JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
34: 129 ~ 135, 2001

X-RAY ARCHIVAL DATA ANALYSIS OF TIME VARIABILITIES IN SEYFERT GALAXY MCG−2-58-22

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(Received Sep. 23, 2001; Accepted Oct. 16, 2001)

ABSTRACT

We report results from an analysis of the X-ray archival data on MCG−2-58-22 obtained with Ginga, ROSAT and ASCA. By analyzing both short- and long-term light curves, we find clear time variations, ranging widely from $\sim 10^3$ s to more than several years, in the X-ray energy range 0.1 − 10 keV. In addition, a flare is detected in 1991, overlaid on a gradual, secular flux decrease from 1979 to 1993; this flare has a time scale of about 1 year, and the X-ray flux increased by at least a factor of 3. The implications of these observational results are discussed in terms of accretion flow dynamics near a supermassive black hole.

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

I. INTRODUCTION

MCG−2-58-22 (Mrk 926) is an active galactic nucleus (AGN) classified as a Seyfert 1 or 1.2 galaxy (Whittle 1992; Kotilainen & Martin 1994), which is located at a luminosity distance of 287 ± 2 Mpc (at $z = 0.0473 \pm 0.0003$, see Huchra et al. 1993; this distance is calculated assuming a standard Friedmann-Robertson-Walker model, with $q_0=1/2$, $\Lambda_0=0$, and $H_0=50$ km s^{-1} Mpc^{-1}). Optical spectra of MCG−2-58-22 display very broad, asymmetric Balmer lines (Schlegel, Finkbeiner, & Davis 1998). In addition, this source showed a continuum variation on a ~ 1 yr time scale in the optical region (de Ruiter & Lub 1986; Whittle 1992) as well as a very wide variability in the profiles and luminosities of the Balmer lines (e.g., Winkler et al. 1992 and references therein). The mass of the putative central supermassive black hole (SMBH) of MCG−2-58-22 is estimated from the UV and optical observations to be a few times $10^8\ M_\odot$ (Padovani & Rafanelli 1988; Wandel 1991).

MCG−2-58-22 is a bright Seyfert in the X-ray region ($\sim 10^{44}$ erg s^{-1}), and hence various X-ray satellites have frequently pointed towards this source over a period of more than two decades. According to earlier observations, its X-ray luminosity is variable on time scales of a few months, and also on longer time scales of years, with variations from $\sim 1 \times 10^{44}$ to $\sim 4 \times 10^{44}$ erg s^{-1} (Marshall, Warwick, & Pounds 1981; Grandi et al. 1992). Many observational characteristics of this source are typical of Seyfert 1 galaxies in X-ray wavelengths: time variability, a power-law continuum spectrum, and a soft X-ray excess phenomenon (Ghosh & Soundararajaperumal 1992; Nandra & Pounds 1994; Weaver et al. 1995; Nandra et al. 1997a; George et al. 1998; Turner et al. 1999). In particular, Ghosh & Soundararajaperumal (1992) found a soft X-ray excess from the EXOSAT LE & ME data on MCG−2-58-22, which is variable on a time scale of a few days, and this excess flux correlates with the spectral slope. However, a detailed, systematic time variability study, covering a wide energy range from soft to hard X-rays, has not yet been made for this source.

Several variability studies for Seyfert 1 galaxies have revealed that the amplitude of rapid time variation anti-correlates, in general, with both the source X-ray luminosity, and with the central black hole mass (Barr & Mushotzky 1986; Green, McHardy, & Lehto 1993; Nandra et al. 1997a; Ptak et al. 1998; Turner et al. 1999; Lu & Yu 2001). One might expect little or no significant short time scale variability from MCG−2-58-22, as it is intrinsically X-ray luminous. However, our study clearly reveals that this source shows both short- and long-time scale variations, over a wide energy range from 0.1 to 10 keV.

