The Astrophysical Journal, 209:L125–L130, 1976 November 1

UHURU OBSERVATIONS OF 4U 1608−52: THE "STEADY" X-RAY SOURCE ASSOCIATED WITH THE X-RAY BURST SOURCE IN NORMA

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Received 1976 July 2; revised 1976 July 29

ABSTRACT

Data are presented for the X-ray source 4U 1608−52 summarizing its light curve, location, and spectral parameters. Evidence is presented showing that this source is the "steady" X-ray counterpart of the X-ray burst source in Norma. The spectrum of the "steady" source is compared to the spectrum observed during two bursts, and we note that there is substantially more low-energy absorption during the bursts. Using the "steady" source spectral data, we examine the optical data and conclude that if the X-ray spectrum is thermal then a globular cluster counterpart probably would have been detected (whereas none has been). Further X-ray and optical observations are suggested for this source, since an optical identification may be central in determining whether all X-ray bursts have a common origin and if this origin requires a globular cluster environment.
Subject headings: X-rays: sources — clusters: globular

I. INTRODUCTION

In early 1972, a new X-ray source in the constellation Norma was detected with the Uhuru observatory. Because of the close proximity in galactic longitude of this new source to the transient source 3U 1543−47, an accurate assessment of its initial appearance and its location was quite difficult. The source was originally discovered by Matilsky *et al.* (1973) and was designated 1611−52; the source was also reported by Sprott (1973) and more recently by Li (1976) using the OSO-7 data.

Our attention was redirected toward this source by the fact that its preliminary location was consistent with the position recently reported by Belian, Conner, and Evans (1976) and later by Grindlay and Gursky (1976*b*) for several X-ray bursts in Norma. In this *Letter* we present new results on the location, spectrum, and intensity variations of this X-ray source and discuss its relationship to the X-ray bursts. We also review the situation for identifying an optical counterpart to the X-ray source.

II. OBSERVATIONS

During the course of our analysis of the X-ray light curve of the transient source 3U 1543−47, it became apparent that another source was present on some occasions at almost precisely the same galactic longitude. Since the scans available for this region of the sky from late 1971 onward were almost all essentially along the galactic plane (and the star sensors were no longer operational), it was difficult to resolve and locate the second source in the raw data scans. However, the analysis of data with the use of the magnetometer aspect processing system (Forman, Jones, and Tananbaum 1976) has now allowed us to determine spin-axis pointing directions and thereby source elevations to an accuracy of order $\pm 0\overset{\circ}{.}25$, while superposing azimuthal data to an accuracy of order $\pm 0\overset{\circ}{.}1$.

We returned to the data for the Norma region and determined that 3U 1543−47 was not in our field of view on some of the days on which our new source was seen in the $\frac{1}{2}° \times 5°$ (FWHM) collimator at galactic longitude $\sim 331°$. Also in support of the conclusion that we were observing a source other than 3U 1543−47, we found that the average spectrum of the new source was significantly flatter or hotter than the spectrum of 3U 1543−47 (Matilsky *et al.* 1972).

We then took the magnetometer lines of position for the new source and adjusted them and their uncertainties for systematic aspect errors using the lines of position and predicted azimuths for nearby 3U sources which had been located to precisions of 1′ to 3′ using the star aspect system before its failure in late 1971. The lines of position were processed using the same maximum-likelihood analysis used to generate the 3U catalog (Giacconi *et al.* 1974). The resultant 90 percent confidence location, shown in Figure 1 (Plate L5), is approximated by an ellipse centered at $\alpha = 16^h08^m28\overset{s}{.}3$, $\delta = -52°15'$ ($l^{II} = 330\overset{\circ}{.}91$, $b^{II} = -0\overset{\circ}{.}78$) with a semimajor axis of $0\overset{\circ}{.}25$ oriented at an angle of 42° toward the west from the north-south line (approximately perpendicular to the galactic plane) and a semiminor axis of $0\overset{\circ}{.}031$. This position is in very good agreement with the OSO-7 location circle reported by Li (1976), with the *Uhuru* error box having a factor of 8 smaller area.

