THE ASTROPHYSICAL JOURNAL, 337:L81–L84, 1989 February 15

DISCOVERY OF A BRIGHT X-RAY NOVA, GS 2000+25

HIROSHI TSUNEMI AND SHUNJI KITAMOTO
Department of Physics, Faculty of Science, Osaka University
SADANORI OKAMURA
Kiso Observatory, Institute of Astronomy, The University of Tokyo
AND
DIANE ROUSSEL-DUPRÉ
Los Alamos National Laboratory, Earth and Space Science Division
Received 1988 September 26; accepted 1988 November 15

ABSTRACT

We report here the discovery of the X-ray transient, GS 2000+25, which appeared in the constellation Vulpecula on 1988 April 23 with the All Sky Monitor (ASM) on board the *Ginga* satellite. The maximum observed intensity was about 12 Crab (1–6 keV). Two stars in the X-ray error box appeared to increase in brightness from the epoch of the Palomar Observatory Sky Survey; one of these was confirmed to be the counterpart by optical spectra and radio measurements. The X-ray spectrum and light curve during the decay phase shows that it belongs to a class of ultrasoft sources which include black hole candidates like A0620−00. A detailed comparison with A0620−00 supports the identification of GS 2000+25 as a possible new black hole candidate.

Subject headings: black holes — stars: novae — stars: X-rays

I. INTRODUCTION

White and Marshall (1984) divide the X-ray sources into three classes based upon the spectral hardness ratio: hard, soft and ultrasoft. Hard and soft sources have been identified as neutron stars with strong and weak magnetic fields, respectively. Ultrasoft X-ray sources like LMC X-1, LMC X-3, A0620−00, GX 339−4, and Cyg X-1 are thought to be black hole candidates. We discovered an ultrasoft X-ray transient with the ASM on board the *Ginga* satellite. We report here these observations as well as the similarities between this source and A0620−00.

II. OBSERVATIONS

The ASM (Tsunemi *et al.* 1988*a*) on board *Ginga* (Makino *et al.* 1987) consists of a pair of proportional counters with three sets of fan beam collimators (1° × 45°) on each detector. The detectors have 16 channels pulse-height, operating in the energy range of 1–20 keV. In normal scanning mode, the satellite rotates once in 20 minutes. These scans are normally performed once per day. In each scan, the instrument is capable of localizing a source to better than 0°.5 at a detection limit of better than 50 mCrab depending on the scan rate. During the nonscanning mode, ASM normally functions continuously as a single-channel (1–20 keV) "staring" monitor, covering those regions of the sky dictated by, and in the opposite direction of, the look direction of the Large Area Counter (LAC). Occasionally, a 16 channel spectrum can be also obtained even in the staring mode. The time resolution for these observations ranges between 0.0625 and 2 s, depending upon the data mode of LAC.

a) X-Ray Observations and Analysis

A bright X-ray transient—designated GS 2000+25—was discovered on 1988 April 26, 3° away from the galactic plane in the constellation Vulpecula, when the ASM scanned the sky during routine monitoring. At this time it was a factor 9–10 times stronger than the intensity of the Crab nebula (1–6 keV) (Makino *et al.* 1988). A previous scan made on 1988 April 22 has set an upper limit (5 σ) for detection of 30 mCrab at this location.

During 1988 April 23–24, the LAC observed BV Pup, which fortuitously is roughly in the opposite direction of GS 2000+25, thus allowing the ASM to observe it almost continuously during its brightening phase. GS 2000+25 was already $\sim$500 mCrab (1–20 keV) on 23 April, 0030 (UT) when the LAC observations of BV Pup began. Except for occasional interruptions by Earth occultations and periods of SAA transits, GS 2000+25 was continuously monitored until April 25, 0410 (UT) when the LAC was maneuvered to observed SN 1987A. These observations, between April 23 and 25, were made partly in the 16 channel staring mode, and made mostly in the single-energy channel mode (1–20 keV), with integration times between 0.0625 and 2 s. The collimator response for these observations was roughly 70%.

