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A SPECTROSCOPIC STUDY OF THE SEYFERT GALAXY MCG−2-58-22

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ABSTRACT

We present analysis results of the energy spectra of MCG−2-58-22 associated with occasional flares which appear in a long-term X-ray light curve. We measure an intrinsic power-law slope of this object to be $\Gamma = 1.74 \pm 0.02$ in the energy range of $\sim 1 - 5$ keV and find that this slope is little affected by flares. We confirm that there exists a broad excess emission above 5 keV to the power-law continuum. The excess emission is less variable compared with a flux variation of flare and tends to be relatively weak during flares. A soft X-ray spectrum is also found to change, implying the presence of a variable soft component. We discuss the implications of these spectral variations.

Key words : galaxies: individual(MCG−2-58-22) — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

I. INTRODUCTION

MCG−2-58-22 (Mrk 926) is a Seyfert 1 galaxy at a redshift z = 0.04732. It is known as a "bare" Seyfert nucleus which shows a small reddening or is little contaminated by the host galaxy (see, e.g., Vaughan et al. 2004; the reddening for MCG−2-58-22 is measured to be E(B-V) = 0.04 by Schlegel, Finkbeiner, & Davis 1998). In optical region, this object shows a $\sim$ 1 yr timescale continuum variation as well as a variation in the broad and asymmetric Balmer line profile (e.g., Whittle 1992 and Winkler et al. 1992).

MCG−2-58-22 is bright in X-ray region ($\sim 10^{44}$ ergs s^{-1}) and exhibits a wide time variability, whose timescale ranges from $\sim 10^3$ s to more than several years (Choi et al. 2001 and references therein). Recently, Choi et al. (2002) found two distinct types of time variations from the analysis of the long-term X-ray light curve of MCG−2-58-22 made with 22 yrs data from various X-ray satellites: one is a gradual and secular decrease of X-ray flux and the other is an occasional flare which shows a flux variation of a factor of 2 − 4 for a duration of $\lesssim$ 2 yrs. However, it is not known yet whether these flux variations are accompanied with a significant spectral variation or not.

In general, energy spectra of Seyfert 1 galaxies are complex and have various structures in X-ray region. Although their (intrinsic) continuum spectra might be a power-law type, a broad iron emission line and a reflection structure could appear in the observed spectra above $\sim$ 5 keV. Moreover, a soft excess structure by the warm absorber could also appear below $\sim$ 1 keV. Because these structures are subject to change in time, careful analysis is needed to quantify the shape of the energy spectra. After taking into account the effects of the various structures, Nandra & Pounds (1994) measured the power-law slope of MCG−2-58-22 to be $\Gamma = 1.67 \pm 0.08$, using data in a quiescence state observed with Ginga. If we select a limited energy range such as 0.5 − 6 keV, MCG−2-58-22 could have little structures in the energy spectra and an intrinsic power-law slope (or the index) could be obtained directly. Based on this consideration, Weaver et al. (1995) measured the slope as $\Gamma = 1.75 \pm 0.05$ with ASCA data for a quiescence state. These power-law indices are less steeper than the canonical value of $\Gamma = 1.9 - 2.0$ for Seyfert 1 galaxies (Nandra & Pounds 1994).

From the analysis of the Ginga data for MCG−2-58-22, Nandra & Pounds (1994) reported on the presence of an iron Kα line which is located at $\sim$6.4 keV and has an equivalent width (EW) of $\approx$ 150 eV. Weaver et al. (1995) also derived the line parameters assuming that there exists no reflection component in the ASCA bandpass: a center energy to be 6.2 keV with a velocity width of 31,000 km s^{-1} (FWHM) and the EW to be 340 eV. Alternatively, they obtained a different set of parameters, i.e. EW of 230 eV with an upper limit of the width of 47,400 km s^{-1}, using the predicted amount of Compton reflection from a face-on accretion disk. Ghosh & Soundararajaperumal (1992) detected a soft excess emission from the analysis of EXOSAT