To search for an optical counterpart, we have looked at the European Southern Observatory Quick Blue

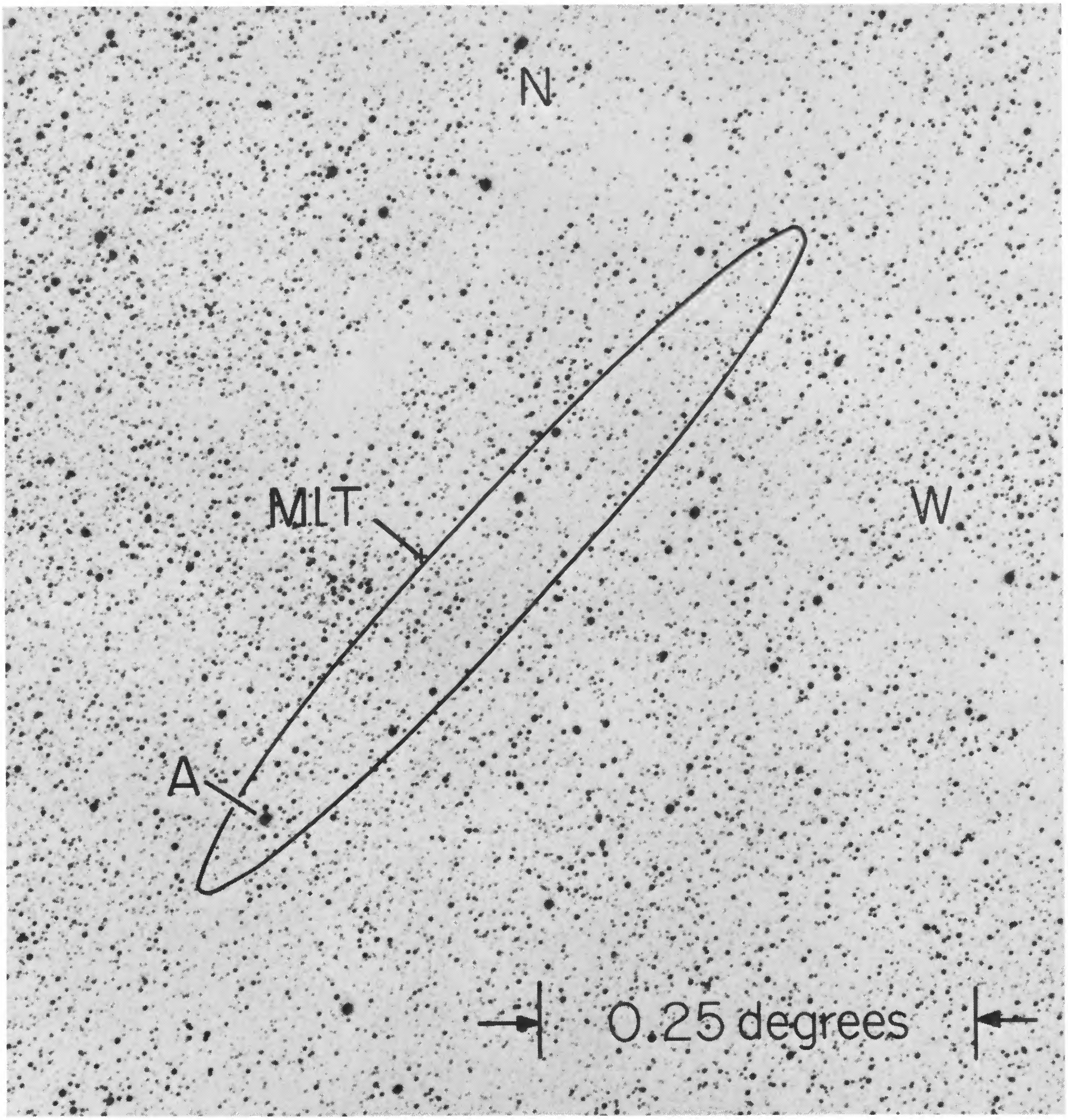

FIG. 1.—The *Uhuru* position for 4U 1608−52 centered at $\alpha = 16^h08^m28^s.3$, $\delta = -52°15'$ (1950) superposed on a red ADH Schmidt plate from the Harvard collection. Star A is SAO 243445 ($m_v \approx 9.7$). "M.I.T." marks the center of the OSO-7 error circle (Li 1976).

