

LONG-TERM X-RAY VARIABILITIES OF THE SEYFERT GALAXY MCG-2-58-22 : SECULAR FLUX DECREASE AND FLARES

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ABSTRACT

We have studied the long-term X-ray light curve (2–10 keV) of the luminous Seyfert 1 galaxy MCG-2-58-22 by compiling data, from various X-ray satellites, which together cover more than 20 years. We have found two distinct types of time variations in the light curve. One is a gradual and secular decrease of the X-ray flux, and the other is the episodic increase of X-ray flux (or flare) by a factor of 2–4 compared with the level expected from the secular variation. We detected 3 such flares in total; a representative duration for the flares is ~ 2 years, with intervening quiescent intervals lasting ~ 6 –8 years. We discuss a few possible origins for these variabilities. Though a standard disk instability theory may explain the displayed time variability in the X-ray light curve, the subsequent accretions of stellar debris, from a tidal disruption event caused by a supermassive black hole in MCG-2-58-22, cannot be ruled out as an alternative explanation.

Key words : black hole physics – galaxies : nuclei – galaxies : individual (MCG-2-58-22) – X-rays : galaxies

I. INTRODUCTION

X-ray observations of active galactic nuclei (AGN) show that many of them are variable, over a range of amplitudes, and on many timescales (Lawrence et al. 1985; Grandi et al. 1992; Mushotzky, Done, & Pounds 1993; Nandra et al. 1997; Ulrich, Marachi, & Urry 1997; Ptak et al. 1998; Turner et al. 1999). Variability of the X-ray emission is a powerful probe of physical processes occurring in the inner regions of AGN. In particular, rapid variability is widely thought to be related to the central regions, and it has actually been used to constrain the physical properties of the central engine. For example, the short-time variability amplitudes of Seyfert 1 galaxies are known to be anti-correlated with the source luminosities (Barr & Mushotzky 1986; Nandra et al. 1997; Ptak et al. 1998). This correlation may reflect differences in the masses of the central supermassive black holes (SMBHs). In addition to the short-time variabilities, the study of long-time variabilities is also important since it may bring out other interesting information, such as the global structure of the accretion disk around the central SMBH, or episodic events such as flares and outbursts.

Detailed studies of the long-term X-ray light curves of AGN have begun only recently. Markowitz & Edel-

son (2001) analyzed 300-day light curves of Seyfert 1 galaxies in the 2–10 keV band. They showed that the X-ray variability of Seyfert 1 galaxies is described by a single, universal power-density spectrum (PDS), and that the cutoff moves to longer timescales for sources with higher luminosity. Soft X-ray outbursts, having an amplitude of about 2 orders of magnitude, were observed from NGC 5905 (Bade, Komossa, & Dahlem 1996) and Zwicky 159.034 (Brandt, Pounds, & Fink 1995). Various possible scenarios for such outbursts have been reviewed by Komossa & Bade (1999). However, long-term modulations in AGN light curves, which exceed several years, have mostly been studied in the optical range. For instance, Webb (1990) reported the results of 61 years of optical observations of 3C 120, and claimed the presence of three variability components: a sinusoidal component with a period of 12.43 years, a linear component, and high amplitude flares on much shorter timescales. Peterson et al. (1998) reported the spectroscopic monitoring of nine Seyfert 1 galaxies in the optical band, the aim of which was to determine the size of the broad line emission regions. In order to perform a similar analysis in the X-ray band, we need to collect all available datasets from the various X-ray satellites. Because the different instruments of the satellites have their own individual properties, and cover different energy ranges, careful analysis is required for such studies in the X-ray region.