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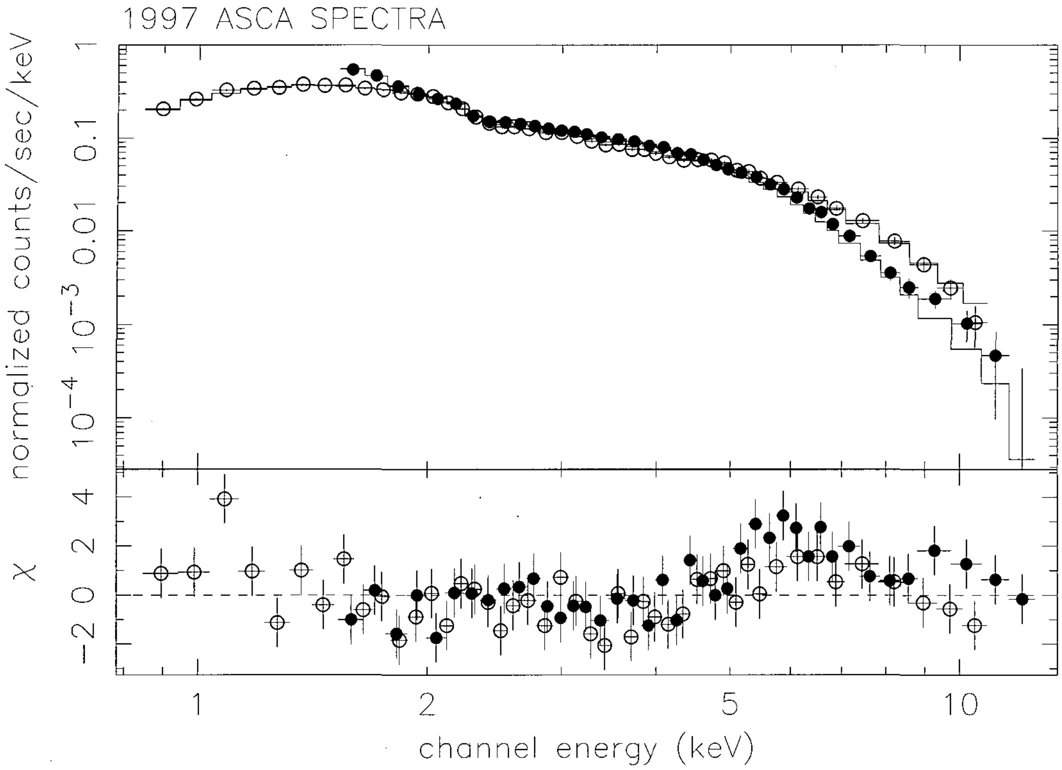

Fig. 1.— Energy spectra of MCG−2-58-22 obtained from the 1997 ASCA data are shown (upper panel), where open circles and filled circles represent the GIS and SIS spectrum, respectively. In this figure, two data sets in 1997 June and December are merged, as well as spectra from the SIS0 and SIS1 instruments and those from the GIS2 and GIS3 are co-added, respectively. Lower panel shows the residuals to the power-law continuum of $\Gamma = 1.74$ which is determined in $1.5-5$ keV range. Excess emission to the power-law continuum is clearly seen above 5 keV.

data for MCG−2-58-22, which is variable in timescale of a few days. The excess phenomena for some selected Seyfert 1 galaxies were studied with ROSAT data by Piro, Matt, & Ricci (1997). According to their results, the power-law index of the present object is much steeper ($\Gamma = 2.1$) than that of the Ginga & ASCA data, implying the presence of a soft-excess component. They suggested that the excess phenomena for the Seyfert 1 galaxies could be explained by the combination of several different effects rather than by a single mechanism.

In this paper, we investigate a spectral variability in connection with the flares appeared in the long-term X-ray light curve of Choi et al. (2002). Particularly, we focus on the two flares occurred in 1991 June – November and in 1997 June – December, which are both confirmed by separated observations. For this purpose, we use the same data presented in Choi et al. (2002; for a detailed data reduction procedure see Choi et al. 2001).

II. SPECTRAL ANALYSIS

To examine how the energy spectrum is affected by flares, we first analyze the flare data obtained with ASCA in 1997 (which are not fully analyzed yet) and compare the spectrum with that of the 1993 quiescence data using a model-independent method of spectral analysis. We then turn to the 1991 flare and the corresponding quiescence data obtained from Ginga and ROSAT observations.