TANANBAUM *et al.* (*see* page L125)

Survey plates (limiting photographic magnitude ~21) and at a red ADH Schmidt plate (m_r limit ~19) from the Harvard collection. As can be seen from Figure 1, which shows the X-ray location superposed on the red plate, the region is densely populated with stars and shows somewhat uneven patches of obscuration. Star A is a G5 star (SAO 243445) with $m_{pg} \approx 10.2$ and $m_v \approx 9.7$. The group of stars just outside to the east of the error box is eye-catching and may be an open cluster worthy of further study. No other unusual objects have been detected optically or studied in this error box.

The long-term intensity behavior over the *Uhuru* lifetime for this source, which we designate 4U 1608−52, is summarized in Table 1. A typical observing period lasted from ½ to 1 day; column (1) gives the Universal Time for the start of each observing period. The 2–6 keV source intensity in counts per second is given in column (2) along with the statistical uncertainty in the rate. The data have been corrected for the nominal elevation of the source in the collimator field of view using the center of the X-ray location box shown in Figure 1. Systematic effects due to aspect uncertainty and source location uncertainty depend on the actual elevation of the source, but typical values range from ±5 percent (e.g., 1972 May 8.0) to no more than ±20 percent (e.g., 1972 October 10.5). The table shows that during the early *Uhuru* observations (1970 December 27.6–1971 March 28.6) the source was not observed with 3 σ upper limits ranging from 3.0 to 7.8 counts per second. The source was actually first observed by us on 1971 December 11.5. For the 1971 December 18.2 observation as well as for the five observations in 1972 March the intensity could not be established accurately because 4U 1608−52 was not fully resolved from 3U 1543−47. As the table shows, 4U 1608−52 was detected during 1972 and early 1973 at each observation subsequent to the initial sighting in 1971 December. *Uhuru* operations ceased in 1973 April, so no further data on the long-term light curve are available from *Uhuru*. Also, difficulties with the *Uhuru* transmitter between 1971 July and 1971 November plus the presence of 3U 1543−47 at between 1 and 2 times the intensity of the Crab from 1971 August until 1971 December (Matilsky *et al.* 1972) prevent us from assessing the behavior of 4U 1608−52 during that period or from specifying the characteristics of its initial turn-on.

TABLE 1

OBSERVATIONS OF 4U 1608−52

Start of Observation (UT) (1)	Source Intensity 2–6 keV (counts s^{-1}) (2)
1970 Dec 27.6....	<7.8*
1971 Feb 14.7....	<5.1*
1971 Mar 19.8....	<3.0*
1971 Mar 28.6....	<3.6*
1971 Dec 11.5....	26.7±4.4
1971 Dec 18.2....	~20†
1971 Dec 20.9....	30.8±2.6
1971 Dec 22.2....	43.6±1.8
1972 Mar 1.8.....	~20†
1972 Mar 2.4.....	~30†
1972 Mar 3.4.....	~20†
1972 Mar 5.2.....	~20†
1972 Mar 6.3.....	~15†
1972 Apr 10.5....	21.0±3.3
1972 May 8.0.....	32.1±1.6
1972 May 12.0....	28.9±2.5
1972 May 29.3....	30.3±3.4
1972 May 29.9....	46.8±6.9
1972 July 29.8....	25.7±3.2
1972 Aug 1.1.....	27.6±3.0
1972 Oct 6.8......	33.9±3.6
1972 Oct 7.7......	43.8±4.3
1972 Oct 8.0......	32.0±2.2
1972 Oct 9.2......	50.4±2.3
1972 Oct 9.7......	60.1±3.4
1972 Oct 10.5.....	49.1±11.0
1972 Oct 12.7.....	15.6±3.4
1972 Oct 13.5.....	13.2±3.6
1973 Feb 9.8.....	32.2±2.3
1973 Feb 11.3....	22.1±1.6
1973 Feb 15.0....	38.8±1.4

* 3-sigma upper limits (source not detected).

† Estimated intensity: source not resolved completely from 3U 1543−47, but clearly present.

The actual observed average intensities in Table 1 show a range of approximately a factor of 5 (maximum/minimum) with such changes occurring over a time as short as 4 days in 1972 October. Analysis of the daily light curves also shows significant variability within a day with a factor as large as 4 for the ratio of maximum to minimum intensity, but there is no evidence for eclipses or periodic variations greater than 50 percent on time scales from 0.1 days to 2.5 days. Eclipsing behavior with a longer period could have been missed, but this seems unlikely in view of the positive detection of the source on each of 27 observing days from 1971 December to 1973 February as shown in Table 1.

