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DISCOVERY AND X-RAY PROPERTIES OF GS 1124−683 (=NOVA MUSCAE)

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ABSTRACT

A bright X-ray nova: GS 1124−683 was discovered by the All Sky Monitor (ASM) on board *Ginga* on 1991 January 8. X-ray properties observed with the ASM from 1991 January 5 to the end of August are presented. The observed spectra were roughly described by a two-component model consisting of a power-law (a hard X-ray) and a disk-blackbody or a blackbody (a soft X-ray) component. In its rising phase, the hard X-ray component appeared first and the soft X-ray component followed with increase of the temperature and the emission area. After the maximum, the intensity of the energy range 1–6 keV decayed exponentially with a time constant of 31.2 ± 0.1 days, whereas the hard component fell off more rapidly with a time constant of ~ 13 days. The state where the hard component has an appreciable fraction of the energy flux can be recognized as a very high state, which is observed in GX 339−4. With the decay of the hard X-ray component, GS 1124−683 would transfer to the so-called high state. The decay of the soft component can be interpreted to be due to the decrease of temperature of the soft X-ray component. On 70 days after the maximum, a hump of the intensity was observed. About 140 days after the maximum the spectrum becomes hard and would change into the so-called low state. Similar behaviors are observed from two ultrasoft transient sources, A0620−00 and GS 2000+25, therefore such behaviors are considered to be common for bright ultrasoft transient sources.

Subject headings: black hole physics — novae, cataclysmic variables — stars: individual (Nova Muscae 1991) — X-rays: stars

1. INTRODUCTION

An X-ray nova: GS 1124−683 was discovered with the All Sky Monitor (ASM) on board *Ginga* on 1991 January 8 (Makino & the *Ginga* team 1991). This source was also independently discovered with the WATCH telescope on board *GRANAT* on 1991 January 9 (Lundt & Brandt 1991).

Although more than 10 bright ultrasoft or soft transient sources have been discovered so far (e.g., Cominsky et al. 1978; Priedhorsky & Holt 1987; Tsunemi et al. 1989; Kitamoto et al. 1990), their nature and also the cause of their appearance have not yet been understood well. The spectral study at the rising phase of a bright X-ray nova: A0620−00 was reported by Ricketts, Pounds, & Turner (1975). They found apparent hard spectra during the rising phase. Kitamoto et al. (1984, 1990) also reported the hard spectra during the rising phase of two ultrasoft transient sources: 4U 1543−47 and GS 1354−64.

The decay phases of the soft and ultrasoft transient sources have been rather well investigated. Tsunemi et al. (1989) pointed out the similarity of the decay between two bright ultrasoft transient sources: A0620−00 and GS 2000+25. Tanaka (1989) and Kitamoto et al. (1990) also pointed out the similarity of the decay time of several bright ultrasoft or soft transient sources. Existence of a hump in the decay phase of GS 2000+25 and A0620−00 (Tsunemi et al. 1989; Matilsky et al. 1976; Kaluzienski et al. 1977) is also a notable phenomenon.

GS 1124−683 is a bright ultrasoft transient source, which reached its maximum X-ray flux of ~ 8 Crab in the energy range 1–6 keV on 1991 January 15. The object was identified as a star of $m_V \sim 13.5$ and the distance to this source was estimated to be 1.4 kpc (Della Valle, Jarvis, & West 1991a, b). GS 1124−683 was extensively observed in broad bands from radio to hard X-rays. Kesteven (1991) reported a detection of variable radio emission. *IUE* data showed a bright ultraviolet spectrum (Shrader & Gonzalez 1991) and *ROSAT* observed soft X-rays (Greiner et al. 1991) and extreme ultraviolet (Kellett 1991). Hard X-rays up to 1300 keV were observed with the ART-P and Sigma telescopes onboard *GRANAT* (Gilfanov et al. 1991; Sunyaev et al 1991) and anomalously hard spectra and hard transient features around 500 keV were detected. The medium energy X-rays from 1 to 37 keV also observed by the Large Area Counters (LAC) and the ASM onboard *Ginga* (Tanaka 1991a). Especially spectra during the rise phase were observed only with the ASM. All of the characteristics are very similar to that of A0620−00, which is considered to contain a black hole (McClintock & Remillard 1986). Thus GS 1124−683 is considered to be a black hole candidate.