(a) Intrinsic Spectral Slope

There are two sets of ASCA observations for the 1997 flare which have an interval of half a year. As seen in the long-term light curve of Choi et al. (2002), these two data show an almost equal flux level. We therefore check whether their spectra show a similar spectral shape or not, using pulse-height−to−amplitude (PHA) ratios between the two spectra, i.e., the ratios of the count rates as a function of X-ray energy. The resulting ratios are almost flat for the two different instrument data: $\chi^2/\nu = 23/45$ for a constant ratio for the Gas Imaging Spectrometer (GIS) spectra in the energy range of $0.8 - 10$ keV and $\chi^2/\nu = 16/36$ for the Solid-state Imaging Spectrometer (SIS) spectra in the range $0.4 - 10$ keV. Since this result indicates that the two flare spectra are very similar to each other, we add up the data to improve statistics.

The summed energy spectra obtained from the GIS and SIS are shown in Figure 1. In this figure, we simply discard the SIS data below 1.5 keV because the lower energy data display an unexpected large deviation from a spectral model and because it is known that the quantum detection efficiency of the SIS has decreased secularly in the lower energy range due to the radiation damage (e.g., Hwang et al. 1999).* We then apply the same method as Weaver et al. (1995) did to the spectra to measure an intrinsic spectral slope consistently. That is, we perform a model fit to the SIS and GIS spectra simultaneously in the energy range of 1.5 − 5 keV with an absorbed power-law model (where the absorption column density is fixed to the Galactic value 3.5×10^{20} cm^{-2}). From this fit, we obtain the spectral slope to be $\Gamma = 1.74 \pm 0.02$, which agrees well with the slope of the 1993 quiescence data (Weaver et al. 1995). This indicates that the intrinsic spectral slope is almost independent of the flux variation.

(b) Broad Excess Emission above 5 keV

If the power-law slope is extended to higher energies, a broad structure in residuals becomes visible above 5 keV (see the lower panel of Figure 1). The excess emission can be regarded as a Compton reflection structure and/or a broad iron-K fluorescent line because these types of emission are often observed in the energy spectra of Seyfert 1 galaxies. Unfortunately, however, the data statistics are still insufficient to confine the possible mechanisms of the structure through a model fit. We thus try to study the structure by inspecting a relative variation of the energy spectra with PHA ratios.

Figure 2 displays the PHA ratios between the quiescence and flare spectra, i.e. the ASCA GIS spectrum of the 1993 data and that of the 1997 data. We here use the GIS data because they have better statistics than the SIS above ~5 keV. As seen in the figure, the ratios are almost flat below ~4 keV, confirming the result we obtained above. That is, the intrinsic power-law slope of the flare is the same as that of the quiescence in the range of 1.5 − 5 keV. On the other hand, there is a tendency that the ratios become larger above 5 keV, marked by arrow in Figure 2. This is marginally significant ($\chi^2/\nu = 9.8/5$ for a constant ratio) and implies that the broad excess emission is relatively weak during the flare. Another interesting point is that the excess emission is less variable compared with the variation of the continuum flux between the flare and quiescence states.

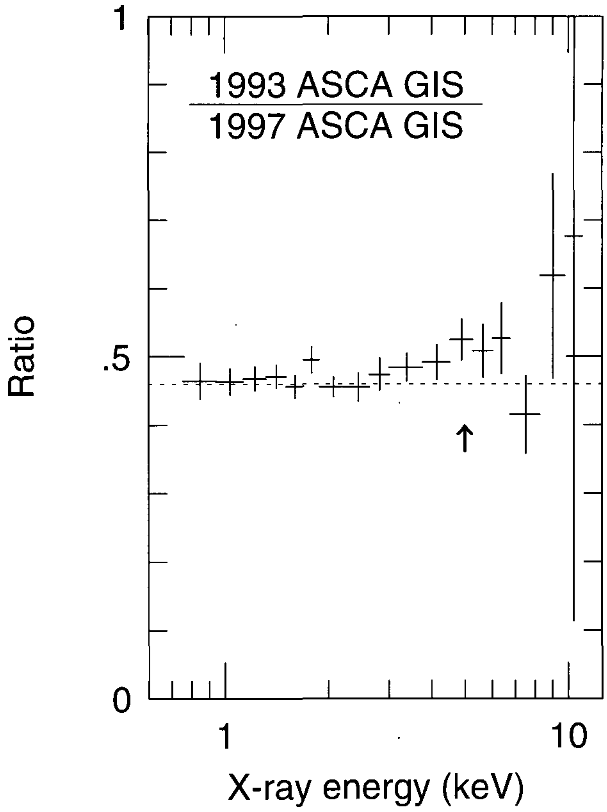

Fig. 2.— PHA ratios between the ASCA GIS spectrum of 1997 data and that of 1993 data. The ratios are flat below ~4 keV, whereas they become slightly larger above ~5 keV to the constant ratio represented by the horizontal dashed line.

