*Mon. Not. R. astr. Soc.* (1989) **238**, 729–736

# X-ray fluorescence from the inner disc in Cygnus X-1

A. C. Fabian,[1] M. J. Rees,[1] L. Stella[2,3] and N. E. White[2]

[1] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2] EXOSAT *Observatory, Astrophysics Division of ESA, Space Science Department, ESTEC, Noordwijk, The Netherlands*
[3] *On leave from ICRA, Department of Physics 'G. Marconi', University of Rome, Italy*

Accepted 1988 December 20. Received 1988 November 28; in original form 1988 October 6

**Summary.** The quasi-blackbody plus power-law spectra of many accreting black-hole sources suggests that relatively cold matter is surrounded by hard X-ray emitting plasma. Fluorescent iron lines are produced by X-irradiation of the cold gas. The shape and variability of these lines can be used to map the innermost regions around the black hole. In the case of a disc geometry for the cold gas, the effects of doppler-broadening and gravitational and transverse redshifts produce a characteristic line profile which depends upon inclination. We show here that the broad, iron emission line found in Cyg X-1 by Barr, White & Page is well modelled by fluorescent emission from the inner parts of an accretion disc inclined at ~30 degrees. The mass of the central object and properties of the accretion flow can be determined by future higher resolution studies of this and similar sources, including Active Galaxies.

## 1 Introduction

The X-ray spectra of sources identified as accreting black holes, such as Cyg X-1 and Seyfert 1 galaxies, often appear to contain two components: the soft X-rays are dominated by a steep spectrum and the harder X-rays by a power law of energy index ~0.7. The first component is

In Fig. 1a–d we show the line profile stepping through a range of each parameter. At each step the other parameters are fixed at $r_i = 10\ r_s$, $r_0 = 100\ r_s$, $i = 30°$ and $q = -2$. The profile is most sensitive to the outer radius and the inclination. It tends to a single broad peak at low inclination, and/or large $r_0$. For the remaining cases it is a double profile, with the blue peak a factor of 2–3 stronger.

It is clear from Fig. 1 that the overall shape of the line can be used as a sensitive diagnostic to determine the inclination of the system, as well as the location of the line-emission region. The

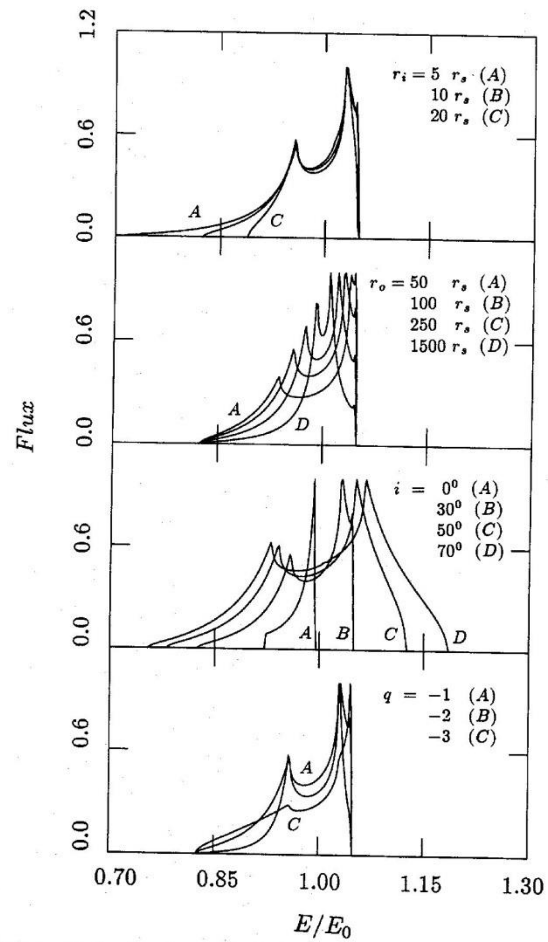
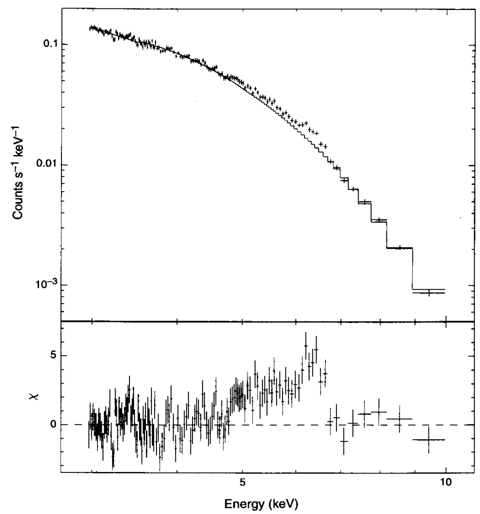