In this work, the intensity and the spectral evolutions of this source observed with the ASM, from the discovery on 1991 January 8 to the end of August when the flux decayed to the detection limit of the ASM, are presented. Some implications about the accretion phenomenon during the X-ray nova activity are briefly described.

2. OBSERVATION

The ASM (Tsunemi et al. 1988) on board *Ginga* (Makino & the Astro-C team 1987) consists of six proportional counters with differently tilted fan beam collimators (1° × 45°). The effective area at the center of the field of view is 70 cm^2 for each of the counters. The energy range of the detectors is 1–20 keV and is divided into 16 energy channels. The satellite rotates once in 20 minutes for the scanning observation with the ASM, which is normally performed about once per day. In each scan, the ASM can localize a source position to better than 0°.5 at a detection limit of ~ 50 mCrab.

A bright X-ray transient; designated GS 1124−683 was discovered on 1991 January 8 in the constellation Musca, when the ASM scanned the sky during the routine monitoring (Makino & the *Ginga* Team 1991). This new transient source was observed by the ASM from January 8 in its rising phase to the end of August when the flux was around the detection limit of the ASM. The follow-up scanning and pointing observations with the Large-Area Proportional Counter (LAC) (Turner et al. 1988) were also performed on and after 1991 January 10. Results with the LAC observations will be published elsewhere.

3. ANALYSIS AND RESULTS

3.1. *Light Curve*

Figure 1 shows a light curve in the energy range 1–6 keV and hardness ratios of GS 1124−683 together with those of GS 2000+25. Similarity of these sources is evident and will be discussed in § 4.1. On January 5, the ASM scanned the region of GS 1124−683 but did not detect a significant flux, with a 90% upper limit of 50 mCrab (0.1 counts s^{-1} cm^{-2}) in 1–6 keV energy range. On January 8, the intensity was 0.8 Crab (1.6 counts s^{-1} cm^{-2}) in the same energy range. After January 8, the flux gradually increased and on January 15, the flux reached its maximum of 8 Crab (16 counts s^{-1} cm^{-2}) in 1–6 keV. The light curve in the decay phase until ~ 70 days after the maximum is roughly represented by an exponential function with a time constant of 31.2 ± 0.1 days. About 70 days after the maximum, the second flare-up of about factor of 2 occurred on the slope of the monotonous decay. After this second flare, the flux again decayed exponentially with a time constant of $\sim 21.9 \pm 0.1$ days. The hardness ratios; I(6–20 keV)/I(1–6 keV) show monotonous decays since the start of the outburst, at least until 50 days after the maximum. It is notable that even in the rising phase the softening of the energy spectrum was observed. After 140 days from the maximum, the hardness ratio becomes large again.

The maximum luminosity on January 15 is calculated as

$$L(1\text{–}20\ \text{keV}) = (5.72 \pm 0.94) \times 10^{37} (D/1.4\ \text{kpc})^2\ \text{ergs s}^{-1} ,$$

where D is the distance to GS 1124−683 in kpc. The distance of 1.4 kpc is based on the estimation by Della Valle et al. (1991b). Assuming the exponential decay with a time constant of 31.2 days, the total energy during this outburst is

$$E_{\text{total}}(1\text{–}20\ \text{keV}) \sim 1.5 \times 10^{44} (D/1.4\ \text{kpc})^2\ \text{ergs} .$$

3.2. *Spectral Fittings*

Energy spectra with 16 channel in the energy range 1–20 keV were obtained with the ASM. Figure 2 shows some examples of the observed energy spectra, where upper four channels were summed up. During the rising phase (see Fig. 2*a*), apparent softening is recognized. After the maximum, the spectrum becomes still softer (see Fig. 2*b*), which is also recognized from the hardness ratio history in Figure 1.