From first detection on April 23 until maximum light on April 28, the source increased linearly to a maximum intensity of 12 Crab in the energy range 1–6 keV. After this time, the source decreased in an exponential decay until the end of June. During a 5 day observation in July, the source was observed to have brightened by 50%. Afterward, the source decreased with a similar decay curve. Figure 1*a* shows the X-ray light curve obtained by the ASM through the end of July. Figure 1*b* shows the rising phase of the outburst. Data after April 25, during the decay phase of the light curve. were obtained with the instrument operating in the scan-mode.

The first X-ray spectrum, obtained on April 24, when the source intensity was about half the maximum, is shown in Figure 2. This observation was performed in the 16 channel staring mode, thus resulting in a high-quality spectrum. When fitting the data with a power-law plus interstellar absorption spectrum in the energy range 1–10 keV in order to compare with others reported in literature, the best-fit power law

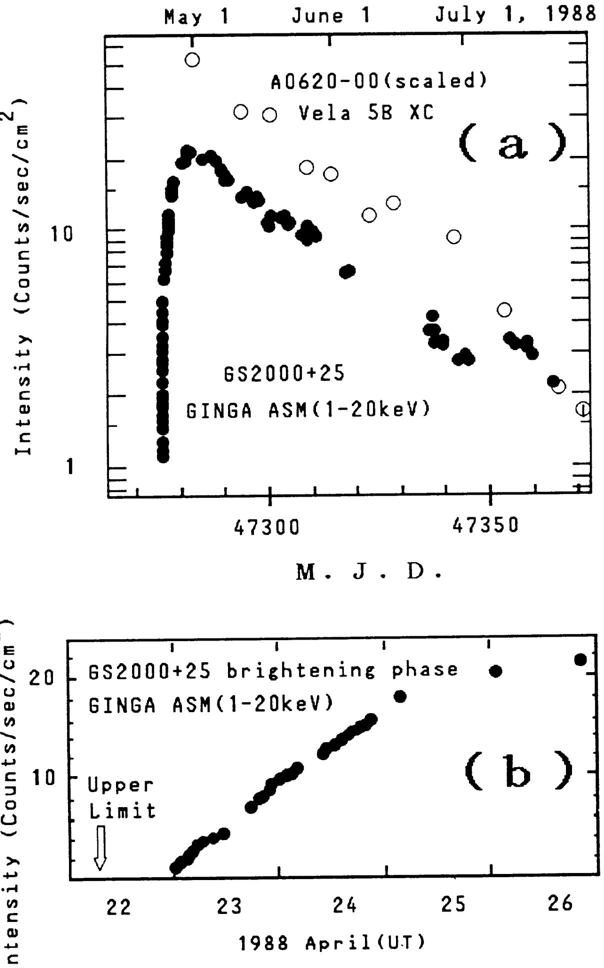

FIG. 1.—(*a*) The GS 2000+25 X-ray light curve (1–20 keV) shown with filled circles. Superposed upon the data with open circles is the scaled light curve of A0620−00 obtained with *Vela 5B* (3–12 keV). Each *Vela* data point is an average of all data in 112 hr bins. (*b*) The X-ray light curve during the brightening phase obtained with the ASM.

photon index is 4.39 ± 0.04 although the fit is poor. This shows that GS 2000+25 belongs to the class of ultrasoft X-ray sources (White and Marshall 1984).

We fitted the data obtained on April 24 with various single-component spectral models (power law, blackbody, thermal bremsstrahlung, and disk-blackbody; Mitsuda *et al.* 1984). None of these single-component models can fit the data. The reduced χ^2 values are 57.8, 12.0, 8.5, and 4.7 (9 D.O.F.), respectively. However, if we include the systematic error of about 0.5% (Tsunemi *et al.* 1988*a*), which decreases the reduced χ^2 by 60%. Therefore, the disk-blackbody spectrum can give an acceptable fit. The best-fit parameters are $T_e = 1.14 \pm 0.02$ keV, $\log N_H = 22.06 \pm 0.06$, where T_e is the temperature of the inner radius of the disk and N_H is the interstellar hydrogen column required to produce the observed low energy absorption. The radius R_s of the inner disk is given by $R_s = 9 \pm 1(D/2\ \text{kpc})(\cos i)^{-1/2}$ km, where D is the distance to the source and i is the inclination of the disk. The other data shown in Figure 1 are obtained by scanning observations of the source and thus have relatively poor statistics due to the limited time on the source. The hardness ratio (6–20 keV/1–6 keV) is essentially constant within the statistical uncertainties (0.03 ± 0.01).