(c) Spectral Variability with the 1991 Flare

It is possible to study a relative spectral variation of the 1991 flare in high and low energy bands because the flare and the corresponding quiescence states were observed by both Ginga Large Area Counter (LAC; which covers the energy range of 2 − 37 keV) and ROSAT Position Sensitive Proportional Counter (PSPC; whose energy coverage is 0.1 − 2 keV). In this subsection, we first analyze the LAC data and then move to the PSPC data. Figure 3(a) displays the PHA ratios between the LAC spectrum of the 1991 data† (obtained at the rise of the flare) and that of the quiescence data in 1989 (before the flare, where we summed all the 4 data sets in 1989; see Table 1 of Choi et al. 2002 for the log of Ginga observations). If we limit the data below 5 keV, the ratios are almost flat which implies that the intrinsic power-law slope is little affected by the flare. This figure also shows an excess structure in 6 − 9 keV, marked by arrows, though the profile and the covered energy range are slightly different from those of the ASCA data in Figure 2.

Figure 3(b) displays the PHA ratios between the PSPC spectrum of 1991 data (peak of the flare) and that of 1993 May data (after the flare; we merged the two data sets in 1993 May because the observation dates are overlapped). From this figure, we see that the ratios deviate from the constant in the lower energy band (< 0.5 keV) and possibly in the higher

This situation makes it difficult to investigate a relative spectral variation of the flare in a soft X-ray range.

†Note that a spectral analysis result of these data is not yet published.

