RELATIVISTIC IRON LINES IN GALACTIC BLACK HOLES:
RECENT RESULTS AND LINES IN THE ASCA ARCHIVE

J. M. MILLER
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street (MS 67), Cambridge MA 02138, USA, jmiller@cfa.harvard.edu (NSF Astronomy and Astrophysics Postdoctoral Fellow)

A. C. FABIAN
Univ. of Cambridge Inst. of Astronomy, Madingley Road, Cambridge CB3 OHA, UK

M. A. NOWAK, W. H. G. LEWIN
MIT Center for Space Research, 70 Vassar Street, Cambridge MA 02139, USA

Recent observations with Chandra and XMM-Newton, aided by broad-band spectral coverage from RXTE, have revealed skewed relativistic iron emission lines in stellar-mass Galactic black hole systems. Such systems are excellent laboratories for testing General relativity, and relativistic iron lines provide an important tool for making such tests. In this contribution to the Proceedings of the 10th Annual Marcel Grossmann Meeting on General Relativity, we briefly review recent developments and present initial results from fits to archival ASCA observations of Galactic black holes. It stands to reason that relativistic effects, if real, should be revealed in many systems (rather than just one or two); the results of our archival work have borne-out this expectation. The ASCA spectra reveal skewed, relativistic lines in XTE J1550−564, GRO J1655−40, GRS 1915+105, and Cygnus X-1.

1. Background

If the innermost regions of an accretion disk around a black hole are irradiated by a source of hard X-rays, a characteristic “disk reflection” spectrum is expected to result ([1], [2]). These predictions have been borne-out observationally in countless results. The most prominent feature produced by reflection is a fluorescent Fe Kα emission line. Fe Kα emission lines produced via reflection from the inner disk can serve as extremely powerful probes of the environment closest to the black hole, as the strong Doppler shifts and gravitational redshifts endemic to the inner regions will be imprinted on the line profile ([3], [4]). Relativistically-skewed lines and reflection spectra have been clearly detected in a number of Seyfert-1 galaxies with ASCA, BeppoSAX, and recently with Chandra and XMM-Newton. The much higher fluxes observed from stellar-mass Galactic black hole systems prevented clear detection of such lines prior to Chandra and XMM-Newton; new observations with
these instruments have revealed relativistic lines that are remarkably similar to those seen in some AGN. For reviews of these topics, the reader is referred to [5] and [6].

2. Recent Developments
The advanced spectrometers aboard Chandra and XMM-Newton have revolutionized the study of relativistic Fe Kα emission lines in stellar-mass Galactic black holes. The line in Cygnus X-1 was revealed to consist of separate narrow and relativistic components [7]. Most interesting of all is the potential for establishing black hole spin using relativistic Fe Kα lines. The innermost stable circular orbit around a black hole with maximal spin is \( r_{in} = 1.2 \, r_g \) (for \( a = 0.998 \), where \( a = cJ/GM^2 \) and \( r_g = GM/c^2 \)), while that around a black hole with zero spin is \( r_{in} = 6 \, r_g \). Lines which are strongly skewed toward lower energies can therefore indicate black hole spin. The extremely skewed line profile in the XMM-Newton spectrum of XTE J1650−500 requires a black hole with near maximal spin [8]. Observations of GX 339−4 with Chandra [9] and XMM-Newton [10] have revealed relativistic lines which strongly require a black hole with near-maximal spin. The XMM-Newton spectrum is particularly exciting because the signal to noise achieved is comparable to the best-defined relativistic lines seen in some Seyfert-1 galaxies.

The initial Cygnus X-1 result bolstered confidence among observers that broad lines seen with low-resolution gas proportional counter detectors, like those that flew aboard BeppoSAX and ASCA, and presently aboard RXTE, are robust features and can be reliably fitted with advanced relativistic spectral models. Analysis of archival BeppoSAX spectra has revealed relativistic lines in SAX J1711.6−3808 [11], XTE J1908+094 [12], GRS 1915+105 [13], and most dramatically in XTE J1650−500 [14]. Park et al. [15] fit relativistic line profiles to over 40 RXTE/PCA observations of 4U 1543−475 during the bright phase of its outburst, and found that skewed line profiles systematically provide better fits than symmetric (Gaussian) line profiles during periods of relatively strong hard X-ray emission.