In this paper, we study the long-term X-ray light

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curve of MCG-2-58-22, covering more than 20 years, and we discuss the potential origins of the long-term behaviors. In previous work, Choi et al. (2001) analyzed the Ginga, ROSAT, and ASCA data for this source, and noticed flare-like events. This motivated us to perform a thorough analysis of the long-term X-ray flux variations in this source. For this purpose, we have gathered X-ray flux measurements of MCG-2-58-22 from the literature, as well as raw X-ray data from the HEASARC public archives at NASA/GSFC, and from the SIRIUS database at ISAS. The observational data we gathered include those of HEAO-1 (Rothschild et al. 1979), Einstein (Giacconi et al. 1979), EXOSAT (Taylor et al. 1981), Ginga (Turner et al. 1989), ROSAT (Pfeffermann & Briel 1986), ASCA (Tanaka, Inoue, & Holt 1994), and RXTE (<http://heasarc.gsfc.nasa.gov/docs/xte>).

MCG-2-58-22 is a luminous Seyfert 1 galaxy at $z = 0.04732 \pm 0.0003$ (e.g. Huchra et al. 1993). The X-ray luminosity of MCG-2-58-22, $L_X \sim 10^{44}$ erg s $^{-1}$, is known to be variable on a timescale of a few times 10^3 seconds to years (Grandi et al. 1992; Nandra & Pounds 1994; Choi et al. 2001). Many observational characteristics are typical of Seyfert 1 galaxies: time variability, a power-law type continuum spectrum, and a soft excess phenomenon (Ghosh & Soundararajaperumal 1992; Nandra & Pounds 1994; Weaver et al. 1995; Nandra et al. 1997; George et al. 1998; Turner et al. 1999). The mass of the putative central SMBH of MCG-2-58-22 is estimated from the UV and optical observations to be a few times $10^8 M_\odot$ (e.g., Padovani & Rafanelli 1988; Wandel 1991). MCG-2-58-22 has also been studied in other wavelength bands. Mundell et al. (2000) observed MCG-2-58-22 using the VLBA at 8.4 GHz, and detected the nuclear radio source, which was without any extended structures, in the parsec-scale image; this suggests that the VLBA radio source could be a “bare” Seyfert 1 nucleus (see also Weaver et al. 1995). In the optical region, this source has displayed a continuum variation on a timescale of ~ 1 year (de Ruiter & Lub 1986; Whittle 1992), as well as a very wide variability in the Balmer line profiles and luminosities (see, e.g., Winkler et al. 1992, and references therein).

II. DATA ANALYSIS AND LIGHT CURVE

(a) Data Analysis and Flux Calibration

To make a long-term X-ray light curve, flux data for MCG-2-58-22 have been taken from the literature; the references are listed in Table 1. Since the instruments onboard various observatories span different energy ranges, we convert the fluxes to the corresponding values in the 2–10 keV band, which is covered by most of the instruments. Having surveyed the reported flux data, we further collected and analyzed the archival data of MCG-2-58-22 from the HEASARC public archives (e.g., the EXOSAT data of 1983 November to 1984 November, the ROSAT data

of 1990 November through 1993 December, the ASCA data of 1993 May through 1997 December, and the RXTE data of 1997 December through 1999 November), and from the SIRIUS database at ISAS in Japan (the Ginga data of 1991 June).

In the analysis of these observations, we apply the standard screening criteria to the raw data, e.g., the rejection of possibly contaminated data from the bright Earth, and also from regions of high particle background, etc. Then, we calculated the X-ray fluxes in the 2–10 keV band through a spectral fit to the screened data, and we list these fluxes in Table 1. In the spectral fit, we assumed a power-law model with a photon index of $\Gamma = 1.75$, and a hydrogen equivalent absorption column density of $N_H = 3.5 \times 10^{20}$ cm $^{-2}$ (see, e.g., Weaver et al. 1995; Piro, Matt, & Ricci 1997). Until now, various authors have used different models for the energy spectra. Therefore, even though the best-fit parameters are available from the literature, we use the spectral parameters stated above to maintain consistency. Systematic errors associated with our method are evaluated below.