The spectra were first fitted by four simple one-component models (a blackbody, a thermal bremsstrahlung, a power-law, and a disk-blackbody [Mitsuda et al. 1984]). The spectra obtained in the rising phase (January 8 and January 10) are roughly represented by a power-law model with a photon index ranging from −1.9 to −2.5 and other models are statistically excluded. On the other hand, the spectra obtained in the decay phase (after March) are represented by a blackbody or a disk-blackbody model rather than the power-law model. Although the ASM data cannot distinguish these two models,

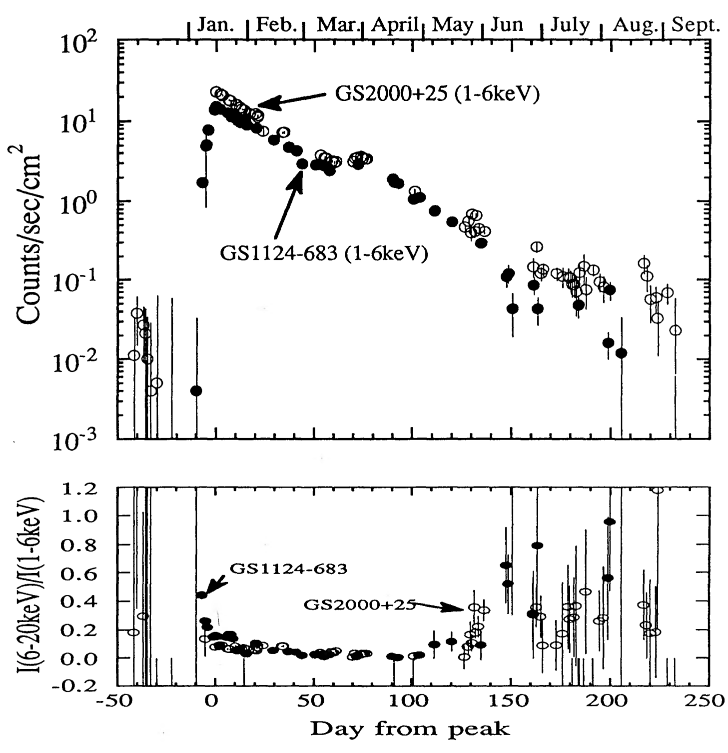

FIG. 1.—Light curves and hardness ratio histories of GS 1124−683 (Nova Muscae 1991) observed by the ASM 1991. Those of GS 2000+25 are also shown. The energy range of the light curve is 1–6 keV and the hardness ratios is I(6–20 keV)/I(1–6 keV). The peak day for GS 1124−683 is defined on 1991 January 15 from the ASM data.

