Correlation between Compton reflection and X-ray slope
Correlation between Compton reflection and X-ray slope in Seyferts and X-ray binaries

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ABSTRACT

We find a very strong correlation between the intrinsic spectral slope in X-rays and the amount of Compton reflection from a cold medium in Seyfert AGNs and in hard state of X-ray binaries with either black holes or weakly-magnetized neutron stars. Objects with soft intrinsic spectra show much stronger reflection than ones with hard spectra. We find that at a given spectral slope, black-hole binaries have similar or more reflection than Seyferts whereas neutron-star binaries in our sample have reflection consistent with that in Seyferts. The existence of the correlation implies a dominant role of the reflecting medium as a source of seed soft photons for thermal Comptonization in the primary X-ray source.

Key words: accretion, accretion discs – binaries: general – galaxies: Seyfert – radiation mechanisms: thermal – X-rays: galaxies – X-rays: stars.

1 INTRODUCTION

Recently, a paradigm has appeared to emerge according to which black-hole binaries in the hard state show weak both Compton reflection (i.e. backscattering of X-rays from a surrounding cold medium) and associated fluorescent Fe Kα lines (as found by Gierlinski et al. 1997; Życki, Done & Smith 1997, 1998; Zdziarski et al. 1998; Ebisawa et al. 1996) whereas Seyfert-1 AGNs would universally show stronger reflection (Nandra & Pounds 1996) and strong and broad Fe Kα lines (Nandra et al. 1997). If this were correct, it would certainly be of importance for our understanding of the physics of X-ray sources in accreting compact objects.

We critically examine this paradigm based on available data. We concentrate on the continuum spectral properties, deferring an analysis of a more complex issue of the Fe Kα fluorescent emission to a future work. Here, we study the strength of Compton reflection as a function of the intrinsic spectral slope. A correlation between these quantities has originally been found in Ginga observations of GX 339–4 (Ueda, Ebisawa & Done 1994). In this work, we consider Seyferts, radio galaxies, and X-ray binaries containing either black holes or weakly-magnetized neutron stars.

2 THE OBSERVED CORRELATION

Our Seyfert sample consists of Ginga (Makino et al. 1987) spectra (extracted from the Leicester database) of radio-quiet (hereafter RQ) Seyfert 1s and narrow emission-line galaxies. The latter are Seyferts intermediate between type 1 and 2 showing moderate X-ray absorption (e.g. Smith & Done 1996). This sample is basically the same as that of the classical study of Ginga spectra of Seyferts of Nandra & Pounds (1994). However, here we exclude 3 radio-loud AGNs, as there are hints that their nature is different from that of RQ ones (Wozniak et al. 1998). On the other hand, we include some late Ginga observations of Seyfert 1s not listed in Nandra & Pounds (1994), which gives us 61 observations of 24 RQ Seyferts. We further include 2 Ginga observations of 4U 0241+61, a low-redshift AGN (z = 0.044), which we find to be of RQ type after correcting its B magnitude for Galactic extinction. Finally, we include an observation of NGC 4151 contemporaneously by both Ginga and the OSSE detector on board of CGRO, which latter data allow a determination of the strength of reflection in this strongly-absorbed bright Seyfert (Zdziarski, Johnson & Magdziarz 1996).

We compare the data for Seyferts with those for 4 X-ray binaries in the hard (also called low) state. Two of them, Cyg X-1 and GX 339–4, are black-hole candidates, and two, GS 1826–238 and 4U 1608–522, are X-ray bursters (thus con-
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Inclusion of the mid-layer data significantly increases the effective area above 10 keV, allowing to measure the hard X-ray spectra much more accurately than with the top layer alone (see Woźniak et al. 1998; Magdziarz et al. 1998). We further select only the data with no systematic differences between the top and mid-layer spectra above 10 keV, which reduces the number of usable Seyfert observations by 10.