(b) Error Estimates

The calculated X-ray fluxes in the 2–10 keV band may include various systematic errors. For example, there could exist contaminating X-ray sources in the vicinity of MCG-2-58-22. We have checked various catalogs, and confirmed that X-ray sources within 3 degrees of MCG-2-58-22 are dimmer than it by at least an order of magnitude. Thus the effect of contaminating sources can be neglected in the present analysis.

Another possible source of error is spectral variability. The power-law slope of MCG-2-58-22 may not be constant, and the energy spectra may include some structure, such as a broad iron line or a Compton reflection hump. The effects of spectral variability on long-term light curves have been evaluated as follows. We first note that the photon indices reported in the literature fall in the range $\Gamma = 1.4 - 1.9$ (e.g., Turner et al. 1991; Ghosh & Soundararajaperumal 1992; Nandra & Pounds 1994; Weaver et al. 1995; George et al. 1998), except for the ROSAT observations. Based on this fact, we have checked how the flux estimation is affected, both by the change in the photon indices, and also by the structures which may exist in the energy spectra (e.g., George et al. 1998). As a result, it is found that differences in the spectral slope and structures mostly affect the higher energy spectrum (say > 5 keV), which carries only relatively little flux. Thus, the systematic error associated with these uncertainties turns out to be much smaller than 10 %, for observations covering the 2–10 keV band. On the other hand, since the ROSAT PSPC did not cover the 2–10 keV range, the calculated ROSAT fluxes may include relatively large systematic errors. In the case of the ROSAT data, it may not be appropriate to assume a simple power-law, because the photon indices are different between the

Table 1. JOURNAL OF X-RAY OBSERVATIONS OF MCG-2-58-22

DATE	OBSERVATORY	INSTRUMENT	FLUX ^a	REFERENCE ^b
1977 September 5 – 1978 March 13	HEAO-1	A2	4.0	(1)
1978 March 14 – 1978 September 11	HEAO-1	A2	5.0	(1)
1979 May 27	Einstein	MPC, SSS	4.2	(2)
1979 June 2	Einstein	MPC, SSS	3.8	(2)
1983 November 6	EXOSAT	ME	6.7	(3)
1984 November 16	EXOSAT	ME	3.0	(3)
1984 November 17	EXOSAT	ME	2.9	(3)
1984 November 20	EXOSAT	ME	3.1	(3)
1984 November 22	EXOSAT	ME	3.2	(3)
1984 November 24	EXOSAT	ME	3.2	(3)
1984 November 26	EXOSAT	ME	2.9	(3)
1989 June 19	Ginga	LAC	1.9	(4)
1989 July 5	Ginga	LAC	2.3	(4)
1989 November 5	Ginga	LAC	1.8	(4)
1989 November 24	Ginga	LAC	2.8	(4)
1990 November 27	ROSAT	PSPC-B	2.5	(3)
1991 June 7 – 8	Ginga	LAC	3.6	(3)
1991 November 21	ROSAT	PSPC-B	5.8	(3)
1993 May 21 – 25	ROSAT	PSPC-B	1.3	(3)
1993 May 24 – 26	ROSAT	PSPC-B	1.5	(3)
1993 May 25 – 26	ASCA	GIS, SIS	1.7	(3)
1993 December 1	ROSAT	PSPC-B	1.0	(3)
1997 June 1 – 2	ASCA	GIS, SIS	3.5	(3)
1997 December 15 – 17	ASCA	GIS, SIS	3.5	(3)
1997 December 15 – 16	RXTE	PCA	4.0	(3)
1999 May 28 – 30	RXTE	PCA	1.8	(3)
1999 June 7 – 9	RXTE	PCA	1.8	(3)
1999 July 30 – August 3	RXTE	PCA	2.8	(3)
1999 November 3–5	RXTE	PCA	3.3	(3)

^a Calculated mean flux in units of 10^{-11} erg cm⁻² s⁻¹, in the energy range 2–10 keV.

