). Case 1 is a line from an accretion disk viewed at 33° (solid profile) and case 2 is a narrow line superimposed over a line from an accretion disk viewed at 70° inclination (dot-dashed profile).

angle, but there are at least two possible descriptions of the Fe Kα line profile. Turner, et al. (1998, ApJ, in press, hereafter T98) have modeled the Kα line with a single accretion-disk line profile, and derive an inclination of $\theta = 33^{+11}_{-4}{}^{\circ}$. On the other hand, Weaver et al. (1997, ApJ, 474, 675, hereafter W97) find an equally good fit to a model of the Kα line with two components, a narrow Gaussian to represent emission from the torus, and a disk-line profile. For this composite model, since the disk model is not forced to try to fit the strong peak at 6.4 keV, W97 find a disk inclination of $> 50°$. The T98 and W97 models are pictured together in Figure 2.

These conflicting interpretations clearly illustrate the ambiguity in spectral modeling of the Fe Kα line with *ASCA* when either of two components may contribute. It is thus vital to learn the best approach for modeling these data to insure that our results are not misleading. A paper in press addresses this issue for MCG–5-23-16 (Weaver et al. 1998), and I am currently extending the analysis to other objects.

2.2. Comparing Disk and Torus Axes Inferred from Data at Different Wavelengths

It has recently been suggested that there are significant misalignments between the axes of the accretion disk, the torus, and the galaxy in Seyfert 2s (Schmitt et al. 1997, ApJ, 477, 623; T98). This implies that the galaxy disk is sufficient to block the optical broad line region from our view in some Seyfert 2 galaxies, and raises the possibility that some Seyfert 2s may not even contain obscuring tori.

Along with Johns Hopkins graduate student Jonathan Gelbord, I am testing this idea by combining data from multiple wavelengths for a radio-selected sample of Seyfert galaxies. Schmitt et al. (1996) have compiled a sample of 46 Seyfert galaxies that have high resolution radio maps showing linear or resolved radio structures. Using the radio axis to define the axis of the torus, they conclude that Seyfert 2s have radio structures distributed in all directions, which implies that their tori are oriented in all directions. We are collecting *ASCA* data for the galaxies in their sample to compare the accretion-disk axis inferred from X-ray data with the torus axis inferred from radio, optical, and X-ray data. If severe misalignments between the torus and the galaxy are confirmed and misalignments between the accretion disk and the torus are found, an extensive modification of the unified model would be necessary.

3. Publications

No publications were expected for year 1, but the publication rate will increase in years 2 and 3. Currently, one paper is in press and four are in preparation.

Weaver, K.A., Krolik J., and Pier E.A. 1998, "**Detecting Compton Reflection and a Broad Iron Line in MCG−5-23-16 with** *RXTE*," ApJ, in press (May)

Abstract

We report the detection with the Rossi X-ray Timing Explorer of a Compton reflection signature in the Seyfert galaxy MCG−5-23-16. RXTE also resolves the Fe Kα fluorescence line with FWHM $\sim$ *48,000 km* s^{-1}*. This measurement provides the first independent confirmation of ASCA detections in Seyfert galaxies of broad Fe Kα lines that are thought to be the signature of emission from the inner regions of an accretion disk orbiting a black hole. Under the assumption that reflection arises from an isotropic source located above a neutral accretion disk, and using a theoretical model that accounts for the dependence of the reflected spectrum on inclination angle, we derive a 90% confidence range for the disk inclination of* $i = 50° - 81°$*. The large inclination is consistent with that expected from the unified model for MCG−5-23-16 based on its Seyfert 1.9 classification. If we assume that the high-energy cutoff in the incident spectrum lies at energies larger than a few hundred keV, then the equivalent width of the Fe Kα line is much larger than predicted for the amount of reflection. This implies either an enhanced iron abundance, a covering factor of reflecting material* $c_f > 0.5$*, or a cutoff in the incident spectrum at energies between* $\sim$*60 and* $\sim$*200 keV.*

Papers currently in preparation

Weaver, K.A. & Reynolds, C.S. "On the Orientation of Accretion Disks in Seyfert 2 Galaxies"

Weaver, K.A. & Yaqoob, T. "On Evidence for Extreme Gravity Effects in MCG−6-30-15"

Weaver, K.A. "Variability of the Iron K Line in MCG−5-23-16"

Weaver, K.A. & Gelbord, J. "A Comparison of Disk Axes Inferred from Radio and X-ray Data"