We fit the data (using XSPEC, Arnaud 1996) with a continuum model consisting of an e-folded power law (unless stated otherwise) and a component due to its Compton reflection (Magdziarz & Zdziarski 1995) at a normalization, \( R \). In the case of an isotropic primary source and no obscuration of either the source or the reflector, \( R = \Omega/2 \), where \( \Omega \) is the solid angle subtended by the reflector. We initially assume the reflector is neutral with the abundances of Anders & Ebihara (1982), but allow for its ionization and/or a free Fe abundance when it is statistically required. We fix the e-folding energy at 400 keV (Zdziarski et al. 1995) and the reflector viewing angle of Seyferts at \( i = 30 \) (Nandra et al. 1997). (For \( i = 45 \), the fits below would typically give \( R \) higher by \( \sim 10 \) per cent.) We model the Fe K\( \alpha \) line as a Gaussian with the line flux as a free parameter, independent of reflection. This allows for resonant absorption and/or additional line components due to either matter in the line of sight (Makishima 1986), scattering of a part of the primary continuum by an ionized medium (Krolik & Kallman 1987) and/or emission of a Thomson-thin torus surrounding an AGN nucleus (e.g., Woźniak et al. 1998).

Then we carefully treat the low-energy part of the spectra. For each object, we initially model absorption of the above continuum by a neutral medium at the redshift of the source (in addition to a fixed local absorber with the Galactic column density). We then test for the effect of either replacing the neutral absorber by an ionized one, ignoring some low-energy channels, or using a broken power-law incident continuum. This is to assure that the hard X-ray power-law photon index, \( \Gamma \), is properly measured and not affected by either the presence of a soft excess or by complex absorption. In the case of NGC 4151, we assume \( i = 65 \) and fit the Ginga/OSSE data with a dual absorber model (Zdziarski et al. 1996) and a thermal-Comptonization continuum model (Mista et al., in preparation).

The above procedure gives us \( R \) and \( \Gamma \) with their error contours. For Seyferts, some detections are rather weak and yield very large error contours. Since our main goal is to study the dependence \( R(\Gamma) \), we have eliminated from the sample observations for which the 1-\( \sigma \) (\( \Delta x^2 = 2.30 \)) error contour has \( \Delta R > 2 \). Inclusion of such data would only weakly affect our fitted dependences (see Section 3) but would confuse our graphical representation of the results.

This criterion eliminates, in particular, all the observations of MCG–6–30–15 and Mkn 335. To improve statistics in those cases, we have coadded multiple observations of each of those objects. In the case of Mkn 335, the resulting \( \Delta R \) was still \( \gg 2 \), and thus we kept it out of the sample. For MCG–6–30–15, we coadded 4 (out of 5) observations that were performed in the standard mode with all the LAC detectors operating, which then resulted in data with an acceptable \( \Delta R < 2 \).

The procedures outlined above give us 47 data sets for 23 RQ AGNs: 4U 0241+61, AKN 120, Fairall 9, IC 4329A, MCG–2–58–22, MCG–5–23–16, MCG–6–30–15, Mkn 509, Mkn 841, NGC 2110, NGC 2992, NGC 3227, NGC 3783, NGC 4051, NGC 4151, NGC 4593, NGC 526A, NGC 5506, NGC 5548, NGC 7172, NGC 7213, NGC 7314 and NGC 7469. Fig. 1a shows their best-fit points in open symbols, and the corresponding 1-\( \sigma \) confidence contours are shown in thin solid line. For clarity, the inset shows the best-fit points (except that of MCG–6–30–15) without the contours. The open circles denote RQ Seyferts from the sample of Nandra & Pounds (1994), and the open square and triangles, NGC 4151 and 4U 0241+61, respectively.

We see an extremely strong correlation. At the hard end, objects with \( \Gamma \sim 1.5 \) have almost no reflection. The reflection strength then increases with increasing \( \Gamma \). Reflection appears to saturate at \( R \sim 2 \) as our softest Seyfert, MCG–6–30–15, has \( R \sim 2 \) at the best-fit \( \Gamma \approx 2.4 \), somewhat below an extrapolation of the trend for objects with harder spectra. We also see that NGC 4151 and 4U 0241+61 show rather average values of \( \Gamma \) and \( R \).