b) *Optical Observations*

After the discovery by the ASM, observations were made to search for the optical counterpart at Kiso Observatory using the 105 cm Schmidt Telescope (Takase *et al.* 1977). Six direct plates were taken in the blue (B) and the near-infrared (I) bands during April 27 and May 2. Two variable objects were found with the X-ray error box (Okamura and Noguchi 1988) reported by Makino *et al.* (1988). Candiate A is a red variable object ($B-R = +4$ mag from the Palomar Observatory Sky Survey [POSS] prints) with $B \sim 18.5$ mag on the POSS print, 19.5 in 1983, and 17.5 on 1988 April 28. Candidate B is totally invisible (>21 mag) on both POSS prints and on Kiso plates taken in 1978 and 1983 but was observed at $B \sim 17.5$ on a Kiso plate taken on April 27. Hjellming, Calovini, and Córdova (1988) detected radio emission from candidate B with the VLA. The similarity of this emission to that of the X-ray nova A0620−00 confirms candidate B as the optical counterpart of GS 2000+25. Spectroscopic observations (Wagner, Henden, and Bertram 1988 and Charles *et al.* 1988) also suggest star B is the optical counterpart. We conclude from our earlier nondetection that star B had increased at least 3.5 mag during this outburst. The position of candidate B measured on a Kiso plate is $\alpha = 20^h00^m42\overset{s}{.}86 \pm 0\overset{s}{.}04$, $\delta = 25°05'43\overset{''}{.}5 \pm 0\overset{''}{.}7$ (1950). Figure 3 (Plate L3) shows the area of GS 2000+25 with indications of the candidates.

III. DISCUSSION

Ultrasoft X-ray transients are thought to be either accreting black hole candidates or bulge sources with spectra in the low-temperature tail of bulge source spectra (White and Marshall 1984). While more than half of the ultrasoft X-ray transients are thought to be black hole candidates, it is risky to conclude that GS 2000+25 is a new black hole candidate based solely upon the spectral index. Therefore, we will make a detailed comparison between GS 2000+25 and A0620−00, another ultrasoft X-ray transient, which has been identified as a black hole candidate based upon dynamical evidence

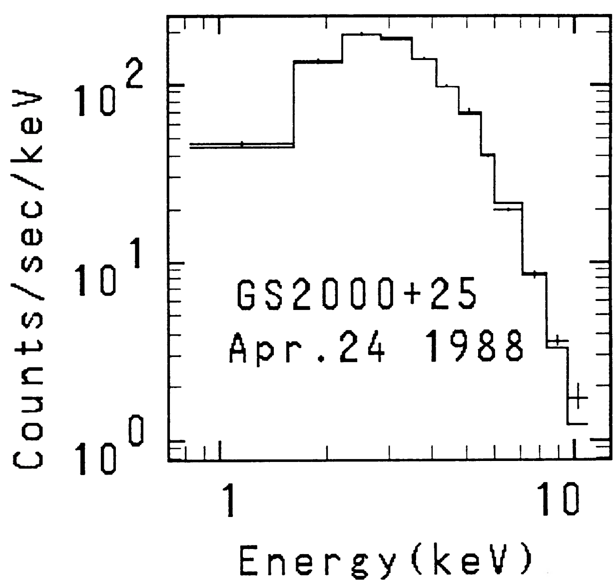

FIG. 2.—The X-ray spectrum obtained with the ASM on 1988 April 24 during its brightening phase at half-maximum. Superposed upon the data is the best-fit, disk-blackbody model spectrum which includes interstellar absorption.