In this paper, we investigate, in detail, the time variability of MCG−2-58-22 through the analysis of short- and long-term light curves. As described in Sections 2 and 3, we find apparent flux variations ranging from $\sim 10^3$ s to more than several years, over a wide energy range: 0.1 − 10 keV. Furthermore, a flare-like event is also found as a result of the long-term light curve analysis, presented in Section 3. The variabilities we ob-

Table 1. JOURNAL OF GINGA, ROSAT & ASCA OBSERVATIONS OF MCG−2-58-22

DATA[1]	OBSERVATION (DATE)	INSTRUMENT	EXPOSURE[2] (ks)	COUNT RATE[3] (c/s)
···	1991 June 7 – 8	LAC	27.2	20
rp700107	1991 November 21	PSPC-B	3.5	4.0
rp701250	1993 May 21 – 25	PSPC-B	18.7	0.9
rp700998	1993 May 24 – 26	PSPC-B	10.6	1.0
rp701364	1993 December 1	PSPC-B	2.2	0.7
ad70004000	1993 May 25 – 26	GIS, SIS	23.3	0.4
ad75049000	1997 June 1 – 2	GIS, SIS	26.3	0.9
ad75049010	1997 December 15 – 17	GIS, SIS	29.8	0.9

[1] The sequential number of the archival data set.

[2] Net exposure time after data screening. In the case of the ASCA observations, the exposure is from a single GIS.

[3] Mean source count-rate before background subtraction (except for the LAC). The background is subtracted from the LAC data. In the case of ASCA, the background is measured for a single GIS.

tained are discussed in Section 4, in terms of a model with a central SMBH accompanied by an accretion flow from its proximity. Finally, the conclusions are summarized in Section 5.

II. OBSERVATIONS AND DATA REDUCTION

A total of 5 LAC (Turner et al. 1989) observations of MCG−2-58-22 were made during the Ginga lifetime. Results from the first 4 observations in 1989 have been published by Nandra & Pounds (1994). Here, we analyze the last observation, made in 1991, which is unpublished. The journal of this, and the other ROSAT and ASCA observations, is given in Table 1. The data were retrieved from the SIRIUS database at the Institute of Space and Astronautical Science (ISAS) in Japan, and they were reduced using a main-frame computer. Standard screening criteria were applied to the data, as well as to nearby blank-sky observations; these had been made one day before, and were used for the background subtraction. Because the data were obtained with relatively low collimator transmission ($\sim 0.2-0.6$), we corrected for the collimator reflection effect in our analysis (e.g. see Turner et al. 1989).

ROSAT PSPC (Pfeffermann et al. 1986) observations of MCG−2-58-22 were made 4 times during the period 1991 to 1993, as listed in Table 1. The ROSAT data were retrieved through the High Energy Astrophysics Science Archive Research Center (HEASARC) on-line service, provided by the NASA/Goddard Space Flight Center (GSFC). Among the available observations, the two data sets of 1991 November 21 (rp700107) and 1993 May 21 (rp701250) have been partially analyzed, and the results were published in, for example: Turner, George, & Mushotzky (1993) and Piro, Matt, & Ricci (1997). In our study, all the currently available data are included. The reduction of these data was done using the FTOOLS v4.2 software package (Turner 1996). Source photons are obtained from a circular region of about $2'$ radius centered on the source, and the background is obtained from annular, source-free regions within the same field of view.

ASCA observations of MCG−2-58-22 were made 3 times in the period 1993 to 1997 (Table 1). Some results from the 1993 ASCA data have been published by several researchers, including Weaver et al. (1995), Reynolds (1997) and Nandra et al. (1997a, 1997b). However, both the 1997 June and December data have not yet been published. Descriptions of the ASCA instruments may be found in Burke et al. (1993) for the Solid-State Imaging Spectrometers (SIS0 & SIS1), in Ohashi et al. (1996) and Makishima et al. (1996) for the Gas Imaging Spectrometers (GIS2 & GIS3), and in Serlemitsos et al. (1995) for the X-ray telescope (XRT). We retrieved all the available ASCA data from the HEASARC public archives. In order to avoid possible X-ray contamination from the bright Earth, and from regions of high particle background, we apply the following data-screening criteria: (1) data are excluded when the pointing direction of the telescope is less than 30° (SIS) and 8° (GIS) from the Earth's limb; (2) only regions where the radiation-belt monitor has a count-rate less than 300 counts s^{-1} are taken for the SIS; and (3) regions of cutoff rigidity greater than 10 GeV are selected for both the SIS and GIS. Hot and flickering pixels are removed from the SIS data. Then, we obtain source photons from a circular region of about $4'$ radius centered on the source. For the background subtraction, we use high-latitude, blank sky data, which is publicly available.