In addition to the above variability, we have detected two events in the $\frac{1}{2}° \times 5°$ collimator which are very likely X-ray bursts. One event was detected at UT 63,308 s 1972 May 10 and the other at UT 1037 s 1972 May 11. These data were obtained while we were scanning along the galactic plane with 3U 1543−47 near the center of the collimator field of view and were first attributed to 3U 1543−47. However, a careful analysis using the magnetometer aspect system and nearby strong X-ray sources has shown that these two events were centered $0.^{\circ}31 \pm 0.^{\circ}03$ and $0.^{\circ}39 \pm 0.^{\circ}03$, respectively, away from 3U 1543−47. The azimuths of the two events were within $0.^{\circ}01$ and $0.^{\circ}08$, however, of the position predicted for our new source 4U 1608−52, which was at respective elevations of $2.^{\circ}50$ and $2.^{\circ}77$ in the $\frac{1}{2}° \times 5°$ collimator. Because of the good agreement of the azimuthal positions with 4U 1608−52 and the lack of agreement with 3U 1543−47, we conclude that the events are in fact associated with 4U 1608−52. If we correct the observed intensities for the elevation in the field of view, we find that the first event corresponded to 228 ± 23 counts per second and the second to 407±30 counts per second in the 2–6 keV band. The source was not present at an intensity of 20 counts per second on the passes 700 s before and after the second event and 700 s after the first event. (No data are available for the pass just prior to the first event.) This behavior, as well as two other events reported by Grindlay and Gursky (1976*b*) for this region for 1972 May 11 detected in the 5° × 5° *Uhuru* collimator, indicate that a burst source was active, and the azimuthal agreement indicates that it is coincident with 4U 1608−52. The centroids determined for the 2 s long passes in the $\frac{1}{2}$° collimator would not have been significantly affected if the burst duration was of order 10 s or more; in fact, the small azimuthal residuals reported above are in the direction expected if the source intensity were decreasing slightly during the pass. With 17 3U sources plus 4U 1608−52 within ±5° of the galactic plane between galactic longitude 330° and 0°, we would expect ~0.06 X-ray sources in an arbitrary 0°.1 wide band (centered in this case on the two bursts above) if the association were random, so that we conclude that the association of 4U 1608−52 with the bursts is very likely real.

Lastly, we consider the spectrum of 4U 1608−52 during two representative intervals of relatively steady behavior (1972 October 7–10 and 1973 February 15) and during the two bursts seen above. The data are shown in Figure 2 as 1 σ and 90 percent confidence contours for the fit of an exponential spectrum plus low-energy cutoff to the data. The contours were generated using $\chi^2_{min} + 2.3$ and $\chi^2_{min} + 4.6$ as appropriate for a two-parameter fit for seven energy channels (Lampton, Margon, and Bowyer 1976; Avni 1976).We see that the spectrum during the two bursts is more cut off at low energies, similar to the behavior reported by Grindlay *et al.* (1976) for the bursts associated with 3U 1820−30 (NGC 6624). Also, the spectrum of the "steady" source shows significant variation from observation to observation as evidenced in particular by the temperatures fitted to the two *Uhuru* "steady" spectra and by the OSO-7 estimate of $kT \sim 30$ keV (Li 1976). A significant point, to which we return in the discussion, is the minimum upper limit for low-energy cutoff of 1.6 keV (90% confidence) for the 1972 October data which is used below to set a maximum limit on the interstellar absorption. Inclusion of a Gaunt factor in our thermal fit increases the temperature by about 2 keV but does not significantly alter the upper limit to the low-energy cutoff. Our 1972 October data could also be fitted by a power-law spectrum with energy index of ~1.5 and a low-energy cutoff of ~1.5 ± 0.5 keV.