We checked in Section 3 below that the correlation is not an artefact of our fitting procedure. Indeed, although there are intrinsic \( R(\Gamma) \) correlations due to finite measurement errors for each observation, we clearly see in Fig. 1a that their extents are much less (especially for data with good statistics) than the extent of the global correlation. Objects with hard power laws and significant reflection would have reflection easily measured by Ginga due to their high count rate at 10 keV. Also, soft power laws without reflection would also have been measured as such by Ginga, albeit with relatively large errors. The absence of such objects in the sample strongly supports the physical reality of the correlation.

We note that a similar \( R(\Gamma) \) correlation has been observed for NGC 5548 (Magdziarz et al. 1998). We show the contours for this object alone in Fig. 1b, including one contour omitted in Fig. 1a [due to our criterion of \( \Delta(R) \leq 2 \)], which also obeys the correlation. We also find an \( R(\Gamma) \) correlation for Mkn 509.

We then consider hard-state X-ray binaries, for which fit results are shown by heavy contours and filled symbols in Fig. 1a. The 12 filled squares correspond to Cyg X-1 (at assumed \( i = 30 \)). We see that Cyg X-1 has typically more reflection than average for Seyferts with the same \( \Gamma \) (although its contours are still within the area covered by Seyferts). Although the presence of an \( R(\Gamma) \) correlation cannot be proven from these data alone, Done & Życki (1999) found such a correlation in observations by EXOSAT and ASCA.

The filled circles in Figs. 1a, c correspond to the data for GX 339–4. We fit the Ginga data as in Zdziarski et al. (1998), assuming \( i = 45 \). We see that the contours show a highly significant correlation themselves, as found before by...
Ueda et al. (1994), and that their correlation is consistent with that for average Seyferts.

Filled triangles in Fig. 1a correspond to the X-ray bursters (at assumed $i = 60$). The large triangle and 2 small ones correspond to GS 1862–238 and 4U 1608–522, respectively, fitted with the same model as that used for Seyferts. We see that strong reflection is present at high statistical significance in both objects, and that its strength is consistent with that typical for Seyferts.

Finally, we consider 6 Ginga observations of 5 nearby radio galaxies, 3C 111, 3C 382, 3C 390.3, 3C 445, Cen A, fitted as in Woźniak et al. (1998). Those authors find that they show significantly less reflection than the average for RQ Seyfert 1s. Those data are shown by crosses in the inset of Fig. 1a. We see that these data points still obey the overall correlation, albeit with reflection indeed much weaker than that average for RQ Seyferts.

3 STATISTICAL ANALYSIS

The correlation between $R$ and $\Gamma$ was first tested using 2 rank-order correlation tests of Spearman and Kendall (Press et al. 1992). We use our sample of RQ Seyferts but excluding MCG –6-30-15, for which $R$ appears saturated. We find $r_S = 0.91$, $\tau_K = 0.76$ with the significance levels of $r_S$ and $\tau_K$ being $>0$ of $<10^{-18}$ and $<10^{-13}$, respectively. Thus, the correlation between $R$ and $\Gamma$ is indeed very strong. Note, however, that those statistical methods do not take into account individual measurement errors.

We have then fitted a few phenomenological functions to these data in order to express quantitatively the dependence. The best model found is a power law, $R = u\Gamma^v$, giving $u = (1.4 \pm 0.1) \times 10^{-4}$, $v = 12.4 \pm 1.2$ at $\chi^2 = 45/44$. Errors along both axes were taken into account in the fitting as described in Brandt (1997).

As pointed out above, the error contours for individual measurements exhibit themselves significant intrinsic correlations, which should be taken into account. Direct estimates of the intrinsic correlation coefficients, $\rho$ (as given by XSPEC), are not reliable due to an asymmetry of the covariance matrix for ($\Gamma$, $R$). However, this asymmetry is reflected in deviation of a contour from the shape of an ellipse with the axes parallel to the coordinate axes, and we can thus estimate $\rho$ by graphically measuring its shape. The obtained values vary from $\rho \sim 0.7$ for contours with $R \sim 0$ to $\rho \sim 0.95$ for those with the strongest reflection.

