DISCOVERY OF HARD X-RAY DELAYS IN THE X-RAY EMISSION OF THE SEYFERT 1 GALAXY MARKARIAN 110: POSSIBLE EVIDENCE OF COMPTONIZATION

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ABSTRACT

We report the discovery of hard X-ray delays in the X-ray emission of the Seyfert 1 galaxy Mrk 110, based on a long XMM-Newton observation. Cross-correlation between the X-ray light curves of different energy bands reveals an energy-dependent delay ranging from a few minutes to an hour. We find that the energy spectrum can be modeled by Comptonization of disk blackbody photons. The energy-dependent delay can be modeled as due to the effect of Comptonization in a hot plasma confined within 10 Schwarzschild radii of the black hole. We discuss our results in the context of inverse Comptonization of the soft photons by highly energetic plasma.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: individual (Markarian 110) — radiation mechanisms: general — X-rays: galaxies

1. INTRODUCTION

The dominant X-ray radiation mechanism in accreting black holes is commonly thought to be inverse Compton scattering of low-energy photons by a cloud of hot (\(T \sim 10^5\)–\(10^6\) K) electron plasma near the black hole (Sunyaev & Titarchuk 1980). The physical geometry of the coronal plasma responsible for scattering the photons is not well constrained by the current observations. The ubiquity of a disk blackbody component accompanied by a power-law tail in the overall spectra of Galactic black hole candidates (GBHCs) motivated several workers to develop the so-called two-phase accretion disk–corona models (see e.g., Haardt & Maraschi 1991, 1993; Poutanen et al. 1997; Svensson & Zdziarski 1994; Stern et al. 1995; Beloborodov 1998). In these models, the blackbody radiation from the cold disk enters the hot corona and is Comptonized into X-rays. A part of the hard X-rays from the corona being reprocessed in the disk produces the reflection hump. The geometry of the corona controls this feedback mechanism, which, in turn, determines the spectral slope of the escaping radiation. The Kompaneets y-parameter (and hence the temperature) is determined by the energy balance between the heating and cooling mechanisms inside the plasma. One important question in all such models is the method by which the gravitational energy is converted to the energy of electrons. The ideas explored in the literature include magnetic flares (Haardt et al. 1994; Stern et al. 1995; Poutanen & Svensson 1996; Beloborodov 1999a, 1999b), advection-dominated disks very close to the black hole (Narayan & Yi 1994), and Bondi-type free fall beyond a shock region (Chakrabarti & Titarchuk 1995), but, as yet, there is no consensus on the exact mechanism. A general prediction of the above models is that the hard X-ray variations should lag behind those in softer bands, as hard photons undergo more scatterings in the plasma before escape. Measurement of such time lags has the potential to constrain the size of the region, which, in turn, will help us to understand the mechanism by which the electron cloud is energized. Frequency-dependent time lags have been observed in GBHCs (Miyamoto et al. 1988, 1991), as well as in a few active galactic nuclei (AGNs; Papadakis et al. 2001; Zhang 2002). Interpreting these lags as due to Comptonization requires the size of the emitting region to be very large, typically several thousand Schwarzschild radii (comparable to the lowest frequency at which the lag is observed), leading to the problem of heating the electron cloud at large distances from the black hole. Hence, sometimes these lags are interpreted as due to the energy-dependent asymmetries in random shots (Miyamoto & Kitamoto 1989); that is interpreting the lags as due to the production of the variability itself.

One of the problems of detecting lags at higher frequencies and relating them to the Comptonization at the innermost regions of the accretion disk around black holes could be observational. If the Comptonization process occurs at 10–20 Schwarzschild radii (\(R_s\)) and if the Comptonization process produces a lag that is a factor of a few larger than the light-travel time in these regions, one expects a lag of a few tens of milliseconds in a black hole of mass 10 \(M_\odot\) and about a day in an AGN of mass 100 \(M_\odot\). Detection of such delays is observationally a difficult task. Bright nearby AGNs with a black hole mass of 10 \(M_\odot\), where one expects a delay of about an hour, are the ideal sources to look for delays due to the process of Comptonization. With this motivation, we have searched for delays in one of the bright low-mass AGNs, Mrk 110, based on a long observation using the XMM-Newton observatory. In this Letter we present the cross-correlation analysis in different energy bands of this source and show that hard X-rays are delayed by a significant amount of time (from a few minutes to an hour). The 0.3–12 keV X-ray spectrum can be represented by a Comptonization model that can explain the measured hard X-ray delay.

