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OUTBURST, IDENTIFICATION, AND X-RAY LIGHT CURVE OF GS 1354–64¹ (=MX 1353–64?, CENTAURUS X-2?)

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ABSTRACT

The All Sky Monitor (ASM) on board the *Ginga* satellite discovered an X-ray nova, GS 1354–64, on 1987 February 13. An optical counterpart was identified on 1987 March 28, which had a visual magnitude of 16.92 mag at discovery. The ASM has monitored almost the entire light curve from the rising phase until it reached the detection limit during the decay. The maximum flux was about $(2.9 \pm 0.1) \times 10^{-9}$ ergs s⁻¹ cm⁻² in the 1–10 keV band. The decay time constant was about 66 days, assuming an exponential decay. The energy spectrum is well-described by an ultrasoft component with a disk blackbody spectrum, with inner disk temperature of 0.7 keV and radius of $51(\cos i)^{-0.5}(D/10 \text{ kpc})$ km, where i is the inclination of the disk and D is the distance to GS 1354–64, plus a hard tail with a power-law shape (photon index = 2.1). Softening of the spectrum during the decay phase was observed, which may be attributed to a temperature decrease of the X-ray emission region or to a decrease of the intervening absorption column density. The position of the source is consistent with the positions of both MX 1353–64 and Cen X-2. However, the characteristics of GS 1354–64 were markedly different from either of these sources.

Subject headings: black holes — stars: individual (GS 1354–64) — stars: novae — X-rays: binaries — X-rays: sources

I. INTRODUCTION

The transient X-ray sources are divided into two categories, hard and soft transients (Cominsky *et al.* 1978; Kaluzienski *et al.* 1977), according to their spectra. Hard transient sources are generally X-ray pulsars, and they are recognized to be massive binary X-ray sources with eccentric orbits (Priedhorsky and Holt 1986). On the other hand, some of the soft transient sources (Aql X-1, X1608–522, Cen X-4, etc.) show X-ray bursts (Koyama *et al.* 1981; Murakami *et al.* 1980; Matsuoka *et al.* 1980), and some of them were optically identified with K or M dwarfs (Bradt and McClintock 1983). Therefore, they are considered to be low-mass X-ray binaries.

White *et al.* (1984) classified binary X-ray sources according to their spectra. They argued that there is an ultrasoft spectral class, called ultrasoft sources, with blackbody temperature ≤ 1 keV, which are preferentially associated with black hole candidates. For example, the high states of Cyg X-1 and GX 339–4, LMC X-1, LMC X-3, and A0620–00 all exhibit ultrasoft X-ray spectra. As well as A0620–00, some soft transient X-ray sources, 4U 1543–475 (Kitamoto *et al.* 1984), X1734–275 (Makino and *Ginga* Team 1988), and GS 2000+25 (Tsunemi *et al.* 1989) also have ultrasoft spectra. The physical relation between ultrasoft spectra and black holes is intriguing but, as yet, not understood.

In this paper, we report the discovery and optical identifica-

tion of an ultrasoft transient X-ray source, GS 1354–64. Its X-ray light curve and spectral behavior are described here. The data were obtained with the All Sky Monitor (ASM) on the *Ginga* X-ray satellite and the ESO 1 m Schmidt and 1.54 m Danish telescopes. The short-term and detailed spectral information obtained with the Large Area Counter (LAC) on *Ginga* and the optical light curve evolution will be reported elsewhere.

II. OBSERVATIONS AND RESULTS

GS 1354–64 was discovered with the ASM on board *Ginga* (Makino and Astro-C Team 1987) on 1987 February 13 (Makino and *Ginga* Team 1987). The ASM consists of six proportional counters equipped with Be window (50 μ m) and filled with Xe + CO₂ (1.2 atm) having an effective area of about 70 cm² in each. The field of view of each detector is 1° × 45° (FWHM), tilted by $\pm 8^\circ$, $\pm 24^\circ$, or $\pm 42^\circ$ to the meridian of the satellite. Details are described elsewhere (Tsunemi *et al.* 1989).