We then use the individual values of $\rho$ in fitting the power-law model using a method of Brandt (1997). This yields $u = (1.7 \pm 0.8) \times 10^{-4}$, $v = 11.9 \pm 0.7$, which is within the 1-$\sigma$ confidence ranges of the $u$, $v$ above. On the other hand, $\chi^2 = 115/44$ is substantially larger than that of the fit above. This can be interpreted as due to the area of the distorted ellipses being much smaller than that of rectangles obtained from taking the errors on $\Gamma$ and $R$ as uncorrelated.

Note that the latter large value of $\chi^2$ reflects an actual spread of values of $R$ for a given $\Gamma$ due to a range of
physical conditions in the objects rather than due to measurement errors. Still, \( R \) is very strongly correlated with \( \Gamma \) even taking into account this physical width of the correlation as well as the measurement-related correlation between the parameters. This can be quantified by fitting a constant, \( R = u \), to the data, which corresponds to the null hypothesis of the absence of a physical correlation. The fit is performed with the same method as above, i.e., taking into account the intrinsic \( R(\Gamma) \) correlation. We obtain \( u = 0.22 \pm 0.02 \) at \( \chi^2 = 312/45 \). From comparison to \( \chi^2 \) for the corresponding power-law dependence, the probability that there is no correlation between \( R \) and \( \Gamma \) beyond the measurement-related one is \( 2 \times 10^{-10} \), as obtained from the F-test.

4 THEORETICAL INTERPRETATION

We note first that since at least some individual objects (NGC 5548, Mkn 509, GX 339–4, Cyg X-1) exhibit an \( R(\Gamma) \) correlation similar to the global one, the correlation cannot be due to an orientation effect (e.g. hard objects with weak reflection being oriented edge-on). Rather, its cause must be some feedback within the source in which the presence of a cold medium (responsible for reflection) affects the hardness of the X-ray spectra. A natural explanation for the feedback is that the cold medium emits soft photons that irradiate the X-ray source and serve as seeds for Compton upscattering. Then, the larger the effective solid angle subtended by the reflector, the stronger the flux of soft photons, and, consequently, the stronger cooling of the plasma. In the case of a thermal plasma, the larger the cooling by seed photons incident on the plasma, the softer the resulting X-ray power-law spectra. Indeed, X-ray and soft \( \gamma \)-ray spectra of both Seyferts and black-hole binaries in the hard state appear to be due to Comptonization by thermal electrons rather than non-thermal ones (Gierlinski et al. 1997; Johnson et al. 1997; Grove et al. 1998; Zdziarski et al. 1996, 1997, 1998).

We consider here 2 models. In the first one, a central uniform, optically-thin, sphere with unit radius and unit luminosity is surrounded by a flat, optically-thick disc (e.g. Poutanen, Krolik & Ryde 1997). The disc extends down to a radius \( d \geq 0 \) (Fig. 2). In the limit of \( d = 0 \), this geometry corresponds to a localized active region above the surface of an optically-thick accretion disc (Haardt, Maraschi & Ghisellini 1994; Stern et al. 1995). On the other hand, \( d \) corresponds to an inner hot accretion disc (Shapiro, Lightman & Eardley 1976), possibly advection-dominated (e.g. Abramowicz et al. 1995; Narayan & Yi 1995; Zdziarski 1998) surrounded by an optically-thick outer disc. We assume that the sphere is a hot plasma radiating via thermal Comptonization and the seed photons for upscattering are the reprocessed ones emitted by the cold disc.

In order to compute the fraction of the emission of the sphere intercepted by the disc, we need the flux, \( F(r) \), incident on the disc at a distance \( r \) from the center. The specific intensity of radiation emitted by the sphere in a direction towards the disc is \( I = j l \), where the emission coefficient is \( j = 3/(4\pi^2) \) for a uniform sphere with unit luminosity and unit radius, and \( l \) is the length through the sphere in this direction. Then \( F(r) = j \int \Omega l \cos \alpha \equiv 3b(r)/(16\pi^2) \), where \( \alpha \) is the angle between the direction of an incoming ray and the disc normal, and we denoted the integral of \( l \) as \( h(r) \).