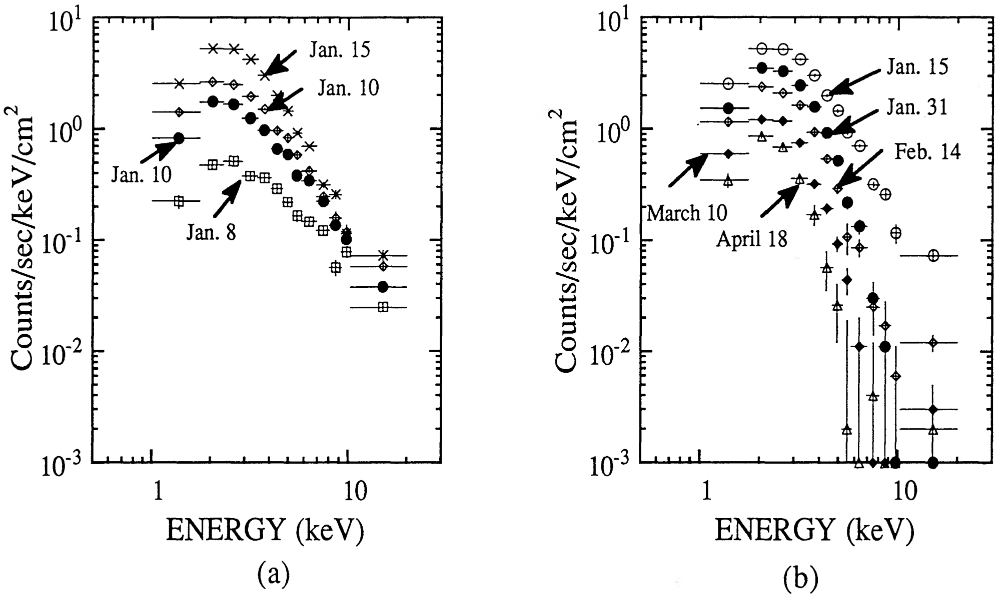

FIG. 2.—The examples of the energy spectra of GS 1124−683 obtained by the ASM. The spectra during the rising phase (*a*) and some typical spectra during the decay phase (*b*) are shown.

the LAC data indicate that the blackbody model can be discarded (Tanaka 1991b).

Thus, a two-component model consisting of a power law and a disk-blackbody was used to fit the data. Here the interstellar absorption column was fixed to be 10^{21} H atoms cm^{-2}, because all the one-component models required the interstellar absorption column less than 10^{21} H atoms cm^{-2} and the detectable column density of the ASM was several times greater than this value. This model can roughly represent all the spectra, although it cannot be statistically accepted for the spectra around the maximum. The results show large scatter of the power-law index with large error, because of the poor statistics of the data above 10 keV. For the next step, the power-law index was fixed to -1.9, which is the best-fit value (1.88 ± 0.09) of the one-component power-law model for the data on January 8. All the data can be fitted by this model with the χ^2 values (0.5–3 except for the data around the maximum), which is similar to those of the previous procedure where the power-law index is a free parameter. Obtained parameters (inner disk radii and temperatures of the disk-blackbody component and normalizations of the power-law component [power-law scale]) are plotted in Figure 3. Around the maximum (January 15) the power-law component contributed $\sim$41% in the observed flux in the energy range 1–20 keV. For $\sim$20 days after the maximum, the power-law component decayed steeply and at 30 days after the maximum it almost disappeared. Although this power-law component is highly variable (see Gilfanov et al. 1991), if an exponential decay is assumed the decay time constant is $\sim$13 days.

The temperature and the inner disk radius of the disk-blackbody component became higher and larger during the rising phase. After the maximum, the inner disk radius kept almost constant value of $10(D/1.4\ \mathrm{kpc})[\cos(i)]^{-0.5}$ km where i was the inclination angle. On the other hand, the temperature gradually decreased. Around the second flare, both the temperature and the inner disk radius are rather constant against the overall monotonous decay of the temperature.

4. DISCUSSION

4.1. *X-Ray Light Curve*

The existence of the common decay time constant in the X-ray light curves of the ultrasoft and soft transient sources has been pointed out by several authors (Tsunemi et al. 1989; Tanaka 1989; Kitamoto et al. 1990). Especially, two well-studied bright ultrasoft X-ray novae; A0620−00 (Kaluzienski et al. 1977) and GS 2000+25 (Tsunemi et al. 1989), have a similar decay time constant of 30 days, and this time constant is again similar to this bright ultrasoft source; GS 1124−683. The rise time also seems to be similar to each other, because all these three sources reached the maximum intensity in 6–10 days. The ASM did not detect a precursor of GS 1124−683 due to a poor sampling rate, although the precursor was observed 6–7 days before the maximum of A0620−00 (Elvis et al. 1975).