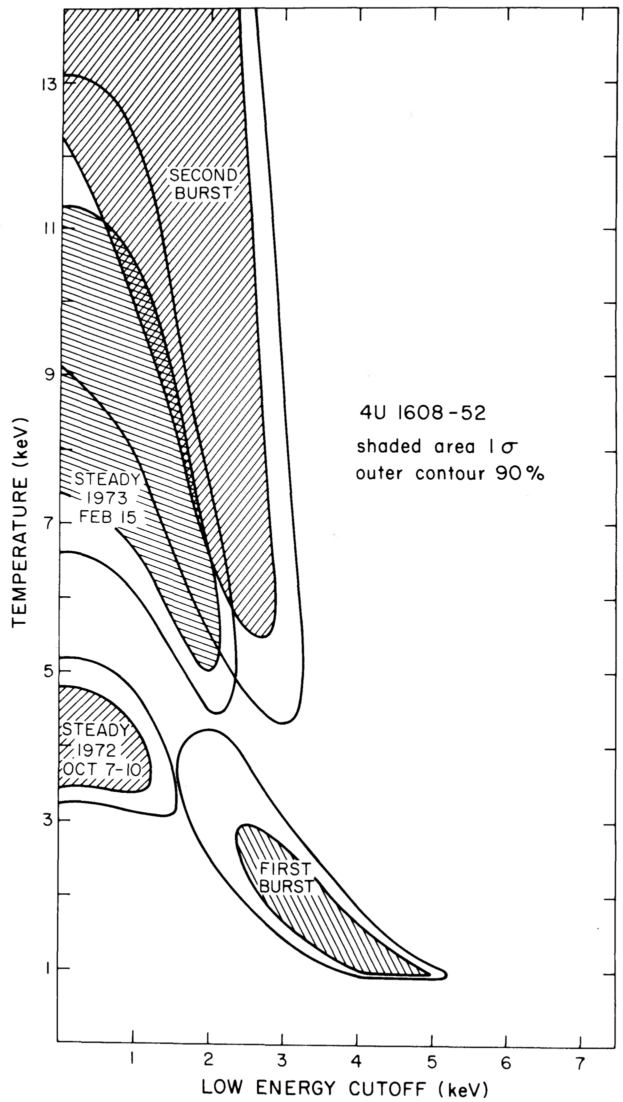

FIG. 2.—Contours of an exponential fit to the spectrum of 4U 1608−52 for the times labeled.

III. DISCUSSION

Optical identification of X-ray burst sources has been hampered by difficulty in obtaining precise positions for many of the burst sources. Also, the proximity of most of the sources to the galactic plane results in large amounts of obscuration and a high density of optical objects. For the three X-ray burst sources for which an identification has been made, the optical counterpart has been a globular cluster. Specifically, Grindlay *et al.* (1976) have observed X-ray bursts from 3U 1820−30 which is identified with the globular cluster NGC 6624; Forman and Jones (1976) have probably observed an X-ray burst from MX 0513−40 which is identified with the globular cluster NGC 1851; and the SAS-3 group (Lewin 1976) has discovered an X-ray burst source MXB 1730−335 for which Heise *et al.* (1976) have obtained an improved position and which W. Liller (1976) has tentatively identified with a faint, highly reddened globular cluster.

These three identifications lead quite naturally to the speculation that all X-ray burst sources may be associated with globular clusters and furthermore, that X-ray sources in globular clusters may be fundamentally different from other galactic binary X-ray sources (Grindlay *et al.* 1976). In addressing the problem of the evolution of binary X-ray sources in a globular cluster and the unexpectedly large number of X-ray sources associated with globular clusters, Clark (1975) suggested a binary system formed by capture, and Bahcall and Ostriker (1975) and Silk and Arons (1975) suggested a massive black hole at the core of the cluster. In the case of 4U 1608−52 which is identified with the X-ray burst source in Norma, we find that there is as yet no observed globular cluster optical counterpart, and therefore that X-ray bursts may not require a unique environment such as a massive black hole at the core of a globular cluster.

To assess the absence of a globular cluster counterpart to 4U 1608−52 in Figure 1, we make use of the 90 percent confidence upper limit of 1.6 keV on the low-energy cutoff of the "steady" source obtained for a thermal fit to the spectrum. Using the Brown and Gould (1970) abundances, we convert the cutoff to an upper limit of 1.75×10^{22} cm^{-2} for the equivalent hydrogen column density to the source. Taking Gorenstein's (1975) relationship of $A_V = 4.5 \times 10^{-22}\ N_H$ mag, we find $A_V \lesssim 7.9$ mag for 4U 1608−52. Using the data of Neckel (1967) in the direction of 4U 1608−52, we find that the upper limit on A_V implies a distance of no more than 12 kpc to 4U 1608−52. To convert the upper limit for A_V to an upper limit A_r for our red plate, we use the approximate relationship given by Allen (1963):

$$A_\lambda = A_V(0.68)(1/\lambda - 0.35), \text{ with } \lambda \text{ in microns}. \quad (1)$$

For our red plate, the effective wavelength is 6400 Å (0.64 microns), and we find $A_r \lesssim 6.5$ mag for 4U 1608−52.