The celestial position determined by ASM for GS 1354–64 is (1950.0 equinox)

$$\alpha = 13^{\text{h}}53^{\text{m}} \pm 2^{\text{m}}4,$$

$$\delta = -64^\circ 24' \pm 18'.$$

A search for an optical counterpart was made as soon as possible after X-ray discovery by comparing a *B* plate taken with the ESO 1 m Schmidt telescope on 1987 March 27 with the corresponding *B* plate of the ESO quick-blue survey. Visual examination by one of us (H. P.) of all stars lying within the

¹ We designated GS 1354–64, previously ASM 1354–64, in *IAU Circ.* No. 4342 (Makino and *Ginga* Team 1987).

Ginga error box revealed an object that was not present in the survey plate. A CCD image taken on the following night (4^h UT 1987 March 28) with the 1.54 m Danish telescope at La Silla confirmed the discovery (Pedersen *et al.* 1987). Magnitude measurements on the CCD frames taken on that night, when transformed into the *UBV* system using observations of Landolt (1983) standards, give $V = 16.92$, $B - V = +1.08$, $U - B = -0.13$. These values are consistent with those of a typical accretion disk in a low-mass X-ray binary (van Paradijs 1983), reddened by $E(B - V) = 1$ mag. Further magnitude measurements were obtained in the following days and weeks, showing a slow decline with superposed large-amplitude variability, and will be reported in a separate paper (Ilovaisky *et al.* 1990).

A 10 minute low-dispersion (13 Å FWHM resolution) spectrum, kindly taken by J. Bergeron using EFOSC on the ESO 3.6 m telescope simultaneously with the CCD photometry at

the 1.54 m Danish telescope, revealed a smooth, reddened continuum with strong emission at He II $\lambda 4686$, typical of low-mass X-ray binaries, thereby confirming the identification. In addition, there are strong interstellar absorption lines at 4430, 6284, (unidentified), and 5890 Å (Na I).

The position of the object was measured in the CCD *V* frame relative to nearby secondary astrometric reference stars which were calibrated with respect to 42 fundamental Perth70 standards, measured on the ESO/SRC glass plate J-097 using the MAMA Reticonscanning machine at Observatoire de Paris (Guibert 1990). The absolute astrometric accuracy of the measured coordinates is $\pm 0''.5$, as derived from the residuals of the Perth standards. The derived 1950.0 coordinates for the GS 1354-64 counterpart are

$$\begin{aligned} 13^{\text{h}}54^{\text{m}}27^{\text{s}}.53, \\ -64^{\circ}29'29''.0. \end{aligned}$$

Inspection of the *R* plate from the ESO/SRC survey shows a very faint image at the position of the counterpart, implying that, when quiescent, it may be near $R = 22$. The CCD image obtained on 1987 March 29 at UT 4^h is shown in Figure 1a. In Figure 1b, the position of the optical counterpart is plotted in equatorial coordinates together with the X-ray error box. Error boxes corresponding to possible detections by other satellites (Markert *et al.* 1977, 1978; Seward *et al.* 1976; Wood *et al.* 1984) are also plotted. We will discuss these detections in § III. A detailed study of the characteristics of the optical counterpart will appear elsewhere.

Figure 2 shows the X-ray light curves in the energy band 1-3 keV and 3-10 keV and the hardness ratio (3-10 keV/1-3 keV) of GS 1354-64 after the discovery on 1987 February 13. All the data points were obtained from single scans of the ASM with the exception of the data point of February 13. The observations on February 13 were made during preliminary system testing. The normal observations were started at the end of February (Makino and *Ginga* Team 1987). The error bars in Figure 2 indicate the effects of statistics and collimator response. The first three points were obtained with a constant spacecraft attitude, and the source was near the center of the

FIG. 1a

FIG. 1b

FIG. 1.—(a) A 5 minute *V* band CCD image of the GS 1354-64 field obtained on 1987 March 29 at 4^h UT with the 1.54 m Danish telescope at La Silla, Chile. The optical counterpart is marked by a cross. The visual magnitude at discovery was $V = 16.92$. North is at the top, and east to the left. The field is approximately $2.4 \times 4'$ in size. (b) The position of the optical counterpart of GS 1354-64 (dot) plotted in equatorial coordinates together with the X-ray error box derived from the ASM. Error boxes corresponding to possible detections by other satellites are also plotted.