^b References for the X-ray fluxes; (1) Piccinotti et al. (1982); (2) Turner et al. (1991); (3) this study; (4) Nandra & Pounds (1994).

0.1–2 keV ROSAT band ($\Gamma \sim 2.1$) and the typical 2–10 keV band ($\Gamma \sim 1.4 - 1.9$). Piro, Matt, & Ricci (1997) attempted to use various models aimed at simultaneously explaining both the Ginga and ROSAT data. We utilize their models to estimate the systematic error in the flux conversion from the PSPC count rate to the 2–10 keV flux. We find that the flux conversion factors change by ~ 20 % between the different models, if we take into account the observed range of power-law slopes (1.4 – 1.9) in the 2–10 keV band. Thus the converted ROSAT flux may include a systematic error as large as ~ 20 %.

In addition to these systematic errors, we also need to consider the cross-calibration error among the instruments. However, accurate instrumental cross-calibration is usually difficult, and quantitative estimations are not available for most of the satellites. Here, we assume 10 % as a representative value. Therefore, if

the 2–10 keV band is covered by the instruments, the systematic error in the flux conversion is probably dominated by the cross-calibration error among the instruments, and this may be estimated to be ~ 10 %. On the other hand, if the 2–10 keV band is not covered by the instrument, as in the case of the ROSAT PSPC, the systematic error in the flux conversion is dominated by the uncertainty in the spectral shape, and this may be as large as ~ 20 %.

(c) Long-Term X-ray Light Curve

The X-ray fluxes for the long-term light curve of MCG-2-58-22 are compiled in Table 1, and they are plotted in Figure 1 along with the above-estimated error bars. It is readily seen that the light curve shows at least two distinct characteristics, i.e., a gradual and secular decrease of the flux, and occasional abrupt in-

creases, or flares. The flux steadily decreases over a duration exceeding 15 years, from 1977 September to 1993 December. We draw attention to the 3 highest data points, as indicated by the arrows in the light curve, which occurred in 1983 November, 1991 June through November, and 1997 June through December, respectively. They are likely to have been flare events. The data points in 1999 could indicate an onset of another flare, or they could be a part of the 1997 flare. The flux increased by at least a factor of $\sim 2 - 4$ during the flares, as compared to the long-term trend of the secular flux decrease. The flares are not due to an underestimation of the cross-calibration error, since they can be identified even in data from a single satellite (multiple flare events occurred in 1983, 1991, and 1997 for EXOSAT, ROSAT, and ASCA & RXTE, respectively). Furthermore, the flares in 1991 and 1997 were observed by the imaging instruments, ROSAT and ASCA. This strongly suggests that MCG-2-58-22 is indeed the source of these flares. We also checked for whether these events could be due to artificial effects, such as background fluctuations, or solar X-ray contamination. We concluded that these flares are intrinsic to the source.

The flare durations, and the intervening intervals, may give important information on the origin of these events. However, it is difficult to accurately measure the true peak flux, and thus duration, of the flares, because of the sparse data sampling. Using the 1991 flare, whose rise is relatively well sampled, we estimate its likely duration to be ~ 2 years. Although the observations may have missed the true peaks, the flare amplitudes, measured relative to the secular decreasing trend, are rather similar, at a level of $\sim 4 \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$. A further interesting feature is that the flares may have occurred quasi-periodically; the time interval between the first and second flares is ~ 8 yrs, and it is ~ 6 yrs between the second and third flares. However, because the sampling is sparse, and includes long data gaps, further observations are needed to confirm this quasi-periodicity.