3. Analysis of Archival ASCA Observations
We have undertaken a uniform analysis of archival ASCA/GIS spectra of stellar-mass Galactic black holes in order to search for relativistic Fe Kα emission lines, and herein we briefly present the most exciting results from this effort. While the ASCA/SIS CCD spectrometer suffered from strong photon pile-up when observing bright sources, the GIS gas spectrometer merely suffered telemetry saturation without significant change to its spectral response characteristics (T. Yaqoob, priv. comm.). Even with deteriorated detector response due to photon pile-up, hints of extremely skewed emission line profiles can be seen in some SIS spectra (see Figure 3 in [16], concerning SIS spectra of GRO J1655−40).
The *ASCA* spectra which appear in the HEASARC archive have been filtered in a robust manner, making them robust for spectral analysis. We have not attempted to extract background spectra for bright Galactic sources; the source flux overwhelmingly dominates the background, and the entire detector plane is illuminated by bright sources. For simplicity, herein we only report on fits to GIS-2 spectra; future work will include joint fits to GIS-2 and GIS-3 spectra. The spectra were analyzed using XSPEC version 11.2.0.

In Table 1, we detail fits to four spectra from the following sources: XTE J1550−564 (net exposure: $25.2 \text{ ksec}$, starting on 1998 Sept. 23.9), GRO J1655−40 (net exposure: $16.5 \text{ ksec}$, starting on 1994 Sept. 27.5) , GRS 1915+105 (net exposure: $65.4 \text{ ksec}$, starting on 2000 Apr. 21.5), and Cygnus X-1 (net exposure: $35.9 \text{ ksec}$, starting on 1996 May 30). The ratio of the lines in these spectra to phenomenological models is shown in Figure 1.

Skewed, relativistic lines are clearly detected in XTE J1550−564, GRO J1655−40, and in Cygnus X-1. The lines detected in XTE J1550−564 and GRO J1655−40 indicate that the black holes in these systems may have a high degree of spin. High frequency ($\text{few} \times 100 \text{ Hz}$) QPOs in these systems also suggest spin ([17], [18], [19]). The evidence for spin in Cygnus X-1 is less clear; future observations obtaining better constraints will be essential to determine the nature of the black hole in Cygnus X-1. The best-fit physically-motivated models for these spectra (see Table 1) are remarkably similar to those applied to other Galactic black holes ([2], [3], [4]) and Seyfert-1 galaxies like MCG−6-30-15, Mrk 766, and NGC 4051. This provides evidence that the inner accretion flow geometry and emission mechanisms may be very similar in these systems. The line seen in GRS 1915+105 is consistent with a radially recessed inner disk edge; however, the constraints from this line are poor. The fact that a broadened line is detected in GRS 1915+105 is consistent with the detection of a broad line in *BeppoSAX* spectra [13].

4. Summary

In the *Chandra* and *XMM-Newton* era, relativistic Fe Kα emission lines have been revealed in stellar-mass Galactic black holes. They have proved to be robust diagnostics of the innermost accretion flow region, which can also constrain the nature of the central black hole. Archival analyses of the kind briefly detailed here show that relativistic lines are in fact common, and not limited to a few special sources. In the near future, we look forward to the high effective area, spectral resolution, and broad energy range of *ASTRO-E2*, to further refine studies of this kind. In the long run, *Constellation-X* will make it possible to study changes in Fe Kα line profiles over short timescales; such investigations will be especially powerful probes of the corona — disk interaction in Galactic black hole systems.
Figure 1. Prominent relativistic line profiles in Galactic black holes observed with ASCA. The plots above show the ratio of GIS spectra to a phenomenological continuum model consisting of multicolor disk blackbody, power-law, and smeared edge components. A narrow Fe XXV/XXVI absorption line and narrow Ca XX absorption line were fit to GRO J1655–40 and GRS 1915+105.

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Table 1. Spectral fit parameters