The second flare in the decay phase, $\sim$70 days after the maximum, is also a common phenomenon observed in the three sources. In the cases of GS 2000+25 and of A0620−00 the second flares occurred $\sim$70 days and $\sim$50 days after the maximum, respectively. Therefore, it is concluded that the second flare in not accidental but should be considered to be a common phenomenon in ultrasoft transient sources. After the second flare, the decay time of GS 1124−683 becomes short. Similar behavior was reported for A0620−00 by Kaluzienski et al. (1977) and can be recognized for GS 2000+25 from Figure 1.

The luminosity even at the maximum is smaller than the Eddington limit and is less than half of it, assuming the mass of the compact star of greater than 1.4 $M_\odot$ and the distance of $\sim$1.4 kpc (Della Valle et al. 1991b).

4.2. *Spectral Evolution*

In the decay phase, if the X-ray energy spectra are simulated by a power-law model, the best-fit index ranges between 3 and

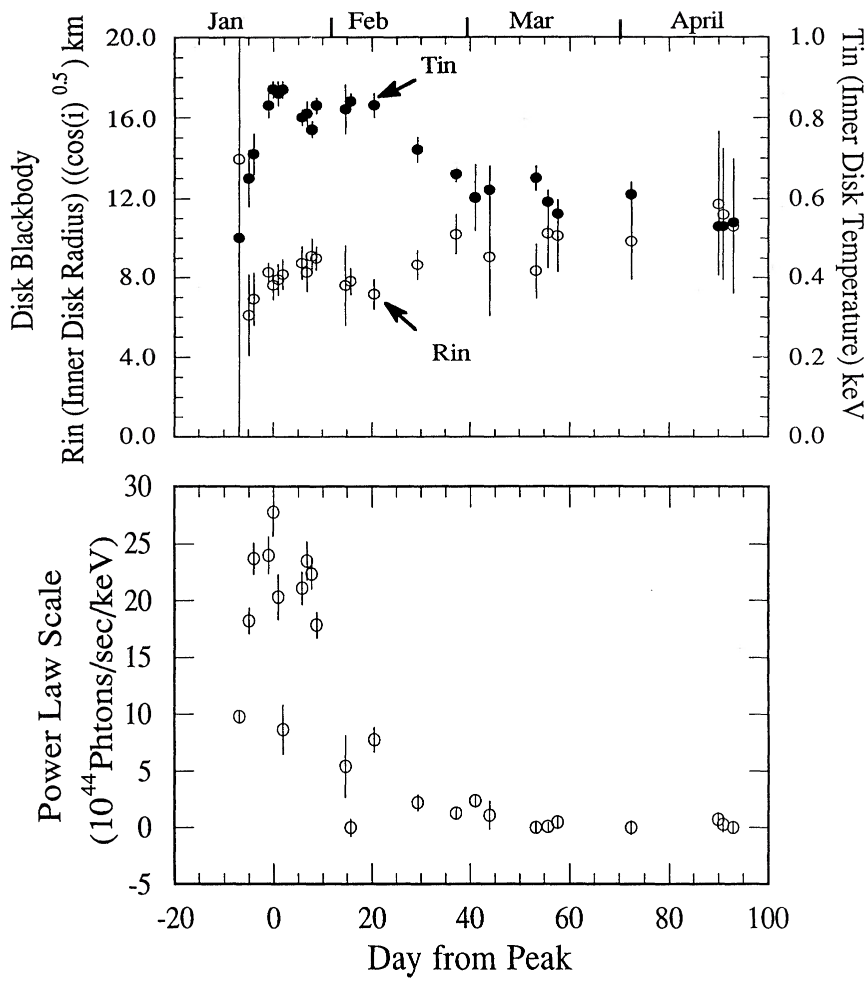

FIG. 3.—The evolution of the best-fit parameters of the model spectra consisting of a disk-blackbody component and a power-law component. The power index and the interstellar absorption column are fixed to 1.9 and 10^{21} H atoms cm^{-2}, respectively.