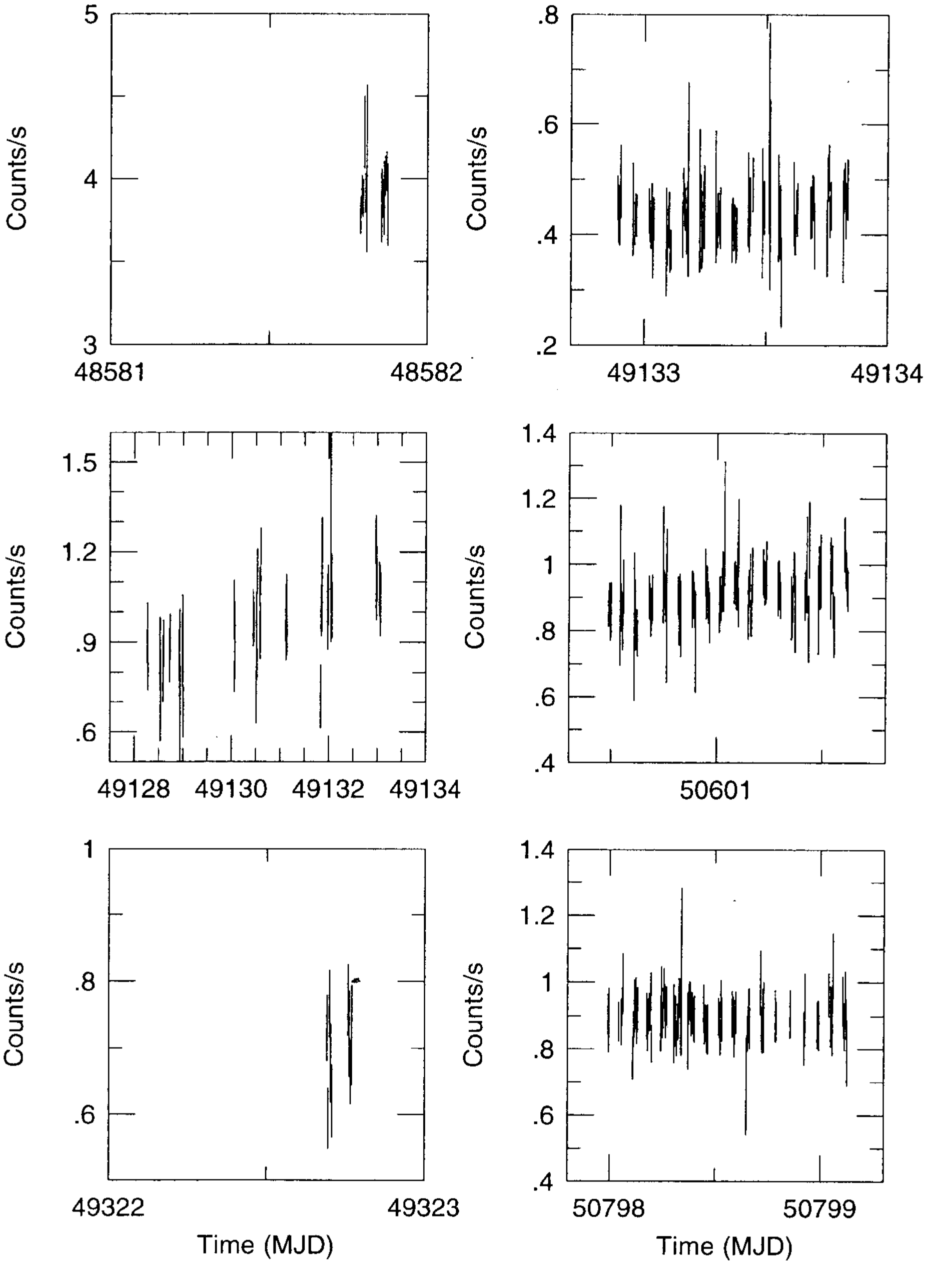

Fig. 1.— X-ray light curves of MCG−2-58-22 obtained from the ROSAT PSPC (left panels; 0.1 – 2.0 keV) and the ASCA GIS (right panels; 0.8 – 10 keV). Data from GIS2 and GIS3 are averaged in the plots. All the light curves are made with data binned in 300 s intervals. The backgrounds, which are negligible in the plots, were not subtracted from the data.