2. OBSERVATION

Mrk 110 is a nearby optically bright, radio-intermediate \(R \sim 1.6\) narrow-line Seyfert 1 (NLS1) galaxy at a redshift \(z = 0.036\). The optical continuum and the broad emission lines of Mrk 110 are highly variable (by a factor of 2–8 within a timescale of 10 yr; Kollatschny & Welsh 2001; Kollatschny 2003). Mrk 110 was observed on 2004 November 15 by XMM-Newton for 47.4 ks. The EPIC pn cameras were operated in prime small-window observing mode using the Thin1 filters. Here we use data only from EPIC pn cameras due to their better efficiency and better calibration at lower energies and absence of pileup. Source spectra and light curves were extracted from the EPIC images using a circular source region centered on the observed source position. Background spectra and light curves were derived from adjacent blank-sky regions.
The EPIC spectra were binned to give a minimum of 50 counts per bin. The xspec version 11.0 and xronos packages were used for spectral and timing analysis, respectively. Errors on fitted parameters are quoted at the nominal 90% confidence level (Δχ² = 2.7) unless otherwise stated.

3. TIMING ANALYSIS

In Figure 1 we plot the binned light curves of Mrk 110 in different energy ranges (not corrected for the 71% duty cycle of pn small-window [SW] mode). The 0.2–12 keV light curve shows peak-to-peak variation of approximately 10% within 3 hr. To quantify the source variability in different energy bands, we calculated the fractional variability in seven energy bands: E₁ (0.2–0.3 keV), E₂ (0.3–0.42 keV), E₃ (0.42–0.58 keV), E₄ (0.58–0.8 keV), E₅ (0.8–1.2 keV), E₆ (1.2–2 keV), and E₇ (2–12 keV), respectively. The energy bands are chosen such that the mean count rate in those bands is approximately the same (within 10% of average). We find significant variability (rms value 2.5–4.5) in all the energy bands for 500 s binning (with a typical error of 0.4%). There is a marginal evidence of increasing variability with increasing energy; the variability is for energy 0.6 keV and it is for energy >0.6 keV. A structure-function analysis (Rutman 1978) of the light curves shows that the shortest correlation timescale is more than a few thousand seconds.

A visual examination of the light curves reveals a gradual decrease in count rate (~0.2 counts in 2 hr) in E₁ at time 10 ks from the starting time. A similar kind of variation is seen after more than an hour in E₂, (marked by arrows in Fig. 1). To search for time lags, we calculated the cross-correlation function (CCF) between E₁ and other energy bands using the crosscor package in ftools. The CCFs between E₁ and Eᵢ (where i = 2, 3, ... , 7) are plotted as a function of the delay, and the successive plots are vertically shifted by 1.6, 1.2, 0.9, 0.6, 0.3, and 0, respectively (see Fig. 2), for clarity. The errors in the CCF values are the standard 1 σ values, which include only the counting statistics errors. The harder light curves systematically lag the softer band. To estimate the amount of the delay, we fitted the central part of the CCF distribution with a Gaussian function and derived values of delays for the different energy bands of 200 ± 700, 400 ± 900, 900 ± 800, 1800 ± 900, 2400 ± 900, and 4500 ± 900 s, respectively. The errors in the delays are estimated by the χ²-fitting method with the prescription Δχ² = 4 (for three parameters). In Figure 3 we plot the derived delay as a function of the energy of the hard band, along with a Comptonization model (see § 5) fitted to the data points (χ²/dof ~ 1/4). For the hypothesis that there is no delay we get a value for χ²/dof of 38/6 and for the hypothesis of energy-independent delay, a value for χ²/dof of 18/5. Hence we can conclude that a delay is detected and that it is energy dependent at higher than the 99% confidence level. We must, however, caution that the above results are based on statistical considerations only and do not include systematic errors, such as the shape of the variation of the CCF with delay. We have also derived cross-correlation using other combinations (i.e., CCFs of Eᵢ with respect to E₄, where i = 1, 2, 3, 5, 6, and 7) to check whether the results are artifacts of the uncertainty of the instrumental calibration of energy below 0.3 keV, and we find similar results.

4. SPECTRAL ANALYSIS

We first modeled the X-ray spectrum of Mrk 110 with an absorbed power law with Galactic column density N_H = 1.6 × 10²⁶ cm⁻². This provides a fairly good fit to the pn data

![Fig. 1](image1.jpg) EPIC pn light curves (1000 s bin) of Mrk 110 in different energy ranges. The start of variability is indicated by downward arrows (see text).

![Fig. 2](image2.jpg) CCFs between light curves of 0.2–0.3 keV and higher energy bands (increasing from top to bottom). The CCF values are vertically shifted for clarity (see text).