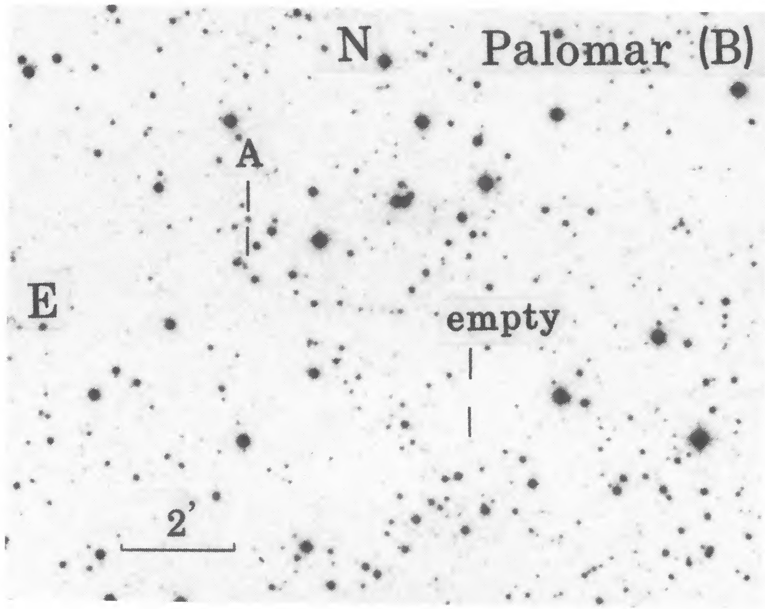

FIG. 3*a*

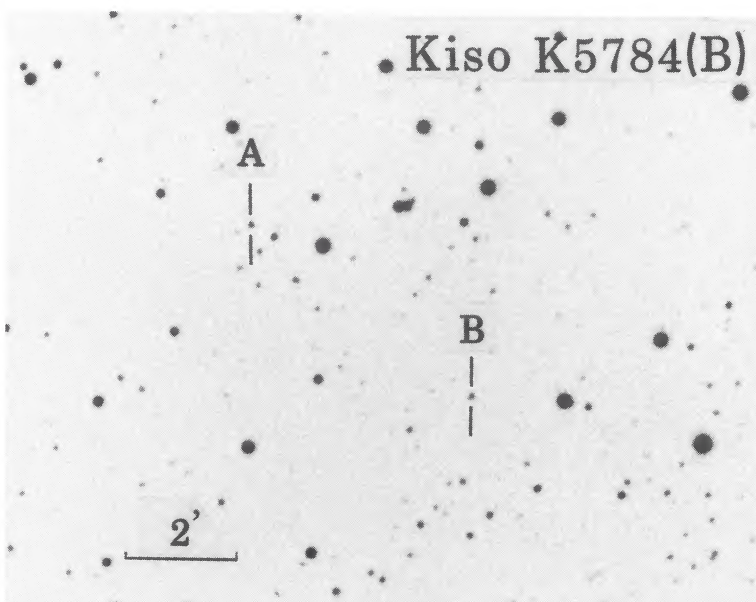

FIG. 3*b*

FIG. 3.—(*a*) The photograph taken by the Schmidt Telescope at Kiso observatory on April 28. The candidates, A and B, are shown by lines. Star B is the optical counterpart of GS 2000+25 confirmed by VLA observation. (*b*) The same field on the POSS blue plate. Star B is not visible.

TSUNEMI *et al.* (*see* **337**, L82)

obtained from optical spectra (McClintock and Remillard 1986).

a) Comparison with A0620−00

i) *X-Ray Light Curve*

The light curve of A0620−00 obtained by *Vela 5B* is included in Figure 1*a* and has been scaled to facilitate comparison with GS 2000+25. There is a striking similarity between the two light curves. The rising phase for both sources consists of a short precursor event 6–7 days before the maximum intensity, a linear increase in intensity until 3 days before maximum followed by a slight rollover to the maximum. Both sources reached the peak intensity in 6–8 days (Elvis *et al.* 1975). The *e*-folding decay time of GS 2000+25 after the maximum is 30.8 ± 0.7 days, while that for A0620−00 is 28.9 ± 1.8 days (Kaluzienski *et al.* 1977) for the first 50 days. Both sources exhibited enhanced brightening during the declining phase (50–75 days after the maximum intensity). A0620−00 was also observed to exhibit an order of magnitude increase in flux approximately 170 days after maximum light. In anticipation of a similar occurrence in GS 2000+25, it will be carefully monitored during this time frame.