FIG. 2.—The light curves of the energy range 1–3 keV and 3–10 keV and the hardness ratio $I(3-10 \text{ keV})/I(1-3 \text{ keV})$. Best-fit exponential lines, after April, are also described.

field of view. Thus the relative intensities of these points are believed to be quite reliable. The scatter of the subsequent points may be due to an underestimate of the error in the response functions.

Our observations appear to include the rising phase (see Fig. 2; 3–10 keV). The flux reached a maximum of about $(2.9 \pm 0.1) \times 10^{-9} \text{ ergs s}^{-1} \text{ cm}^{-2}$ during 1987 March and gradually decreased to the detection limit of the ASM in August. If we assume an exponential decay after April, the decay time constant is derived to be 66.3 ± 0.2 days in the energy range 1–3 keV and 61.5 ± 0.3 days in the energy range 3–10 keV. We can also see a gradual decrease of the hardness ratio with a decay time constant of 202 ± 0.5 days.

The energy spectrum, integrated from February 25 to July 25, is shown in Figure 3. Four simple models (blackbody, thermal bremsstrahlung, power-law, and disk blackbody; Mitsuda *et al.* 1984) were fitted to the observed spectrum. The best-fit parameters are listed in Table 1. No single-component model satisfactorily fits the data, which is confirmed by the LAC observation. However, the photon index of the best-fit power-law model was about 4.7, which is similar to that of A0620–00 (Ricketts *et al.* 1975). Therefore, GS 1354–64 and

A0620–00 belong to the same category (ultrasoft sources). This is confirmed by plotting the data for GS 1354–64 on the X-ray color-color diagram (White *et al.* 1984).

The residuals of the observed data from the best-fit single-component model are mainly due to a high-energy excess. Generally, ultrasoft sources are well-described by the spectrum consisting of a blackbody (or a disk blackbody) component and a hard-tail component with a power-law shape (Bedford *et al.* 1981; Makishima *et al.* 1986). Thus, two two-component models were fitted to the data: (i) a blackbody and a power-law, and (ii) a disk blackbody and a power-law. Both models fit to the observed data well. The best-fit parameters are shown in Table 2.

To check the spectral change during the decay phase, the energy spectra in three intervals (from February 25 to March 20, from March 24 to April 21, and from June 15 to June 25) were investigated. The two-component models did not yield significant changes of the parameters because of poor statistics. Therefore, we used a single-component model, blackbody and disk blackbody, restricting the energy range from 1 keV to 6 keV. The best-fit parameters are shown in Figure 4. We found that the observed softening during the decay phase may be

TABLE 1
BEST-FIT PARAMETERS FOR THE SPECTRA INTEGRATED FROM FEBRUARY 25 TO JUNE 25

Model	Best-fit Parameters		χ^2/dof
Power-law	Scale = $(1.5 \pm 0.8) \times 10^{48} (D/10 \text{ kpc})^2$ at 1 keV	Photon index = 4.74 ± 0.23 $\log(N_H) = (22.80 \pm 0.04)$	18/8
Thermal bremsstrahlung	$n^2 V = (8.3 \pm 1.9) \times 10^{61} (D/10 \text{ kpc})^2 \text{ cm}^{-3}$	$kT_e = (1.63 \pm 0.13) \text{ keV}$ $\log(N_H) = (22.58 \pm 0.05)$	34/8
Blackbody	$r = (4.8 \pm 0.6) \times 10^6 (D/10 \text{ kpc}) \text{ cm}$	$kT = (0.71 \pm 0.03) \text{ keV}$ $\log(N_H) = (22.13 \pm 0.13)$	56/8
Disk blackbody	$R_{in} = (2.3 \pm 0.4) \times 10^6 (\cos i)^{-0.5} (D/10 \text{ kpc}) \text{ cm}$	$kT_{in} = (0.89 \pm 0.03) \text{ keV}$ $\log(N_H) = (22.39 \pm 0.06)$	46/8

FIG. 3.—The energy spectrum integrated from February 25 to July 25. The best-fit model spectra, composed of a disk blackbody and a power-law, are also shown (histograms).

attributed to a temperature decrease of the X-ray emission region or to a decrease of the intervening absorption column density.

A search for periodicity from 5 to 40 days was carried out with a folding method. No significant periodicity was detected. The upper limit (90% confidence) on the amplitude of modulation was 45% of the mean intensity.