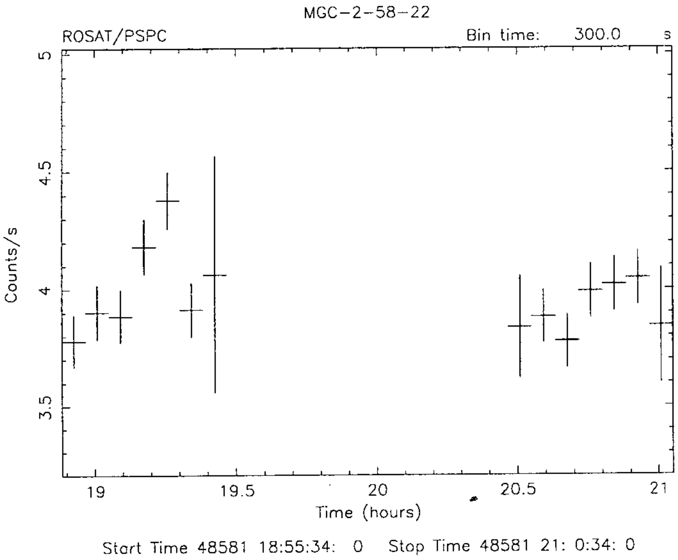

Fig. 2.— ROSAT PSPC light curve of MCG−2-58-22, extracted from the data of 1991 November 21. Data are binned in 300 s intervals. This figure clearly shows that there is an ultra-rapid flux variation at an observation time of 19.2 hr.

III. LIGHT CURVES AND TIME VARIABILITIES

(a) Short Time Variability

Figure 1 shows six light curves obtained from the ROSAT PSPC data (left panels; 0.1 – 2.0 keV) and the ASCA GIS data (right panels; 0.8 – 10 keV). We do not show the Ginga LAC data, because they are not useful for analyzing the short-term light curve, due to poor count statistics. In this figure, the GIS2 and GIS3 data were averaged, and each data point is the result of binning in 300 s intervals. The X-ray backgrounds, which are negligible in the plots, were not subtracted.

X-ray flux variations are immediately noticeable in some of the light curves, e.g., in the left- and right-middle panels. To evaluate the significance of these flux variations, we performed a reduced-χ^2-test against a constant flux hypothesis, and obtained $\chi^2_\nu \equiv \chi^2/\nu$ (where ν is the number of degrees of freedom) = 325.2/110 and χ^2_ν = 149.6/98, respectively, for the ROSAT light curve of 1993 May 21−26 (left-middle panel) and for the ASCA light curve of 1997 June 1−2 (right-middle panel). These χ^2_ν values indicate that the observed fluxes are variable in these light curves, and that the variations are statistically meaningful. To consistently compare our results with those of other Seyfert 1 galaxies, we also calculate the normalized excess variance $\sigma^2_{\rm rms}$, as defined in Nandra et al. (1997a), for these two light curves. The results are $\sigma^2_{\rm rms} = (1.2 \pm 0.1) \times 10^{-2}$ and $(4 \pm 2) \times 10^{-4}$ for the ROSAT and ASCA light curves, respectively, in their full energy bands; this implies that there exist significant time variations. We checked for the occurrence of both attitude drift, and background variation, during these observations, and concluded that the flux variations are intrinsic to the source. This implies that the X-ray flux from MCG−2-58-22 is variable on a time scale of days, in both the ASCA and ROSAT energy bands. We also performed the χ^2_ν test for the remaining ASCA and ROSAT light curves, but obtained little or marginally significant variations (e.g., $\chi^2/\nu = 103.9/87$ and 106.6/102 for the 1993 May and 1997 December ASCA data, respectively).