![Fig. 3](image3.jpg) Energy dependence of lag between the light curves of energy 0.2–0.3 keV and higher energies.
in the 2–12 keV range ($\chi^2/\nu = 1037/1022$), giving a photon index $\Gamma = 1.75 \pm 0.01$. Inclusion of a narrow Gaussian emission line improves the fit significantly ($\chi^2/\nu = 997/1020$), giving the energy of the line $6.42 \pm 0.02$ keV. Extrapolating the best-fit model to 0.3 keV shows a huge soft excess in the spectrum ($\chi^2/\nu = 9447/1363$). Refitting still provides a rather poor fit ($\chi^2/\nu = 7350/1363$). A power law plus a blackbody law (generally, the soft-excess component in AGNs is modeled by a thermal blackbody, but the origin is still unknown) to model the soft excess improves the quality of the fit, but it is still not acceptable ($\chi^2/\nu = 2109/1361$). The temperature of the blackbody becomes $kT = 100 \pm 2$ eV. Fitting the data with a more realistic thermal accretion disc spectrum like diskbb (Mitsuda et al. 1984) or diskpn (Gierlinski et al. 1999) provides a poor fit to the data ($\chi^2/\nu = 1780/1361$ and $\chi^2/\nu = 1782/1360$, respectively), and the temperature becomes very high ($kT = 155 \pm 2$ and $159 \pm 3$ eV, respectively). These results would seem to refute an origin for the soft excess in terms of unmodified thermal blackbody emission. Addition of a power law instead of a blackbody law improves the fit ($\chi^2/\nu = 1680/1361$). The values of the power-law indices are $2.47 \pm 0.02$ and $1.21 \pm 0.04$. A model in the 0.3–12 keV range, which consists of a broken power law and the 6.4 keV Gaussian emission line improves the fit slightly ($\chi^2/\nu = 1597/1361$). The power-law indices are $2.29 \pm 0.01$ and $1.78 \pm 0.01$, and the break energy is $1.66 \pm 0.04$ keV.

Reflection off the surface could also produce strong soft excess at low energies. To test this, the ionized reflection model pexriv (Magdziarz & Zdziarski 1995) was fitted to the 0.3–12 keV spectrum, resulting in a poor fit to the data ($\chi^2/\nu \sim 2185/1361$). The best-fitting parameters were $\Gamma = 2.26 \pm 0.01$, $R = 8.14 \pm 0.12$, and $\xi < 10^{-3}$.

The energy-dependent time lags are strongly suggestive of Comptonization of low-energy seed photons by a population of high temperature electrons ($\text{§ 1}$). The comptt code (Titarchuk 1994) was used to model Comptonization of soft photons in a thermal plasma. A power law plus a Comptonization component gives a good fit to the data ($\chi^2/\nu = 1477/1359$) with $\Gamma = 1.51 \pm 0.05$ and the seed photon temperature $kT_{bb} = 69 \pm 2$ eV. The temperature and optical depth of the Comptonizing plasma are strongly covariant parameters and thus cannot be constrained simultaneously. Fitting the data with the compss model (Poutanen & Svensson 1996), along with the power law gives a reasonable fit ($\chi^2/\nu = 1483/1359$). In this model the soft flux is equal to the sum of the absorbed incident flux from the corona and the flux due to local energy dissipation in the cold disk. The spectral shapes of the soft components are assumed to be Planckian, with temperature $T_{bb}$ and $T_{disk}$, respectively ($T_{bb} > T_{disk}$). The inner disk temperature $kT_{disk}$ is fixed at 40 eV (calculated for a black hole of mass $10^7 M_\odot$ and assuming a standard accretion disk). The best-fit values of the parameters are $\tau = 3.2^{+0.7}_{-1.0}$, $kT = 14.0^{+0.3}_{-1.2}$ keV, $kT_{bb} = 99^{+3}_{-3}$ eV, and $\Gamma = 1.57^{+0.05}_{-0.03}$.