The maximum luminosity in the energy range between 1.0 and 10.0 keV is estimated from the maximum flux as

$$L_{\max} = (3.5 \pm 0.1) \times 10^{37} (D/10 \text{ kpc})^2 \text{ ergs s}^{-1},$$

where D is the distance to the source. Since this luminosity must be less than the Eddington luminosity, the upper limit of the distance is given as

$$(D/10 \text{ kpc}) < 1.93 \pm 0.03 (M/M_{\odot})^{0.5},$$

where M is the mass of the compact star. If the energy source is gravitational energy, which is released by the matter falling onto the compact star, the required mass accretion rate at the maximum intensity is

$$\dot{M} = (4.1 \pm 0.1) \times 10^{-9} (r/10 \text{ km}) (M/M_{\odot})^{-1} \times (D/10 \text{ kpc})^2 \eta^{-1} M_{\odot} \text{ yr}^{-1},$$

where r is the radius of the X-ray star and η is the efficiency for conversion of gravitational energy to radiation energy. The

total energy, E_{tot} , and the total accreted mass, M_{tot} , during this outburst are estimated as

$$E_{\text{tot}} \sim 1.9 \times 10^{44} (D/10 \text{ kpc})^2 \text{ ergs},$$

$$M_{\text{tot}} \sim 7.3 \times 10^{-10} (r/10 \text{ km}) (M/M_{\odot})^{-1} (D/10 \text{ kpc})^2 \eta^{-1} M_{\odot}.$$

III. DISCUSSION

The position of GS 1354-64 is consistent with that of MX 1353-64 observed by *OSO 7* during 1971 and 1972 (Markert *et al.* 1977, 1979), and that of Cen X-2, which showed an outburst in 1966 November (e.g., Francey 1971). Near the sky region of the position reported here, *Ariel 5* detected a faint source, A1354-64, during 1974 and 1976 observations (Seward *et al.* 1976), and *HEAO 1* also detected a faint source, 1H 1359-645 (Wood *et al.* 1984). (The *HEAO 1* error box missed the star; this might be due to influences of a nearby source, 1H 1348-633; Remillard 1990. These observations indicate the recurrence of this source, as suggested by Markert *et al.* (1977). Cen X-2 is one of the strongest soft transient sources (Cooke and Pounds 1971; Cominsky *et al.* 1978). The maximum intensity of Cen X-2 was about 50 times stronger than our observation, while that of MX 1353-64 was similar. The outbursts of Cen X-2 and MX 1353-64 seem to have a similar duration, one or two months. The sources A1354-64 and 1H1359-645 are about 50 times weaker than GS 1354-64, and no details on their temporal behavior have been reported. Cen X-2 is reported to show a power-law index of 1.15-2.8 in various observations (see Francey 1971) in the energy range of several keV, but Chodil *et al.* (1968) reported that the spectrum of Cen X-2 was softer than that of Sco X-1. This implies that Cen X-2 belongs to the ultrasoft transients, but that the spectrum is variable. On the other hand, the spectral information reported by Markert *et al.* (1979) indicates that the spectrum of MX 1353-64 was harder than that of Crab Nebula, which is quite different from our results. Remillard (1990) also reported that the spectrum may be harder in the *HEAO 1* detection, when it was about 50 times weaker than GS 1354-64. If we assume that all detections are of same source, then it shows at least four states; intense and soft (or variable) (Cen X-2); medium intensity and soft (GS 1354-64); medium intensity and hard (MX 1353-64); and faint (or "off") and probably hard states. However, it is possible that some of the early rocket sightings of Cen X-2 may concern a different source. We note that different spectral states for a given ultrasoft X-ray transient have been observed several times in at least two other sources, 4U 1630-47 (Parmar *et al.* 1986) and GX 393-4 (Ricketts 1983; Ilovaisky *et al.* 1986).