We next examined for rapid time variability in the light curves, through a careful visual inspection, as such variability is difficult to detect through the χ^2_ν test alone, due to the fact that it may sometimes exist in only a small number of time bins. Based on this further inspection, we found an "ultra-rapid" flux variation in the 1991 November 21 light curve, as shown in Figure 2. It is clear from this figure that there is a sudden increase and decrease of flux, from 3.9 counts $\rm s^{-1}$ to 4.4 counts $\rm s^{-1}$ and back, at an observation time of $\sim$ 19.2 hr. This variation has a total duration of $\sim 10^3$ s. In order to investigate whether this variation is associated with background fluctuations, we checked the background count-rates extracted from the source-free region. We found that the background was stable during the variation.

(b) Long Time Variability and Flare

As seen in Figure 1, the X-ray flux level exhibits a relative variation by a factor of 2 – 4 over a period of a few years, in both ROSAT and ASCA data. To examine these variations in detail, we made a long-term light curve which covers a total of about 18 yrs (Figure 3). Since the instruments of various satellites 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. For this light curve, after background subtraction for each data set, we calculated the X-ray fluxes (in 2 – 10 keV) using a spectral model consisting of a simple power-law with photon index Γ = 1.75, and with a hydrogen equivalent absorption column density of $N_H = 3.5 \times 10^{20}$ $\rm cm^{-2}$ along the line of sight to the source (e.g., Weaver et al. 1995; Piro, Matt, & Ricci 1997). Some X-ray flux data for MCG−2-58-22 have also been taken from the literature (see the caption for Fig. 3), and from the ROSAT all-sky survey observations (Voges et al. 1999). The systematic error associated with the flux conversion, which is largest in the ROSAT data, is estimated to be $\sim$20 %.

The combined time sequence of X-ray fluxes is shown in Figure 3. It is readily seen that there is a gradual, secular decrease of flux from 1979 through 1993. Of particular interest is the apparent flare-like event occurring in 1991. Note that there are 2 data points, one

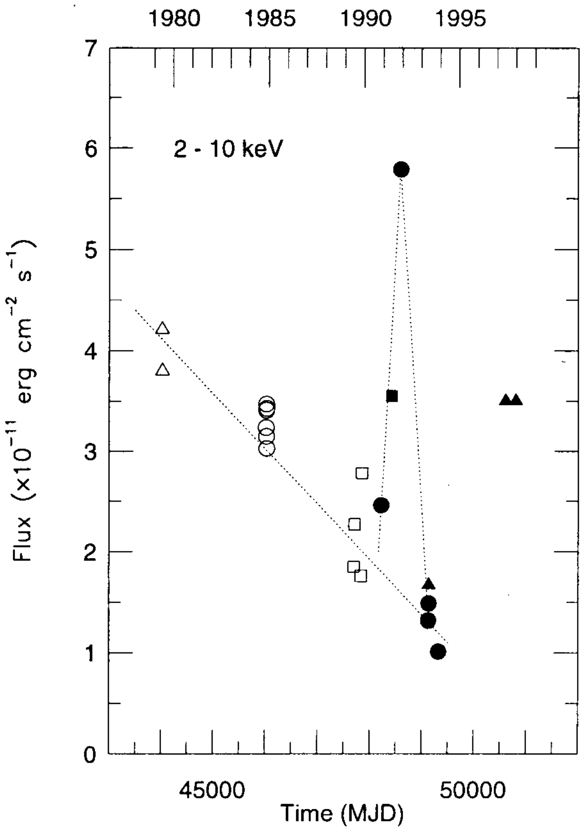

Fig. 3.— Long-term X-ray light curve of MCG−2-58-22 in the 2 – 10 keV range. Open symbols represent the flux data adapted from the literature: Turner et al. (1991; *open triangles*), Ghosh & Soundararajaperumal (1992; *open circles*), and Nandra & Pounds (1994; *open squares*). The *filled squares*, *filled circles*, and *filled triangles* represent the data from Ginga, ROSAT, and ASCA, respectively, as calculated in the current study. The 2 *dotted lines* indicate the gradual, secular flux decrease, and the flare, respectively. The systematic error associated with the flux conversion, which is largest in the ROSAT data, is estimated to be ∼20 %.

from Ginga (*filled square*), and the other from ROSAT (*filled circle*), which together strongly indicate that there indeed was flaring activity. During this event, the flux increased by about 3 times compared with the level expected from the gradual, secular flux decrease. It is difficult to accurately calculate the true peak flux and duration of the flare, since we have only 2 data points for the flare itself. We roughly assess that the actual duration of the flare is less than a few years, and that the peak flux level is higher by at least 3 times the level expected from the gradual decrease.