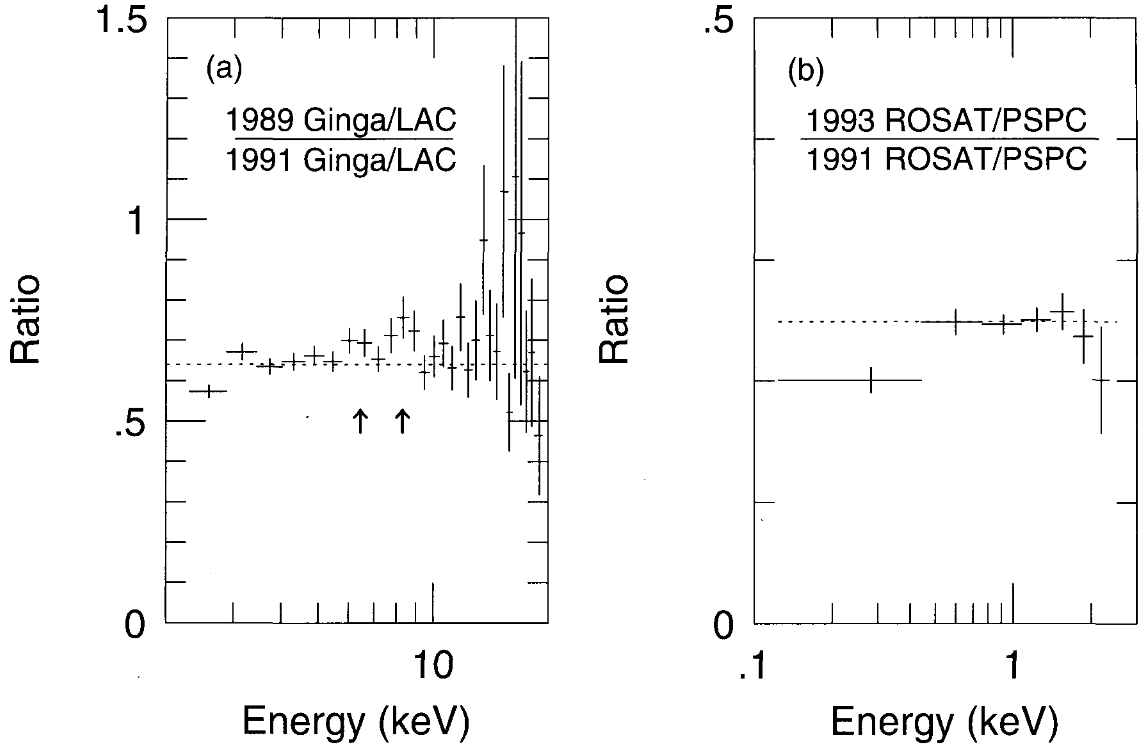

Fig. 3.— (a) PHA ratios between the LAC spectrum of the 1991 flare data and that of the averaged quiescence data in 1989. The ratios are almost flat below ~5 keV, whereas an excess structure is seen above 5 keV to the best-fit constant ratio determined below 5 keV (dashed line). (b) PHA ratios between the 1991 PSPC spectrum (peak of the flare) and that of 1993 (after the flare). This figure shows that the ratios deviate from a constant ratio (dashed line) in the lower energy band (< 0.5 keV) and possibly in the higher energy band (> 1.5 keV).

energy band (> 1.5 keV). However, it should be careful to interpret these deviations because the PSPC is known to suffer from a gain change during the operation life. According to Prieto, Hasinger & Snowden (1996), the gain change rate of the PSPC is energy dependent, e.g., it increases with energy up to ~1 keV and then decreases down to the normal value at ~1.5 keV. Thus the energy scale evolves non-linearly. If the intrinsic spectra between 1991 and 1993 are the same, the PHA ratios would show a concave feature taking a minimum near 1 keV and going up to unity around 1.5 keV due to the gain change. However, the ratios we obtained are clearly different from that expected from the gain change. That is, the ratios are almost constant in $0.5-1.5$ keV and show rather convex feature in the full energy range. The deviations of the PHA ratios in Figure 3(b) are therefore considered to reflect the intrinsic spectral variation of the object.

To confirm the spectral change in the soft energy band, we fit an absorbed power-law model to the 1991 & 1993 PSPC spectra separately and compare the results. The resulting confidence contours between the power-law (or photon) index and the hydrogen-equivalent column density are shown in Figure 4. From this figure, it is immediately noticed that the allowed range of the power-law index, $\Gamma = 2.1 \pm 0.1$, is considerably larger than that of the Ginga & ASCA data. It is also noticed that the spectral change can be explained mainly by the change of the column density. The most probable column density for the 1993 spectrum (contours by broken lines) is consistent with the Galactic value 3.5×10^{20} cm^{-2}, while the column density for the 1991 spectrum (contours by solid lines) is smaller than the Galactic value. Because MCG−2-58-22 is a bare Seyfert nucleus which has little intrinsic absorption and the Galactic column density is unlikely to change, the apparent change of the absorption column density can be attributed to the spectral variation of the soft component (i.e., the flare spectrum is relatively soft in the lower energy range).

III. DISCUSSION AND SUMMARY

In this study, we have considered that an intrinsic energy spectrum of the Seyfert galaxy MCG−2-58-22 has a simple power-law shape, whereas various structures and emission components make the spectrum complicated below ~1 keV and above ~5 keV. Based on this consideration, we measured the intrinsic spectral slope to be $\Gamma = 1.74 \pm 0.02$ using the 1997 flare data in the energy range $\sim 1-5$ keV. This slope is consistent with that of the 1993 quiescence spectrum

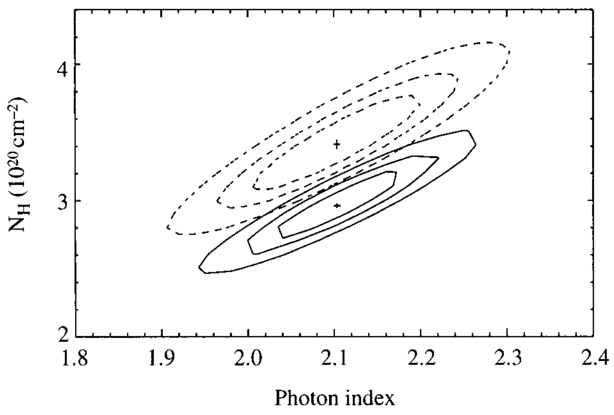

Fig. 4.— Confidence contours (68%, 90%, and 99% levels) for a power-law (or photon) index vs. hydrogen equivalent column density for a fit to the ROSAT PSPC spectra of 1991 (contours by solid lines) and 1993 (contours by broken lines).