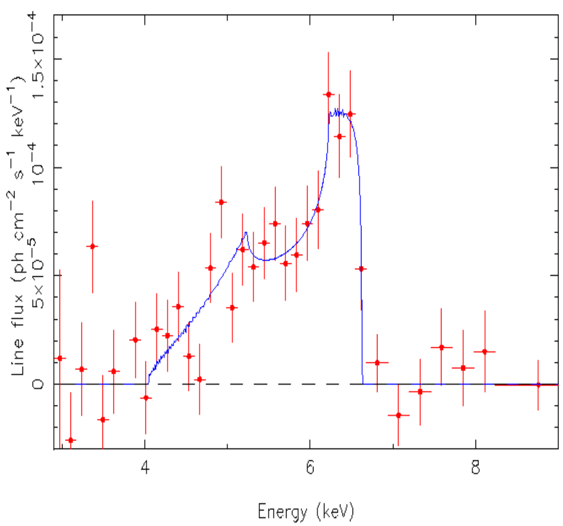

**Figure 1.** Line profiles computed using the method given in the Appendix. When not specified, the other parameters are fixed at $r_i = 10\ r_s$, $r_0 = 100\ r_s$, $i = 30°$ and $q = -2$. Note that the blue horn is always brighter than the red one and a net redshift only occurs for low inclinations. The small spike on the high-energy side of the blue horn (see curves with $r_i = 10\ r_s$ and $i = 30°$) is due to radiation emitted by the most blueshifted regions of the disc ( ~ 15 $r_s$ for $i = 30°$).

# <u>Observations</u>

Tanaka, Nandra, Fabian. Nature, 1995, **<u>375</u>**, 659.
Galaxy MCG-6-30-15, ASCA satellite, SIS detectors




## Sy 1 type




The line profile of iron K$\alpha$ line in
X-ray emission from MCG-6-30-15.

Width corresponds to 80000 – 100000 km/s.

- **Variability**

Sulentic, Marziani, Calvani. ApJL, 1998, **<u>497</u>**, L65.

# <u>Properties of wide lines at 6.4 keV</u>

- Line width corresponds to velocity
  - v ~ 80000 – 100000 km/s    MCG-6-30-15
  - v ~ 48000 km/s    MCG-5-23-16
  - v ~ 20000 – 30000 km/s    many other galaxies

- Asymmetric structure (profile)
  - two-peak shape
  - narrow bright **blue** wing
  - wide faint **red** wing

- Variability of both
  - line shape
  - intensity

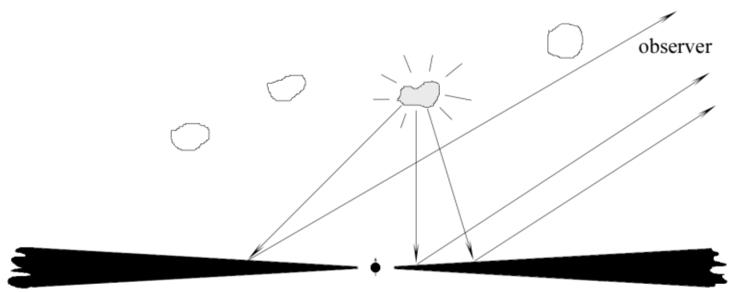
# Possible interpretation

- • iron K$\alpha$ emission line
  - ○ 6.4 – 6.9 – 7.1 keV

- • radiation of inner part of accretion disk around a supermassive **black hole** in the center of the galaxy