By integration, we obtain,

\[
\begin{align*}
\text{for } r < 1: & \quad \int \left[ (4 - r^2) E (r^2) + (r^2 - 1) K (r^2) \right] \, d\Omega, \\
\text{for } r \geq 1: & \quad \int \left[ (2r - r^2 - 1) K (r^2) + 2 (r^1 - r) K (r^2) \right] \, d\Omega
\end{align*}
\]

where \( E \) and \( K \) are complete elliptic integrals. The function \( h(r) \) has the following properties: \( h(0) = 0, h(1) = 4/3, h(r > 1) \to /((4r^2), \int_1^\infty dr \, rh(r) = 8/9, \int_0^1 dr \, rh(r) = 2/3, \) and \( \int_0^\infty dr \, rh(r)^2 = 2/3. \) The luminosity of the disc is obtained by integrating the flux over the surface, \( L_d(d) = 4 \int_0^\infty d\Omega \, I(r)h(r) \).

In particular, \( L_d(0) = 1/2 \) (as expected from the isotropy of the sphere emission) and \( L_d(1) = 2/(3) \) (as found by Chen & Halpern 1989). The ratio of the luminosity of the disc to the part of the sphere luminosity radiated outward can be identified with the average strength of Compton reflection, \( R = L_d/(1 - L_d) \).

The reflection albedo is relatively low, \( a \approx 0.1 \)–0.2 (e.g., Magdziara & Zdziarski 1995), and most of the incident flux is reradiated isotropically as soft blackbody radiation with the specific intensity \( I(r) = \eta F(r)/r \), where \( \eta \equiv 1 - a \). If the disc radiates solely the reprocessed flux, \( I(r) = 3\eta h(r)/(16\pi^2) \).

The power in seed photons scattered in the sphere (assuming a unit optical depth) is then,

\[
L_s(d) \approx 4 \int_d^\infty dr \, r \, \eta \, h(r) = \frac{3\eta}{4\pi} \int_d^\infty dr \, rh(r)^2,
\]

where \( L_s(0) \approx \eta/4, A(d) \equiv 1/L_s(d) \) is the amplification factor of the process of thermal Comptonization.

We then use an estimate of Beloborodov (1999a) for \( \Gamma(A), \Gamma \approx 2.33(A - 1)^{-\delta} \), where \( \delta \approx 1/6, 1/10 \) for X-ray binaries and AGNs, respectively. From \( \Gamma[A(d)] \) and \( R(d) \) above, we obtain the model prediction for \( R(\Gamma) \), plotted for \( \delta = 1/10 \) and \( a = 0.15 \) in a dashed curve in the inset of Fig. 1a. We see that this model can reproduce the data in a middle range of \( \Gamma \) and \( R \) (especially for black-hole binaries), but it cannot reproduce \( R \) > 1. In fact, scattering of reflected photons in the hot plasma (neglected in the above model) will significantly reduce reflection for small \( d \), i.e., for large \( \Gamma \), which reduces the maximum possible \( R \) to a value < 1 (e.g., Poutanen et al. 1997). (Also, intrinsic dissipation in the disc will reduce \( R \) for given \( \Gamma \).) Disc flaring (Shakura & Sunyaev 1973; enhanced by irradiation, Vrtilek et al. 1990) and the presence of Thomson-thick molecular torii in some Seyferts can increase \( R \). However, such torii should also be present in some Seyferts with \( \Gamma > 1.6 \), contrary to our data showing \( R \ll 1 \). Concluding, this model may apply to some sources but it is unlikely to account for the full range of \( R \) observed in Seyferts.