4.4. This value is similar to that of GS 2000+25 (4.39 $\pm$ 0.04) (Tsunemi et al. 1989) and that of A0620−00 ($\sim$4–5) (Ricketts et al. 1975), and indicates that this source belongs to ultrasoft sources (White & Marshal 1984).

On January 8 in the rising phase, the spectra is represented by a power-law model with a power index of 1.9. A0620−00 (Ricketts et al. 1975) also showed similar hard spectra during the rising phase. The indications of the hard spectrum in the early rising phase of other two ultrasoft transient sources, 4U 1543−47 and GS 1354−67, have been reported (Kitamoto et al. 1984, 1990). Thus this is also interpreted to be a common phenomenon of the ultrasoft transient sources. Gilfanov et al. (1991) reported that the maximum of intensity in hard X-rays were reached significantly earlier than in 1–20 keV band. Especially strong hard X-rays above 30 keV were observed on 1991 January 10, and an indication of the existence of these hard X-rays was also found in the data on January 8–9. This component sharply dropped more than one order of magnitude within 1 week. Probably these hard X-rays relate to the power-law component, which we observed in the early phase. However, the light curve of the power-law component is somewhat different from those of the hard X-rays $\sim$30 keV and exhibits no clear peak and no sharp drop comparing the hard X-ray light curve. The photon index determined from the ASM at the rising phase on January 8 was 1.88 $\pm$ 0.09, and this value is significantly different from the photon index of $\sim$2.5 determined above 30 keV, although around the peak and after the peak the ASM data cannot determine the photon index and the value of 2.5 is consistent with our data. These facts indicate an apparent spectral softening of the power law component below the 30 keV during the rise phase, although Gilfanov et al (1991) claimed that no changes of spectral shape in 35–200 keV band had occurred.

Around the maximum, the spectra cannot be represented by simple one-component models. The two-component model consisting of a power law and a disk-blackbody (or a blackbody) model can roughly simulate all the spectra, although the determination of the power index is statistically difficult. Based on the two-component model, the results indicate that at the early phase of the outburst a nonthermal mechanism producing the power-law component and/or hard X-rays component (Gilfanov et al. 1991) is predominant and a thermal mechanism producing a disk-blackbody (or a blackbody) component follows. It is notable that even at the maximum the luminosity does not reach the Eddington luminosity on the assumptions of the mass of the compact star of greater than 1.4 $M_{\odot}$, 1.4 kpc distance and a spherical emission. Thus the nonthermal mechanism at the early phase of the outburst plays a role even in the non–supercritical accretion (see Mineshige, Rees, & Fabian 1991).

During the decay phase, the power-law component decreased rapidly and, since ~ 30 days after the maximum the power-law component could not be detected. The temperature of the disk-blackbody component monotonously decreases, but its inner disk radius keeps roughly constant. This behavior is the same to that of GS 2000+25 (Tanaka 1989). This phenomenon is interpreted that the disk-blackbody component is originated from the accretion disk, the temperature of which decrease with time but the inner edge of which is kept at some value; probably it is the inner most stable Keplerian orbit. It should be noted that the obtained inner disk radius of $10(D/1.4 \text{ kpc})[\cos(i)]^{-0.5}$ km is not inconsistent to the inner most stable Keplerian orbit for the compact star of the mass of $\sim 1.4\ M_\odot$ for any inclination. If the mass of the compact star is a black hole and has a mass of greater than 3 $M_\odot$, large inclination ($i > 85°$) is required, but this difficulty is solved by introducing the difference between the color temperature and the effective temperature (Kitamoto, Tsunemi, & Roussel-Dupre 1992).

At the second flare, which occurred ~ 70 day after the maximum, both the temperature and the inner-disk radius of the disk-blackbody become constant against the overall monotonous-decay of the temperature.