III. DISCUSSION AND CONCLUSION

As shown in Figure 1, MCG-2-58-22 clearly shows two characteristic variabilities: the gradual, secular decrease of the X-ray flux, and multiple flares with a representative duration of ~ 2 years. These two characteristic variabilities imply that the source undergoes at least two distinctly different physical processes. Magnetic reconnection may be considered as a mechanism for the flares, but it seems unlikely that this process could explain their duration and repetition frequency, since the magnetic field evolution timescale in an accretion disk is of order the dynamical time (Romanova et al. 1998; Poutanen & Fabian 1999). Another possible, and more likely, origin of the variabilities are the instabilities which could arise from the accretion disk. Such instabilities may result in the modulation of the

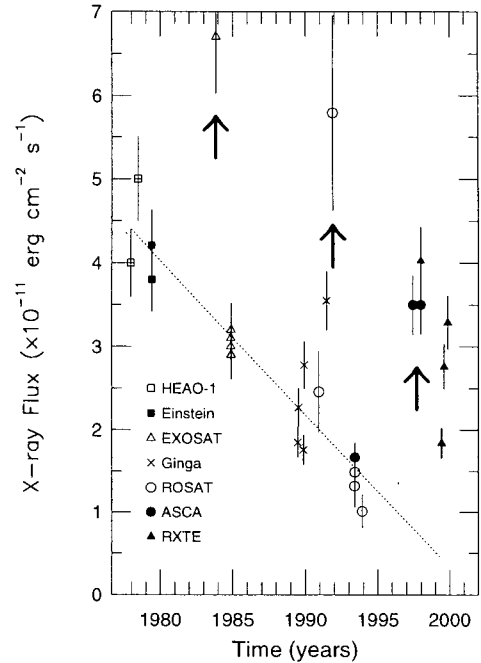


Fig. 1.— Long-term X-ray light curve of MCG-2-58-22 in the energy range 2–10 keV. Flux data are either taken from the references indicated in Table 1, or calculated in this study using a spectral fit to the data. Different symbols are used to distinguish the data from the various observatories. The short-dashed line, and the arrows, indicate the gradual, secular flux decrease, and the flares, respectively.

mass-accretion rate, leading then to the observed flux variations.

Disk instabilities which could be appropriate for the variabilities in MCG-2-58-22 are the viscous-thermal and the viscous instabilities. If the disk experiences a viscous-thermal instability caused by a sudden change in the hydrogen ionization state, we estimate the instability timescale to be $t_{\text{vis-th}} \sim 6 \times 10^2 (\alpha/0.1)^{-1} M_8^{1/3} (M/10^{-4} M_\odot \text{ yr}^{-1})^{1/3}$ yr, where M_8 is the SMBH mass in units of $10^8 M_\odot$. On the other hand, the viscous timescale near the innermost radius of the standard α -disk can be a few tens of years for a black-hole mass of $10^8 M_\odot$. Because these timescales are much longer than the observed duration of the flares, the viscous-thermal and the viscous instabilities are probably not the cause of the flares. However, the gradual and secular decrease of the X-ray flux has a longer timescale, and this slower variation could be caused by these types of disk instability.

Temporal increases of the mass accretion rate could arise, in principle, from other mechanisms. One entertaining possibility is the tidal disruption of stars by the