We also checked for whether the flare-like event could be due to an artificial effect. By referring to the Sun angles, and inspecting the energy spectra, we ruled out the possibility of solar X-ray contamination. For example, the Sun angle was greater than 90° during the Ginga LAC observation. Also, two strong spectral components that characteristically appear at ∼ 0.2 keV and ∼ 0.5 keV in the solar X-ray spectrum (e.g., Prieto, Hasinger, & Snowden 1996) were not visible in the ROSAT PSPC data. The gain error in the PSPC cannot explain the magnitude of the flux increase we detected. It is important to note that the apparent flare is real; it shows much too large a flux increase to be due to a systematic error in the flux conversion. The flux variation is seen in both the ROSAT and Ginga data points. Therefore, we conclude that the flare-like event is intrinsic to the source.

IV. DISCUSSION

Long time scale modulations in AGN light curves are well studied in the optical range. The long-term X-ray light curve of MCG−2-58-22 that we obtained appears interestingly similar to some of the optical light curves. The large amplitude flare and gradual long time scale modulation could imply that this system is undergoing at least two distinctly different physical processes. Webb (1990) reported the results of 61 yrs of optical observations of the Seyfert galaxy 3C 120, and claimed that the variations are composed of a gradual and possibly sinusoidally variable component, with period 12.43 yrs, accompanied by high amplitude flares on much shorter time scales. This behavior is very similar to the long time scale X-ray variations in MCG−2-58-22. It is also interesting to point out that Dibai & Lyütyi (1984) claimed that AGN such as NGC 3516, and others, essentially have two variability time scales: 10 – 30 d flares and 10 – 30 yr sinusoidal variations. Thus, variations with these two different time scales may be common in Seyfert AGN.

The flare we detected in 1991 could have been caused by a temporary increase in the mass accretion rate onto the central black hole. We found that the shape of the energy spectrum (especially the power-law slope) did not change much during the flare; the change was mainly in the normalization. Thus, the flare may be considered to reflect a real increase in the source luminosity. Such a temporary increase may be related to the thermal or viscous instabilities in the X-ray emission region of the accretion disk. Although the relevant parameters, such as the mass of the central black hole, the disk radius where the instability occurs, and the viscosity, are not well known, the time scale of these instabilities could be of order ∼ 10 yrs. However, it is unclear what triggers such thermal or viscous instabilities. One possible mechanism is the disruption of stars in the tidal field of the SMBH (e.g., Cannizzo et al. 1990; Lee & Kim 1996; Kim, Park, & Lee 1999). In a closely related scenario, a star could plunge into the accretion disk, causing drag-heating in the disk, leading to a sudden episode of heating and emission (e.g., Hall et al. 1996, and references therein). The frequency, duration, and intensity of such encounters depend on many dynamical as well as other details, such as plasma physics, all of which are beyond the scope of this paper.

As in some Galactic binary systems, the accretion disk could have a hot corona which Compton-upscatters the lower energy photons emitted by the accretion disk. Any such coronal model for X-ray emission requires an electron acceleration mechanism, such as magnetic flares, or dissipation driven by magnetic field buoyancy and reconnection. Such processes are inherently flare-like, and occur on relatively short time scales (e.g., Di Matteo, Blackman, & Fabian 1997). Similar processes may cause flare-like events in AGN, with a time scale of many years.