$\Gamma = 1.75 \pm 0.05$ (Weaver et al. 1995) and with that of the 1989 quiescence spectrum $\Gamma = 1.67 \pm 0.08$ within the error (Nandra & Pounds 1994). We note that Bianchi et al. (2004) also obtained a similar spectral slope to ours, $\Gamma \approx 1.74$, through a various model fit to the recently observed XMM-Newton and BeppoSAX data of the present object. In addition, as shown in Figure 3(a), the 1991 flare shows no significant spectral difference to the quiescence in the energy range. Based on these results, we conclude that the intrinsic spectral slope of MCG−2-58-22 is not significantly affected by the flux variation of the flare.

We confirm the existence of the broad excess emission above 5 keV to the spectral slope as seen in Figure 1. Although we studied only two PHA ratios (one from ASCA data and the other from Ginga data), the results clearly indicate that the excess emission is less variable than the continuum flux which shows a factor of $2-4$ variation between flare and quiescence states. Among the possible mechanisms to the excess emission, a broad iron-line (disk line) and a Compton reflection models have been adopted frequently. The excess emission we detected is broad and covers at least the energy range of $5-8$ keV. If the disk line is responsible for the excess emission, it should be produced at a region very close to the central black hole of MCG−2-58-22 to explain the large width. Furthermore, its intensity should show a close correlation with the continuum flux. However, we did not find any hints of such a correlation. As shown in Figure 2 and Figure 3(a), the excess emission tends to be relatively weak during flare, and hence the disk line model seems to be inadequate to interpret the behavior of the excess emission. On the other hand, if the excess emission results from the Compton reflection, a large time lag and smearing could exist in the excess emission depending on the location of the reflection site. Because the reflection site can be located far from the X-ray emission region, smaller variability in the excess emission may be readily explained. The Compton reflection model is therefore preferred in this study to explain the origin of the excess emission. Origin of the excess emission has been studied so far mostly based on the result of model fits to the spectra. Nandra & Pounds (1994) found little reflection structure from the 1989 Ginga spectra. Weaver et al. (1995) also did not find a strong evidence of the reflection structure from the 1993 ASCA spectrum. However, it may be tricky to identify the origin of the excess emission from the spectral-fit only, because the model spectra sometimes show a similar spectral shape even if the origin is very different. We here stress the usefulness of a model-independent method of spectral analysis to study the variability of the emission and its origin.

We detected a spectral variation with ROSAT data in a lower energy range and confirmed that the variation is intrinsic to the object rather than due to an artifact. Ghosh & Soundararajaperumal (1992) investigated the soft X-ray spectrum of MCG−2-58-22 in detail using the EXOSAT data and thereby, they detected a soft component which is variable in timescale of a few days. They reported that an additional power-law model provides a good fit to the soft component and its flux correlates with the power-law index of the component. This spectral variation is similar to our result in the sense that the spectrum becomes soft when the flux level is high. According to their report on the timescale of the variation, it seems that the variation of the soft X-rays detected in this study is not closely related with the flaring activities. Magdziarz et al. (1998) have studied the broad-band spectrum of the Seyfert 1 galaxy NGC 5548 and found that a soft-excess component could be explained by the thermal Comptonization in optically thick and warm plasma. We speculate that a similar process might work in MCG−2-58-22.

We summarize our results of this study as follows. We measure an intrinsic power-law slope to be $\Gamma = 1.74 \pm 0.02$ for the 1997 flare spectra in the energy range $\sim 1-5$ keV and find that this slope has maintained as stable for about 8 yrs, from 1989 to 1997, irrespective of the flaring activities. We confirm that the energy spectra show a broad excess emission above $\sim$5 keV over the power-law continuum. This excess emission tends to be relatively weak during the flares. We suggest that this excess emission could be explained by the Compton reflection. The soft X-ray spectrum (< 0.5 keV) undergoes a temporal variation and this confirms the previous results by Ghosh & Soundararajaperumal (1992) and Piro et al. (1997).

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