$r_{emission} \sim 1 - 4\ r_g$

$$r_g = \frac{2km}{c^2}$$



# Equations of motion

Kerr metric

$$ds^2 = -\frac{\Delta}{\rho^2}\left(dt - a\sin^2\theta d\phi\right)^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 +$$

$$+\frac{\sin^2\theta}{\rho^2}\left[\left(r^2 + a^2\right)d\phi - a dt\right]^2$$

or

$$ds^2 = -\left(1 - \frac{2Mr}{\rho^2}\right)dt^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 +$$

$$+\left(r^2 + a^2 + \frac{2Mra^2}{\rho^2}\sin^2\theta\right)\sin^2\theta\, d\phi^2 - \frac{4Mra}{\rho^2}\sin^2\theta\, d\phi dt,$$

# Equations of motion

Equations of photon motion:

$$\frac{dt}{d\lambda} = -\frac{r_g r a}{\rho^2 \Delta} L + \frac{\omega_0}{\Delta}\left(r^2 + a^2 + \frac{r_r r a^2}{\rho^2} \sin^2\theta\right)$$

$$\frac{d\phi}{d\lambda} = \frac{L}{\Delta \sin^2\theta}\left(1 - \frac{r_g r}{\rho^2}\right) + \frac{r_g r a}{\rho^2 \Delta}\,\omega_0$$

$$\left(\frac{dr}{d\lambda}\right)^2 = \frac{1}{\rho^4}\left[\left(r^2 + a^2\right)\omega_0 - aL\right] - \frac{K\Delta}{\rho^4}$$

$$\left(\frac{d\theta}{d\lambda}\right)^2 = \frac{K}{\rho^4} - \frac{1}{\rho^4}\left[a\,\omega_0 \sin\theta - \frac{L}{\sin\theta}\right]^2$$

where

$$\Delta = r^2 - r_g r + a^2, \qquad \rho^2 = r^2 + a^2\cos^2\theta,$$

$$r_g = 2km, \qquad a = M/m$$

# Equations of motion

For numerical solution the system should be replaced with

$$
\begin{aligned}
\frac{dt'}{d\sigma} &= -\hat{a}\left(\hat{a}\sin^2\theta - \xi\right) + \frac{\hat{r}^2 + \hat{a}^2}{\hat{\Delta}}\left(\hat{r}^2 + \hat{a}^2 - \xi\hat{a}\right), \\
\frac{d\hat{r}}{d\sigma} &= r_1, \\
\frac{dr_1}{d\sigma} &= 2\hat{r}^3 + \left(\hat{a}^2 - \xi^2 - \eta\right)\hat{r} + (\hat{a} - \xi) + \eta, \\
\frac{d\theta}{d\sigma} &= \theta_1, \\
\frac{d\theta_1}{d\sigma} &= \cos\theta\left(\frac{\xi^2}{\sin^3\theta} - \hat{a}^2\sin\theta\right), \\
\frac{d\phi}{d\sigma} &= -\left(\hat{a} - \frac{\xi}{\sin^2\theta}\right) + \frac{\hat{a}}{\hat{\Delta}}\left(\hat{r}^2 + \hat{a}^2 - \xi\hat{a}\right).
\end{aligned}
$$