The decay constant of the X-ray transient light curve may reflect the time scale for matter to fall from the accretion disk. Because the decay times of GS 2000+25 and A0620−00 are the same during the initial declining phase, the disks should be the same size if the viscosities are equal. Because the disk size is determined by the mass transfer rate, viscosity, and binary separation, therefore, these similar values for A0620−00 and GS 2000+25 suggest that the two binary systems are very similar.

ii) *X-Ray Variability and Spectrum*

Neither source was observed to have significant steady X-ray periodic variations. Doxsey *et al.* (1976) set an upper limit to pulsed power from A0620−00 of 2% for periods between 0.2 ms and 0.25 s and 0.4% for periods between 0.8 and 435 s. This study sets an upper limit (5 σ) of 2% pulse fraction for periods between 0.125 s and 100 s for GS 2000+25 in the staring mode data set.

The A0620−00 spectral energy index changed from 0.6 in the precursor phase to 4.15 at maximum light (Ricketts, Pounds, and Turner 1975). This variation in spectral index is similar to other ultrasoft X-ray sources like GX 339−4, Cir X-1, and Cyg X-1 which have bimodal spectral behavior associated with high and low activity states (White and Marshall 1984). Unfortunately, no spectral information of the early rise phase was available for GS 2000+25. The only available data during the rising phase showed it to belong to the ultrasoft sources. During the decay phase, smaller changes in spectral index are observed although the statistics is poor.

Both sources were observed to have hard energy tails above 10 keV (Ricketts, Pounds, and Turner 1975; Sunyaev *et al.* 1988; Tsunemi *et al.* 1988*b*). Single-parameter models were unsuccessful in fitting the A0620−00 data. The GS 2000+25 data indicate that all single-parameter models with possibly the exception of the disk-blackbody model also provide inadequate fits to the data between 1 and 20 keV.

iii) *Optical Counterparts and Radio Emission*

The optical counterparts of both A0620−00 and GS 2000+25 exhibited dramatic increases in intensity between the quiescent and active states, $\Delta m = 8$ and >3.5, respectively. A0620−00 reached a maximum brightness of $m_B = 12.5$, while GS 2000+25 only reached $m_B = 17.5$, a difference of 5 mag. Assuming that they are the same types of systems whose luminosity peaked at the same level, we may interpret that such a difference of 5 mag consists of two components. A difference of 1.5 mag would be due to the differences in source distances. The remaining 3.5 mag can be accounted for by the larger reddening we find for GS 2000+25 ($A_v = 4.41$) from the relationship between column densities and E_{B-V} obtained by Ryter, Cesarsky, and Audouze (1975) and the column densities derived from the disk-blackbody fits. This leads us to predict that GS 2000+25 during quiescence will be $m_B = 25.5$. Only definitive optical measurements made during quiescence phase, similar to that obtained for A0620−00 (McClintock and Remillard 1986), can conclusively determine whether or not this system is indeed a new black hole candidate. Unfortunately, an observation of such low intensitiy is beyond the capability of any existing instrument.

Finally, optical spectra of A0620−00 and GS 2000+25 at maximum are also similar in that a featureless, reddened continuum is observed to be lacking major emission and absorption lines (Boley *et al.* 1976; Gull *et al.* 1976; Wagner, Henden, and Bertram 1988).

The radio emission observed from both sources is also very similar. Detailed discussions are done by Hjellming *et al.* (1988).

iv) *Recurrence Times*

A0620−00 is known to be a recurrent transient with a recurrence time of 57 yr (Eachus, Wright, and Liller 1976). No previous observations of X-ray outbursts at the location of GS 2000+25 were found in either the *Uhuru* and *HEAO 1* X-ray catalogs, or the *Vela* data base which spans the time 1969 through 1979. Therefore, the recurrence time is greater than 20 yr, unless a recent outburst was missed due to lack of continuous X-ray monitoring.