To predict the apparent brightness at 6400 Å of a globular cluster counterpart to 4U 1608−52, we can use the data available for five of the globular clusters identified with X-ray sources, namely, NGC 6624, NGC 1851, M15, NGC 6641, and NGC 6712 (the first two of which have been identified with burst sources). Two other globular clusters identified with X-ray sources (NGC 6440 and the faint, highly reddened cluster identified by Liller 1976 with MXB 1730−335) cannot be included in our analysis because not all of the required optical parameters are known. For the five available clusters the first four columns of Table 2 give the cluster name, the core radius in arc minutes, the core brightness in magnitudes per square minute of arc, and the color excess E_{B-V}. We obtain the unreddened visual magnitude by using $A_V = 3.3\ E_{B-V}$ leading to the values of V_1 given in column (5). For an extended object of radius r_{obs} and an unreddened brightness V_1 (mag arcmin^{-2}), the total observed brightness will be

$$V_2 = V_1 - 2.5 \log \pi r_{obs}^2 . \quad (2)$$

If this object is at a distance D_{obs} (kpc) (col. [6] of Table 2) and we want to know its brightness V_3 at a new distance D_x, we have

$$V_3 = V_2 + 2.5 \log (D_x/D_{obs})^2 . \quad (3)$$

If we use the typical globular cluster color data of Liller and Grindlay (1976) of $B - V = 0.8$ mag and $V - R = 0.65$ mag to predict $V - r \approx 0.60$ mag and take into account the upper limit of 6.5 mag for interstellar reddening (A_r), we obtain the following which is used to generate column (7) of Table 2:

$$r_{pred} = V_1 - 2.5 \log \pi r_{obs}^2 + 2.5 \log (D_x/D_{obs})^2 - 0.6 + 6.5 . \quad (4)$$

In evaluating this expression we use $D_x = 12$ kpc.

By converting our red plate limit of 19 mag in 2 arcsec^{-2} seeing to a limit for an extended object assuming we are background-limited, we find

$$r_{limit} = 19.0 - 2.5 \log \left[\frac{3600\pi r_{obs}^2}{2}\left(\frac{D_{obs}}{D_x}\right)\right]^{1/2} ; \quad (5)$$

and we use this expression to compute column (8) in Table 2 for $D_x = 12$ kpc. By comparing columns (7) and (8) we see that the plate limit is such that the margin for seeing the four clusters ranges from 0.9 to 2.5 mag.

These results depend somewhat on the assumed colors and relationships between colors and absorption at different colors. For example, the actual value of $V - r$ might differ from the value of 0.6 mag that we used by a few tenths of a magnitude while our conversion from X-ray cutoff to A_V is also uncertain by ~0.5 mag. The conversion from A_V to A_r using equation (1) is also only approximate; and if we use the E_{B-V} and E_{V-R} data of Johnson (1968) to evaluate the uncertainty in

TABLE 2

Globular Cluster Parameters—Observed and Projected

Cluster (1)	Core Radius (arcmin) (2)	Observed Core Brightness (V_{obs}) (mag arcmin^{-2}) (3)	Color Excess E_{B-V} (mag) (4)	Core Brightness Unreddened (V_1) (mag arcmin^{-2}) (5)	Distance (D_{obs}) (kpc) (6)	r_{pred} (mag) (7)	r_{limit} (mag) (8)
NGC 6624	0.13[a]	6.99[b]	0.36[b]	5.80	5.0[c]	16.4	17.3
NGC 1851	0.13[b]	5.81[b]	0.14[b]	5.35	9.5[b]	14.9	16.8
NGC 7078 (M15)	0.23[b]	6.20[b]	0.12[b]	5.80	10.0[b]	14.1	16.1
NGC 6441	0.15[d]	6.29[d]	0.45[d]	4.80	9.3[d]	14.1	16.6
NGC 6712	0.81[b]	9.87[b]	0.48[b]	8.29	6.8[b]	13.6	15.2