Our observed spectrum indicates that GS 1354-64 belongs to the ultrasoft sources (White *et al.* 1984), which are considered to be black hole candidates. The fact that the spectra

TABLE 2
BEST-FIT PARAMETER OF THE TWO-COMPONENT MODELS FOR THE SPECTRUM INTEGRATED FROM FEBRUARY 25 TO JUNE 25

Model	Best-fit Parameters	$\log(N_{\text{H}})$	χ^2/dof
Blackbody + power-law:			
Blackbody	$r = (8.7(+2.2, -2.5)) \times 10^6 (D/10 \text{ kpc}) \text{ cm}$	$22.46(+0.22, -0.16)$	3.7/7
Power-law	Scale = $(1.01(+34.0, -0.99)) \times 10^{46} (D/10 \text{ kpc})^2 \text{ at } 1 \text{ keV}$		
	$kT = (0.57(+0.07, -0.09)) \text{ keV}$		
	Photon index = $2.2(+1.7, -1.5)$		
Disk blackbody + power-law:			
Disk blackbody	$R_{\text{in}} = (5.1(+1.7, -2.0)) \times 10^6 (\cos \eta)^{-0.5} (D/10 \text{ kpc}) \text{ cm}$	$22.57(+0.14, -0.09)$	4.5/7
Power-law	Scale = $(6.45(+316, -6.36)) \times 10^{45} (D/10 \text{ kpc})^2 \text{ at } 1 \text{ keV}$		
	$kT_{\text{in}} = (0.69(+0.21, -0.13)) \text{ keV}$		
	Photon index = $2.1(+1.9, -1.7)$

FIG. 4.—The best-fit parameters of (a) blackbody and (b) disk blackbody to the spectra in three intervals (from February 25 to March 20, from March 24 to April 21, and from June 15 to June 25). The contours correspond to 68% confidence levels.

are well-described by a disk blackbody (Mitsuda *et al.* 1984) plus a power-law hard tail indicates that the central compact source is a black hole, because of the absence of X-rays from the surface of a neutron star.

The hard tail is also a characteristic feature of the spectrum of black hole candidates (Makishima *et al.* 1986; Oda 1977). The origin of the hard tail is recognized to be the result of Comptonization by a hot plasma (Liang and Nolan 1984), though some problems still remain to be solved (Miyamoto *et al.* 1988).

The spectral fitting analyses for the decay phase indicate a decrease of the temperature of the X-ray emitting region or a decrease of the intervening absorption column density. Kitamoto *et al.* (1984) reported that 4U 1543–47 showed a hardening during the rising phase in the 1983 outburst, and the hardening is interpreted as an increase of the intervening absorption column density. In our observations, there is also a suggestion of hardening during the rising phase (see Fig. 2). If the intervening gas is created during the rising phase and gradually disappears during the decay phase, the spectral evolution can be consistently explained.

An anticorrelation between hard tail and soft X-ray component, which is observed in the blackhole candidates Cyg X-1 and A0620–00 (Coe *et al.* 1976; Ricketts *et al.* 1975), could not be observed here because of poor statistics in the hard tail region. If MX 1353–64 is the same source, it might correspond to a so-called low (or hard) state similar to those seen in black hole candidates such as Cyg X-1 and GX 339-4.

The e -folding decay time of about 2 months we observed is similar to the 1966 outburst of Cen X-2 (Chodil *et al.* 1968), and is also similar to that of other bright soft transient sources:

3U 1543–47 (=4U 1543–47) (Matilsky *et al.* 1972; Li *et al.* 1976), A1524–62 (Kaluziński *et al.* 1975), A0620–00 (Kaluziński *et al.* 1977), and GS 2000+25 (Tsunemi *et al.* 1989). These time scales may relate to the accretion disk formation or the viscosity (α -value) in the accretion disk (e.g., Bath and Pringle 1981).

IV. CONCLUSION

We reported the discovery, the X-ray light curve, and the optical identification of the ultrasoft X-ray transient source, GS 1354–64. The X-ray spectrum consists of two components: a disk blackbody spectrum with a temperature of 0.7 keV and a power-law component with a photon index of 2.1. This is one of the characteristics of the black hole candidates studied so far. There are two X-ray outbursts reported in this region: MX 1353–63 and Cen X-2. However, both of these sources showed different characteristics than GS 1354–64. If they are the same source, it has at least four states. There is as yet no decisive evidence that the system contains a black hole. Optical observations during the X-ray inactive phase, just as in the case of A0620–00 (McClintock and Remillard 1986), may clarify this.

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