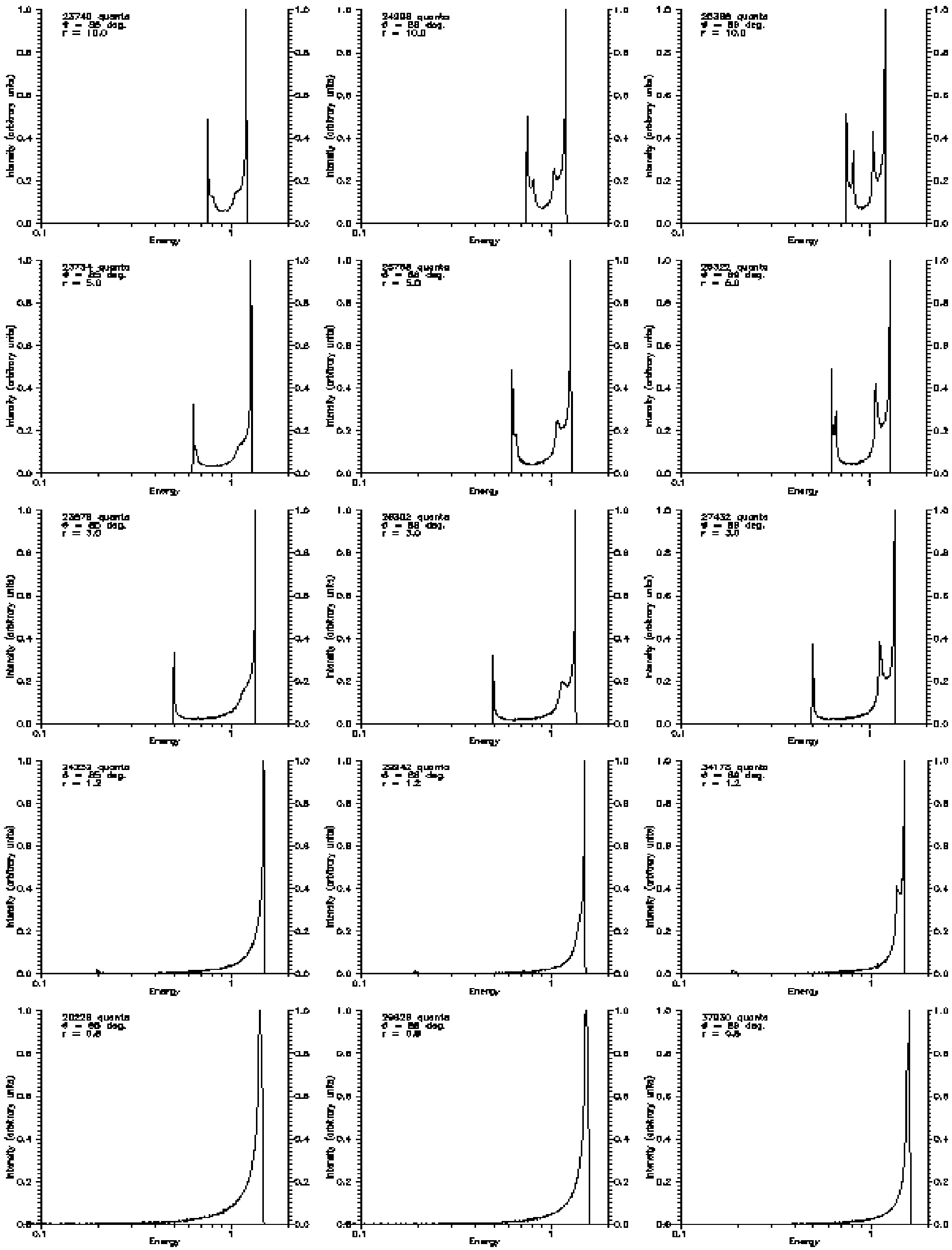
The system has two integrals:

$$
\begin{aligned}
\epsilon_1 &\equiv r_1^2 - \hat{r}^4 - \left(\hat{a}^2 - \xi^2 - \eta\right)\hat{r}^2 - 2\left[(\hat{a} - \xi)^2 + \eta\right]\hat{r} + \hat{a}^2\eta = 0, \\
\epsilon_2 &\equiv \theta_1^2 - \eta - \cos^2\theta\left(\hat{a}^2 - \frac{\xi^2}{\sin^2\theta}\right) = 0,
\end{aligned}
$$

# Gallery of profiles

A.F. Zakharov & S.V. Repin, **Mem. SAIt, 7, 60 (2005) ; New Astronomy, 11, 405 (2006)**; astro-ph/0510548

# Simulation result



verview of possible line profiles
a hot spot for different values of
dial coordinate and inclination
gle.
he radial coordinate decreases
m 10 $r_g$ on the top to 0.8 $r_g$ on the
ttom. The inclination angle
reases from 85 degrees in the left
umn to 89 degrees in the right.

arov A.F, Repin S.V. A&A, 2003,
, 7.