SMBH (e.g., Rees 1988; Lee & Kim 1996; Kim, Park, & Lee 1999). In this model, the frequency with which a star passes within a distance r from the SMBH can be estimated to be $\approx 10^{-3} M_8^{4/3} (N_*/10^6 \text{ pc}^{-3}) (\sigma/300 \text{ km s}^{-1}) (r/r_t) \text{ yr}^{-1}$, where N_* is the number density of the stars, σ is the virial velocity of the stars, and r_t is the tidal radius of the SMBH. Although the number density of the stars and their velocity dispersion near the SMBH are not known, the flare events we observed from MCG-2-58-22 may be difficult to interpret as independent tidal disruption events, because the event rate would then be too high. Instead, the resulting flares may be produced when the bound material from the tidally disrupted star returns to the pericenter, with an orbital period of a few years (Rees 1988; Ulmer 1999). The observed peak luminosity of $\sim 4 \times 10^{44} \text{ erg s}^{-1}$ for the flares corresponds to that from the debris of $\sim 0.1 M_\odot$ being swallowed steadily with 10 % efficiency over a year's duration. However, it is known that a star may be captured by the SMBH without tidal disruption, provided the SMBH is a Schwarzschild black hole heavier than $\sim 10^8 M_\odot$; this limit is comparable to previous estimates of the SMBH mass in MCG-2-58-22. If we consider a Kerr black hole, the tidal disruption may still be possible, depending on the trajectory of the approaching star (Beloborodov et al. 1992). Moreover, the atmospheres of giant stars could be stripped off before being captured by the SMBH, and this process may be the actual cause of the flares (e.g., Nolthenius & Katz 1982; Carter & Luminet 1983; Rees 1988; Laguna et al. 1993; Ulmer 1999). Thus, the observed flares are not inconsistent with those caused by the tidally disrupted stellar debris near the SMBH, even though the flare properties would depend on many unknown parameters, such as: the type of the disrupted star, the spin of the SMBH, and the minimum radius of the trajectory.

The long-term optical light curve of MCG-2-58-22 was obtained by Winkler et al. (1992), as a result of a 4-year campaign to monitor 35 southern Seyfert galaxies. The campaign period from 1987 through 1990 overlaps with the Ginga observations of 1989 and 1990. During this time, a clear variation of about 0.3 mag is reported in the V-band. Unfortunately, however, the optical light curve does not cover the time periods of the X-ray flares we detect, and it shows only gradual and smooth variations. Over this time, the X-ray flux varied by about 40 %. This is comparable to the 0.3 mag variations in the V-band. Thus, at least the fractional amplitude of the long-term variations may be similar between the optical and X-ray wavelength bands. It is difficult to ascertain whether the optical variation is physically related to that in X-rays, since the optical observation period is too short, compared with that of the X-ray light curve.

The variabilities we detected from MCG-2-58-22 may be reminiscent of the rapid time variations seen in the galactic black hole candidates (GBHCs). Phe-

nomenologically, the presence of a characteristic timescale is known both in GBHCs in the hard state, and in the SMBHs (Hayashida et al. 1998; Markowitz & Edelson 2001). In both kinds of sources, the characteristic timescale corresponds to the cutoff in the PDS, and this timescales may be scaled almost linearly with the black hole mass. The canonical galactic black hole, Cyg X-1, contains about $10 M_\odot$, and it shows a PDS cutoff at around ~ 10 sec. The PDS of Cyg X-1 may be reproduced by the superposition of shot noise impulses, whose typical duration determines the PDS cutoff frequency (e.g. Negoro, Kitamoto, & Mineshige 2001). If we assume that the SMBH in MCG-2-58-22 has a mass of $10^8 M_\odot$ (e.g., Padovani & Rafanelli 1998; Wandel 1991), the characteristic timescale is about a few years. This is just about equal to the duration of the flares we detected. Thus the flares in MCG-2-58-22 may be analogous to the shot noise seen in galactic black holes in their hard state.

In conclusion, we have detected two characteristic variabilities in the long-term X-ray light curve of MCG-2-58-22, by analyzing archival data from various X-ray satellites. One variation is the gradual, secular decrease of the X-ray flux, which may have a timescale of several decades, and the other is the flaring. Although it is difficult to accurately measure the duration of, and intervals between, the flares, due to the sparse sampling in the observational data, a representative duration is $\lesssim 2$ years, with an intervening interval of $\lesssim 6-8$ years. These two distinct timescales may be accounted for by a model with a supermassive black hole accompanied by an unstable accretion disk; the long-term secular variation would be expected from instabilities in the disk, while the short-term flaring would arise from the tidal disruption of stars by the supermassive black hole. Further observations and spectral analysis in other wavelength bands should be explored, in order to verify this scenario.

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