The Comptonization model, along with the power law described above, has the two spectrally identified continua originating in two distinct thermal Comptonizing plasmas. An alternative is that the whole spectrum is produced by a single plasma with a hybrid thermal/nonthermal electron distribution (Coppi 1999). The definite detection of a nonthermal Comptonization component requires high-energy and high-quality data. As noted by Pounds et al. (1995) the X-ray spectra of ultral soft Seyfert galaxies do resemble that of Cyg X-1 in its high/soft state. Thus, it seems reasonable to test whether a hybrid thermal/nonthermal plasma is a viable model for the X-ray continuum for Mrk 110. To test this idea we tried the hybrid Comptonization model, compss (for a detailed description of parameters, see Zdziarski et al. 2005). We assume a spherical geometry of hot plasma. We fitted the model ($\chi^2/\nu = 1455/1359$), and the best-fit values of the parameters are $\tau = 4.8^{+1.6}_{-1.4}$, $kT = 11.1^{+9.4}_{-2.1}$ keV, $kT_{bb} = 105^{+84}_{-15}$ eV, $\Gamma_{in} = 2.3^{+2.2}_{-1.6}$, and $\gamma_{min} = 1.19^{+1.3}_{-0.13}$. The unfolded spectrum is shown in Figure 4. A similar attempt has been made to model the X-ray spectrum of NLS1 galaxy Ton S180 (Vaughan et al. 2002).

5. DISCUSSION AND CONCLUSION

We find a significant energy-dependent delay between the hard and soft X-ray emission in the Seyfert 1 galaxy Mrk 110. Similar delays were also found in the bright Seyfert 1 galaxy MCG –6-30-15 (Ponti et al. 2004). Gallo et al. (2004) found alternating leads and lags in the NLS1 galaxy IRAS 13224–3809. Although other interpretations such as geometric effects and the energy-dependent shape of shots can also explain the observed energy-dependent delays in Mrk 110, we prefer to interpret the results as due to Comptonization, particularly because the spectral analysis favors a two-component Comptonization model. We consider a static Compton cloud with optical depth $\tau_c$ and electron temperature $T = kT_{in}/m_e c^2$. A soft seed photon of energy $E_o$ injected into the cloud increases its energy by a factor of $A = 1 + 40 + 160^2$ on average after each scattering, so that after $n$ scatterings its energy is $E_n = A^n E_o$. The photon mean free path is $\lambda \approx kT_{in}/(1, \tau_c)$ (where $R$ is the size of the X-ray-emitting region). The time difference between successive scatterings is then $\tau_s = (\lambda c)/\max (1, \tau_c)$, where $\tau_s = N \sigma_T R$ is the Thompson optical depth, $\sigma_T$ is the cross section of Thompson scattering, and $N$ is the electron number density of the scattering medium. The time needed to reach the energy $E_n$ is $\tau_n = n \tau_s$, (Sunyaev & Titarchuk 1980; Payne 1980). We have calculated time lags of different high-energy bands with respect to the 0.2–0.3 keV band. Hence in our case $E_o = 0.25$ keV. We fit the above equation ($\tau_s = n \tau_s$) to the result (hard lag as a function of energy) of our analysis and find that the data are in good agreement with the equation (Fig. 3). Using the values of the best-fit parameters of the above result and the parameters of the Comptonization model fitted to the spectrum, we get $R \sim 2 \times 10^{13} \text{m} \sim 10 R_S$. This value of $R$ is physically realistic, as most of the energy is dissipated within $10 R_S$. Böttcher & Liang (1998) pointed out that any scenario in which the observed hard time lags are purely due to static Comptonization requires that the radial extent of the hot corona exceed $\sim 10 R_S$ of a solar-mass black hole $(R > 10^8 m)$. This is incompatible with current models of accretion flows onto Galactic black holes (see the review by Liang 1998), even from simple energy arguments (see § 1). But the results...
reported here pertain to lags at very short timescale and hence are consistent with the static Comptonization model. The harder power-law emission extending to 12 keV (and presumably beyond) can also be produced by Comptonization, either in another purely thermal plasma or by nonthermal electrons in a plasma with a hybrid thermal/nonthermal distribution.

The origin of the hot plasma above the accretion disk is quite debatable. If the radiation pressure inside the accretion disk very close to the black hole is very high, then the accretion disk can be puffed up and the hot thermal plasma can be formed just above the accretion disk. Hybrid thermal/nonthermal plasmas have often been successfully used to model the observed data (Gierlinski et al. 1999; Poutanen & Coppi 1998). A possible origin of the nonthermal component is in process of magnetohydrodynamic turbulence occurring in the corona (Li & Miller 1997). Stochastic acceleration of particles by stochastic gyroresonant acceleration in an accreting plasma can also accelerate particles to higher energies (Dermer et al. 1996; Li et al. 1996).

We conclude that inverse Compton scattering of soft photons by highly energetic electron distribution provides a satisfactory explanation of the hard X-ray time lag observed in the XMM-Newton observation. The energy spectrum in the 0.3–12 keV band can be modeled either by two-component Comptonization or by a hybrid thermal/nonthermal Comptonization. It is not possible to distinguish between them without good-quality high-energy data.

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