We also detected flux variations from MCG−2-58-22 on a time scale of days. In addition, there are ultra-rapid variations as short as 10^3 s. It is known that there is a good anti-correlation between the amplitude of X-ray variations and the X-ray luminosity of Seyfert 1 galaxies (Nandra et al. 1997a; Turner et al. 1999). According to these studies, little short time scale flux variation is expected from MCG−2-58-22, as this is a luminous Seyfert ($L_{2-10\ \mathrm{keV}} = 1-4\times10^{44}$ ergs s^{-1}). The normalized excess variance is expected to be $\sigma^2_{\mathrm{rms}} \sim 10^{-3}$ for sources with luminosities comparable to MCG−2-58-22 (Nandra et al. 1997a). Although our calculation of the variance was performed in a slightly different bin width to that of Nandra et al., we clearly detected flux variations in the 1997 June ASCA data, which has a variance of $\sigma^2_{\mathrm{rms}} = (4 \pm 2) \times 10^{-4}$. This is about the expected variance for MCG−2-58-22. On the other hand, the flux variations we detected from the 1993 May ROSAT data have a larger variance: $\sigma^2_{\mathrm{rms}} = (1.2 \pm 0.1) \times 10^{-2}$. Nandra et al. (1997a) found evidence that the variation amplitude below 2 keV is larger than that in the hard X-ray band. They conjectured that this may indicate that there exist additional variable components in the soft band, in addition to the underlying power-law component. Our detection of larger flux variations in the ROSAT data supports their conjecture. We have clearly detected an ultra-rapid variation ($\sim 10^3$ s) in the ROSAT data. This may be related to the relatively larger variation amplitudes observed below 2 keV. Thus, these soft X-ray variable components, in addition to having larger amplitude swings, may also be ultra-rapid.

It is difficult to estimate even an approximate mass value for the central SMBH, solely from the duration of a single ultra-rapid X-ray variation. However, we may proceed to roughly estimate a range of possible SMBH masses, given an assumed accretion and flaring scenario, as follows.

We adopt the assumption that the origin of the ultra-rapid time variation is from a point near a central SMBH. Such ultra-rapid variations associated with an accreting black hole would be expected to occur in the immediate vicinity of the inner boundary region of the accretion disk, which probably lies near the radius R_{MS} of the innermost (marginally) stable circular orbit around the black hole. Depending on whether the black hole has significant spin angular momentum, and on whether the inner disk boundary is in retrograde or prograde motion, the marginally stable circular orbit could lie anywhere in the range $0.5 < R_{MS}/r_g < 4.5$, where $r_g = 2GM/c^2$ is the event horizon radius for a Schwarzschild black hole. The light-crossing time of the X-ray flaring region is limited, by causality, to be smaller than the observed flare duration, so the radius R_{FLARE} of an assumed circular X-ray flaring patch should be no larger than ~500 light-seconds (see Fig. 2). If we further assume that this light-crossing time is comparable to the inner disk dynamical time scale (i.e. the Keplerian orbital period), then the ratio R_{FLARE}/r_g will not be very far from unity. To be more precise, if the origin of the flare is close to the SMBH, we may expect the ratio R_{FLARE}/R_{MS} to be close to unity; for the sake of our crude estimation, we assume $0.5 < R_{FLARE}/R_{MS} < 2.0$. Given this scenario, and all its attendant assumptions, it is straightforward to translate the upper limit on the flare patch radius R_{FLARE} to an upper limit on the SMBH mass M. Within the limits of the stated assumptions and observational uncertainties, we estimate from the observed ultra-rapid variation that the black hole mass lies in the range $4 \times 10^6 M_\odot \lesssim M \lesssim 3 \times 10^8 M_\odot$. This result is consistent with previous (also uncertain) estimates (e.g., Padovani & Rafanelli 1988 and Wandel 1991).

V. CONCLUSION

We have analyzed Ginga, ROSAT and ASCA archival data on MCG−2-58-22, including all available unpublished data. From an analysis of the long-term light curve spanning 18 yrs, we find that this source has undergone a gradual and secular decrease of X-ray flux from 1979 to 1993, as well as an X-ray flare. This flare had a duration of ~1 yr, and the flux increased by at least a factor of 3. In addition, short time scale variations ranging from $\sim 10^3$ s to days are detected from our analysis of the ROSAT and ASCA light curves, confirming earlier results. In particular, ultra-rapid variations having a time scale of $\sim 10^3$ s, and a relative amplitude of about 10 %, are detected for the first time in MCG−2-58-22, in this study. We conclude that these variabilities could be explained in the context of a SMBH model, with accompanying accretion flow dynamics near the central black hole.

This research has made use of data obtained through the HEASARC on-line service provided by NASA/GSFC, and also data from the SIRIUS database of ISAS in Japan.

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