Another model to explain the observed range of \( \Gamma \) and \( R \) has been proposed by Beloborodov (1999a, b). In this

\textbf{Figure 2.} The geometry with a central hot plasma surrounded by a cold disc, see Section 4.
model, the parameter controlling the spectral shape is the bulk-motion velocity of the X-ray emitting plasma located above an accretion disc. A mildly relativistic outflow reduces the downward flux, which in turn reduces both reflection and reprocessing in the disc. The reduction of the reprocessed flux incident on the hot plasma leads to a spectral hardening (analogously to the previous model). Such outflows were also proposed by Wo´zniak et al. (1998) to explain the weakness of reflection in radio galaxies. On the other hand, a mildly relativistic motion directed towards the disc will enhance reflection and cooling, leading to soft spectra.

Beloborodov [1999a, eqs. (3) and (7)] derives approximate formulae for \( R \) and \( A \) as functions of the bulk motion velocity. We show here the same model as in Beloborodov (1999b), for \( \delta = 1/10, i = 45 \) and his geometry-dependent factor, \( \mu_s = 0.55 \), by solid curve in the inset of Fig. 1a. This model reproduces well the observed average \( R(\Gamma) \). Variations in the energy of the seed photons, the plasma temperature and optical depth (affecting \( \delta \)), plasma geometry and orientation from source to source can reproduce the width of the correlation. Thus, this model appears fully capable to explain the observed correlation.

5 DISCUSSION

Our main finding is of a very strong correlation between the intrinsic spectral slope and the relative strength of Compton reflection in Seyferts. The statistical significance of the correlation is \( 1 - 2 \times 10^{-10} \) after removing the effect of an intrinsic correlation between those two quantities in each individual measurement. We have also found that the correlation is satisfied by hard-state spectra of 4 X-ray binaries containing either black holes or weakly-magnetized neutron stars. Since that sample is limited, more data are needed to test the generality of the correlation in X-ray binaries.

Our general interpretation of the correlation is as follows. The X-ray and soft \( \gamma \)-ray spectra of these classes of sources are well modeled by thermal Comptonization in hot plasmas, which emit power-law X-ray spectra with the slope related to the rate of cooling by incident soft photons. Then, the spectral slope will be correlated with the strength of reflection provided the main source of the cooling photons is emission of the same medium that is responsible for the observed reflection. A specific model with a mildly relativistic bulk motion of the hot plasma above an accretion disk (Beloborodov 1999a) can quantitatively explain the correlation.

An observational prediction of our interpretation of the correlation in terms of plasma cooling is that objects with soft X-ray spectra should on average have lower electron temperatures than those with hard X-ray spectra. This effect might, however, be compensated for by a reduction of the temperature due to \( e^+ \) pair production, which is more efficient in hotter plasmas.

The presence of the correlation strongly argues against thermal synchrotron radiation being a significant source of seed photons for Comptonization in those sources. This agrees with modeling of that process showing it to be insignificant in luminous sources (Zdziarski et al. 1998; Wardziński & Zdziarski, in preparation).

An interesting issue is whether black-hole binaries in the soft state obey the correlation. Their spectra in hard X-rays are typically power laws with \( \Gamma \sim 2-3 \) (Grove et al. 1998). No systematic studies of the presence of reflection in this state exist yet. In the case of Cyg X-1, Gierliński et al. (1999) find \( R < 1 \), which is less than that predicted by the correlation found here. This can be explained by hard X-ray spectra in the soft state being due to emission by non-thermal plasmas (Poutanen & Coppi 1998; Gierliński et al. 1999), in which case an \( R(\Gamma) \) correlation is not expected theoretically. This is because Compton scattering by non-thermal electrons leads to a photon spectrum with the slope related to the slope of the electron distribution rather than to the cooling rate.

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REFERENCES

Done C., Zyci k P. T., 1999, MN RAS, in press
Nandra K., Pounds K. A., 1994, MN RAS, 268, 405
Nandra K., Pounds K. A., 1994, MN RAS, 268, 405
Correlation between Compton reflection and X-ray slope

Strickman M., Skibo J., Purcell R., Barret D., Motch C., 1996, A&AS, 120, (III) 217
Ueda Y., Ebisawa K., Done C., 1994, PASJ, 46, 107

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