References.—(*a*) Bahcall 1976. (*b*) Peterson and King 1975. (*c*) Liller and Liller 1976. (*d*) Illingworth and Illingworth 1976.

this conversion, we find that the equation used is relatively conservative and for 12 out of 15 regions sampled by Johnson $A_r \leq 6.6$ mag for $A_V \leq 3.3$ E_{B-V}. If $A_V = 4$ E_{B-V}, then Johnson's data allow $A_r \leq 6.9$ mag for these same regions. Also, if we allow a reddening coefficient as large as 4, then the unreddened core magnitudes of the clusters brighten by 0.08 to 0.34 mag, tending to offset this increase in A_r. If the reddening coefficient is taken as 3, then the unreddened core magnitudes dim by 0.04 to 0.14 mag; but then $A_r \leq 6.4$ mag, offsetting this effect. A final effect concerns the uncertainty in estimating the distance D_x from the value of A_V. If we allow D_x to be as much as 50 percent larger (18 kpc versus 12 kpc), we can take the difference between equations (4) and (5) to see that the margin for observing our clusters will decrease by 2.5 log 1.5 or 0.44 mag. The sum total of all of these uncertainties does not exceed 1 mag.

Our conclusions based upon these calculations and considerations is that for a thermal X-ray spectrum the margins are sufficient that a globular cluster optical counterpart to 4U 1608−52 probably would have been detected. Since this would be the first X-ray burst source for which the counterpart is not a globular cluster, two further measurements are suggested. The first involves obtaining plates at least 2 mag more sensitive to cover the entire intrinsic range of globular-cluster core luminosities. (Grindlay and Gursky 1976*b* have already obtained a plate which is 0.6 mag more sensitive than the plate we used and still observe no globular cluster.) The second involves an improved measurement of the nonbursting X-ray spectrum to determine an actual value for the low-energy cutoff rather than the upper limit we have used. Also, one might then be able to choose between a power law spectrum and a thermal or exponential spectrum for the source, which is significant since if the power law spectrum is valid the actual cutoff may be as high as 2 keV, giving $N_H \leq 3 \times 10^{22}$ cm^{-2}, $A_V \leq 9.9$ mag, $A_r \leq 8.1$ mag and a distance of up to 15 kpc. These factors would reduce the predicted margin for a globular cluster counterpart by 1.8 mag, which would place NGC 6624 beyond our plate limit. Of course, some of the low-energy absorption may be intrinsic to the source, which would reduce the interstellar contribution and thereby the distance and the optical extinction.

If 4U 1608−52 is not identified with a globular cluster, then further improvements in the X-ray position will be required in order to make an identification and choose between possible alternative models. One final point concerns the detection of two additional X-ray bursts as reported by Grindlay and Gursky (1976*b*) for this source on 1971 December 22 and 23. On these days the average intensity we report for 4U 1608−52 is 42.3 ± 1.8 counts per second. This is among the higher values recorded in Table 1. Canizares (1976) has presented a reverberation model to explain the X-ray bursts in which a scattering cloud surrounds a source of short intense X-ray pulses and produces the observed spectral and intensity evolution of the event by scattering the initial pulse. This model is similar to one presented by Grindlay and Gursky (1976*a*) in which they required a very massive central object to bind the cloud, except that Canizares's model requires only a few solar masses for the central object. The model ascribes the persistent X-ray emission to the scattering cloud and specifically calculates the persistent luminosity as proportional to the square of the optical depth and predicts that when the persistent luminosity is relatively high then the optical depth will be so large as to significantly smear out bursts or even make them disappear. Our very limited data on burst activity and average intensity suggests that the simple correlation may not hold for 4U 1608−52 but more importantly points out 4U 1608−52 as a source worthy of further observations of average intensity and burst parameters, in addition to its spectrum and location. Also, if this object is the source reported by Kaluzienski *et al.* (1975) of the intense 3-day or longer outburst with intensity roughly half that of the Crab in 1975 November, then a regular monitoring of its behavior is further indicated.

We thank W. Liller for many helpful discussions in interpreting the optical data and for working through many of the steps needed to interpret the absence of an optical counterpart. We thank H. Gursky and J. Grindlay for many important discussions on various aspects of this paper and L. Cominsky for assistance with the data analysis. We also thank the referee for several useful comments affecting the discussion of a possible globular cluster optical counterpart.

This work was supported under NASA grant NAS5-20048.

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