In this way, based upon similarities in the light curve during all phases of the outburst, the lack of rapid X-ray variability, the ultrasoft spectrum, the increased brightening, the spectra of the optical counterparts, and the radio emission, we conclude that GS 2000+25, being remarkably similar to A0620−00, should be considered a new black hole candidate. Conclusive evidence that GS 2000+25 is a black hole can only come from optical studies similar to the work of McClintock and Remillard (1986) for A0620−00. If the predicted quiescence magnitude of $m_B = 25.5$ proves to be correct, only the Hubble Telescope will be capable of making such observations.

The authors express their thanks to the other members of the *Ginga* team as well as the launch staff at the Institute of Space and Astronautical Science. We would also like to thank the staff and visiting astronomers at Kiso Observatory who took part in the optical identification, and Mr. T. Misch of Lick Observatory for making several optical observations. Dr. J. Ling gave useful comments. This work was partly supported by the Grant-in-Aid for scientific research 63540197. One of us (D. R. D.) was partially funded under the auspices of the US Department of Energy.

REFERENCES

Boley, F., Wolfren, R., Bradt, H., Doxsey, R., Jernigan, G., and Hiltner, W. A. 1976, *Ap. J. (Letters)*, **203**, L13.
Charles, P., Hassall, B., Machin, G., Smale, A., and Allington-Smith, J. 1988, *IAU Circ.*, No. 4609.
Doxsey, R., *et al.* 1976, *Ap. J. (Letters)*, **203**, L9.
Eachus, L., Wright, E., and Liller, W. 1976, *Ap. J. (Letters)*, **203**, L17.
Elvis, M., *et al.* 1975, *Nature*, **257**, 656.
Gull, T. R., York, D. G., Snow, T. P., Jr., and Henize, K. G. 1976, *Ap. J.*, **206**, 260.
Hjellming, R. M., Calovini, T. A., and Córdova, F. A. 1988, *IAU Circ.*, No. 4607.
Hjellming, R. M., Calovini, T. A., Han, X. H., and Córdova, F. A. 1988, *Ap. J. (Letters)*, **335**, L75.
Kaluzienski, L. J., Holt, S. S., Boldt, E. A., and Serlemitsos, P. J. 1977, *Ap. J.*, **212**, 203.
Makino, F., and *Ginga* Team. 1987, *Ap. Letters Comm.*, **25**, 223.
———. 1988, *IAU Circ.*, No. 4588.
McClintock, J. E., and Remillard, R. A. 1986, *Ap. J.*, **308**, 110.
Mitsuda, K., *et al.* 1984, *Pub. Astr. Soc. Japan*, **36**, 741.
Okamura, S., and Noguchi, T. 1988, *IAU Circ.*, No. 4606.
Ricketts, M. J., Pounds, K. A., and Turner, M. J. L. 1975, *Nature*, **257**, 657.
Ryter, C., Cesarsky, C. J., and Audouze, J. 1975, *Ap. J.*, **198**, 103.
Sunyaev, R., and *Kvant* Team. 1988, *IAU Circ.*, No. 4606.
Takase, B., Ishida, K., Shimizu, M., Maehara, H., Hamajima, K., Noguchi, T., and Ohashi, M. 1977, *Ann. Tokyo Astr. Obs.*, 2d Ser., **16**, 74.
Tsunemi, H., Kitamoto, S., Manabe, M., Miyamoto, S., Yamashita, K., and Nakagawa, M. 1988*a*, *Pub. Astr. Soc. Japan*, submitted.
Tsunemi, H., Kitamoto, S., Okamura, N., and Roussel-Dupré, D. 1988*b*, *Bull. Inst. Space Astr. Sci.*, in press.
Wagner, R. M., Henden, A. A., and Bertram, R. 1988, *IAU Circ.*, No. 4600.
White, N. E., and Marshall, F. E. 1984, *Ap. J.*, **281**, 354.

S. Kitamoto and H. Tsunemi: Department of Physics, Faculty of Science, Osaka University, 1-1, Machikaneyama-cho, Toyonaka, Osaka 560, Japan

S. Okamura: Kiso Observatory, Institute of Astronomy, The University of Tokyo, Mitake-Mura, Kiso-gun, Nagano, 397-01, Japan

D. Roussel-Dupré: Los Alamos National Laboratory, Earth and Space Science Division, Los Alamos, NM 87545