A very high state of GX 339−4 has been reported by Miyamoto et al. (1991) and is observed near the peak of a flare and its luminosity is 2 or 3 times larger than that of the high state. The notable characteristics of this very high state are a considerable energy fraction of the hard component ranging from 0.35 to 0.13 and an appreciable rapid time variation at time scales of less than 60 s, including 6 Hz QPO, which appears in the hard component. Around the peak of GS 1124−683, the energy fraction of the hard component is also large (~ 0.4). In this sense, GS 1124−683 might be in the similar state (the very high state) to that of GX 339−4 reported by Miyamoto et al. (1991). In fact, the LAC data obtained around the peak show similar power density spectra and QPOs to those observed in GX 339−4 in its very high state (Takizawa et al. 1992; Iga 1992). After the rapid decay of the hard component, GS 1124−683 might be in a so-called high state, where the rapid time variation is smaller than that in the very high state.

Since ~ 140 days after the maximum, the hardness ratio becomes large, although the luminosity is almost comparable to the detection limit. From the analogy of the known phenomena of Cyg X-1 and GX 339−4, it can be interpreted as an indication of a transition to a so-called low-state (or a hard state).

4.3. *Accretion Phenomena of the X-Ray Novae*

As discussed in §§ 4.1 and 4.2, there are many similarities among the ultrasoft transient sources, at least among the three bright, well-studied sources; A0620−00, GS 2000+25 and GS 1124−683. Thus, it is natural to consider that the ultrasoft transients are the same phenomena occurring in the similar systems.

Based on the observational results, a phenomenological scenario of the transient phenomenon can be described as follows.

By some reason (generally considered to be the accretion disk instability or the mass overflow instability), a sudden mass accretion onto the compact star occurs. In the early phase, a hard X-ray production mechanism (nonthermal mechanism) works and the power-law type spectra are observed. In ~ 1 week, a thermal component increases both in the emission area and in the temperature, and reaches the maximum intensity. This thermal component can be interpreted to be an emission from inner accretion disk. Around the maximum intensity, these two components (nonthermal and thermal components) exist together and might show the characteristics of the very high state (i.e., considerable rapid time variation in the nonthermal component). After the maximum intensity, the accretion disk, keeping the inner disk radius constant, gradually cools down, and the luminosity of the thermal component decreases exponentially with a time constant of ~ 30 days, whereas the power-law component decays rapidly and becomes a so-called high state (or a soft state). About 70 days after the maximum, a second mass accretion occurs or the structure of the accretion disk changes, with the result that the X-ray intensity slightly increases. Subsequently the accretion disk cools again with a little bit smaller time constant of ~ 22 days. At ~ 140 days after the maximum, a transition takes place from a high state (or a soft state) to a so-called low state (or a hard state) like Cyg X-1 or GX 339−4.

5. CONCLUSION

GS 1124−683, which was an ultrasoft transient source, was discovered with the ASM and studied the intensity and the spectral evolution. The spectra are roughly represented by a two-component model consisting of a power law and a thermal (a disk-blackbody or a blackbody) component. In its rising phase, the power-law component was dominant and the thermal component gradually grew up as both the temperature and the emission area increased. In the decay phase, the power-law component decreased rapidly, whereas the thermal (disk-blackbody or blackbody) component decayed exponentially with a time constant of 31.2 ± 0.1 days. Existence of the power-law component around the maximum could characterize the very high state, which would be responsible for the rapid time variations such as QPOs. With the decay of the power-law component, GS 1124−683 would transfer to the so-called high state. The second flare ~ 70 days after the maximum was observed. After the second flare the thermal component decayed again with a little bit smaller time constant of ~ 22 days. About 140 days after the maximum, the spectrum becomes hard and changes into the so-called low state. This behavior is considered to be common for bright ultrasoft transient sources.

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