|                      | XTE J1550−564 | GRO J1655−40 | GRS 1915+105 | Cygnus X-1                  |
|----------------------|--------------|--------------|--------------|-----------------------------|
|                      | phenomenological models |                |              |                             |
| $N_H$ (10$^{21}$)    | 0.7(1)       | 1.3(1)       | 4.0(1)       | 5.3(3)                      |
| $kT$ (keV)           | 0.65$^{+0.7}_{-0.03}$ | 1.26(1)       | –            | 0.42(1)                     |
| Norm.                | 900$^{+400}_{-200}$ | 150(10)       | –            | 6100(500)                   |
| $\Gamma$             | 2.2(2)       | 5.2(3)       | 2.24(8)      | 2.6(1)                      |
| Norm.                | 2.3(4)       | 5.4$^{+1}_{-0.6}$ | 7.4$^{+0.2}_{-0.06}$ | 1.1(1)                     |
| $E_{Laor}$ (keV)     | 6.4$^{+0.6}_{-0.06}$ | 6.8(2)       | 6.40$^{+0.6}_{-0.06}$ | 6.8$^{+0.2}_{-0.4}$        |
| $q$                  | 5$^{+1}_{-2}$ | 5.5(5)       | 5(1)         | 4$^{+2}_{-1}$               |
| $r_{in}$ (r_g)       | 2$^{+2}_{-1}$ | 1.4$^{+0.6}_{-0.2}$ | 1.8$^{+1.5}_{-0.8}$ | 2.2 $\pm$ 1.0              |
| $\nu$ (deg)          | 60$^{+15}_{-30}$ | 45$^{+15}_{-5}$ | 60$^{+10}_{-20}$ | 45$^{+15}_{-15}$            |
| EW (eV)              | 170(100)     | 550(50)      | 140$^{+50}_{-60}$ | 400(80)                     |
| Norm. (10$^{-3}$)    | 17(10)       | 57(4)        | $18^{+6}_{-8}$ | 3.6 $\pm$ 0.8              |
| $E_{smedge}$         | 8.3(3)       | 8.0          | 8.8          | 9.3$^{+2.1}_{-2.1}$         |
| $\tau$              | 0.6$^{+0.4}_{-0.2}$ | 1.0          | 0.3$^{+1.2}_{-0.2}$ | 1.0$^{+0.5}_{-1.0}$        |
| $W_{smedge}$ (keV)   | 7.0          | 7.0          | 7.0          | 7.0                         |
| $\chi^2$/dof         | 857.0/741    | 972.9/647    | 1113.8/751   | 780.8/654                   |
|                      | blured reflection (pexriv) models |                |              |                             |
| $N_H$ (10$^{21}$)    | 0.58(2)      | 1.3(2)       | 4.1$^{(l)}$  | 4.8(2)                      |
| $kT$ (keV)           | 0.68(3)      | 1.26(1)      | –            | 0.45(1)                     |
| Norm.                | 1300(200)    | 155(5)       | –            | 5000(400)                   |
| $\Gamma$             | 1.6$^{+0.3}_{-0.1}$ | 6.0(1)       | 2.30(5)      | 2.4(3)                      |
| Norm.                | 0.5(1)       | 10(1)        | 7.8(6)       | 0.6(4)                      |
| $E_{Laor}$ (keV)     | 6.3$^{+0.5}_{-0.1}$ | 6.97$^{+0.1}_{-0.1}$ | 6.4$^{+0.2}_{-0.0}$ | 6.7(3)                     |
| $q$                  | 5(1)         | 5.5(5)       | $3^{+3}_{-3}$ | 3.5$^{+1.0}_{-0.5}$         |
| $r_{in}$ (r_g)       | 1.6$^{+4.0}_{-0.4}$ | 1.8$^{+0.5}_{-0.6}$ | $26^{400}_{-10}$ | 1.2$^{+3.0}_{-3.0}$        |
| $\nu$ (deg)          | 50(20)       | 50(10)       | 70(20)       | 50(20)                      |
| EW (eV)              | 260(70)      | 480(50)      | 50           | 400(200)                    |
| Norm. (10$^{-3}$)    | 4.4(4)       | 4(3)         | 2(1)         |                             |
| $R$ (Ω/2π)           | 1.0(3)       | 1.0(2)       | 0.3(2)       | 1.0(3)                      |
| $E_{fold}$ (keV)     | 200          | 200          | 30           | 200                         |
| $\xi$ (10$^{4}$)     | 1.0          | 1.0          | 0.1          | 1.0                         |
| $\chi^2$/dof         | 815.1/741    | 918.7/648    | 1041.6/752   | 849.5/655                   |

Note: All errors are 90% confidence errors. Where errors are not given, the parameter was fixed at the given value. The Laor line energy range was constrained to the 6.40–6.97 keV range, and the emissivity index was constrained to vary in the 3–6 range. Within pexriv, the abundance flags were set to solar values, the inclination to the value determined by the Laor line model, and the disk temperature to 1 keV. The fit to the spectrum of GRO J1655−40 also included a Gaussian absorption line (FWHM=0 keV, EW=25 eV) at 6.7 keV (Fe XXV). The spectrum of GRS 1915+105 included a Gaussian absorption line (FWHM=0 keV, EW=8 eV) at 4.9 keV (Ca XX); the disk temperature in pexriv was set to 0.1 keV for GRS 1915+105. The extraordinary S/N achieved with these observations makes residual narrow calibration uncertainties important (particularly around 2 keV, and below), and prevents formally acceptable fits in most cases.