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OPTICAL, INFRARED, AND X-RAY OBSERVATIONS OF NGC 6624

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ABSTRACT

We have observed the globular cluster NGC 6624 and the associated X-ray source 3U 1820−30 at optical, infrared, X-ray, and radio wavelengths. We find that at the center of NGC 6624 there is an extended distribution of optical and infrared emission. These observations suggest that the brightest stars populating the center of the cluster are luminous red-giant stars. We interpret the X-ray flux measurements as coming from a blackbody whose temperature varies, rising rapidly during an X-ray burst. The X-ray object, in this picture, is a spherical, collapsed object that is accreting matter. Its radius is $r \approx 47$ km, and its mass is $M \leqslant 15.8\ M_{\odot}$.

Subject headings: clusters: globular — infrared: sources — radio sources: general — X-rays: sources

I. INTRODUCTION

The X-ray source 3U 1820−30 is of interest because it is coincident (within 1′) of the center of the globular cluster NGC 6624 (Jernigan, Clark, and Canizares 1975). Canizares and Neighbours (1975) have reported that 3U 1820−30 is variable by a factor of 5 or more on a time scale of 10 months or less. One important finding of their OSO-7 observations is that X-ray variations show a slow rise (over weeks or months) to X-ray maximum, which is then followed by a more rapid fall (in about half the previous rise time) to X-ray minimum. Observations of giant X-ray bursts from 3U 1820−30 in which the flux increases by ~20 in ~1 s were first reported by Grindlay and Heise (1975), with the ANS satellite, and also by Clark (1976), using SAS-3 data. These X-ray bursts are usually observed when 3U 1820−30 is near X-ray minimum.

Bahcall (1976) has counted the projected star density in NGC 6624 as a function of distance from the center, using *V* filter photographs, and has discovered that NGC 6624 contains a bright, unresolved region (region R) at the center of the cluster.

Our paper reports on observations of region R made in 1975 September. These observations were carried out at optical wavelengths, using an SEC vidicon camera with and without a 4650 Å (Strömgren *b*) filter, and at infrared wavelengths, using a *JHKL* photometer. We looked through the 4650 Å filter in an attempt to find optical flux variations that correlated with X-ray variability (McClintock, Canizares, and Tarter 1975). Our observing program was made in conjunction with X-ray observations of 3U 1820−30 by the OAO-C satellite. Support observations of NGC 6624 were also made at 8 to 13 μm at European Southern Observatory (ESO) in Chile and at 3.5 mm at the National Radio Astronomy Observatory 36 foot (11 m) telescope. The primary purpose of our program was to obtain observations over as broad a spectral band as possible in order to understand better the nature of this unusual object. In addition, we hoped to identify optical flux variations that correlated with the X-ray bursts.

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II. OBSERVATIONS

a) Optical Observations

The Marshall Space Flight Center vidicon camera (Duncan *et al.* 1975) was placed at the Cassegrain focus of the 1 m telescope of the Lunar and Planetary Laboratory of the University of Arizona. The camera uses a specially selected 25 mm SEC vidicon (type WX-30691NC) with an S-20 photocathode. The camera target was prepared by a series of flashes and reads. Exposure times could be varied from 4 to 512 s with a TTL logic control unit. The target was read into a digital video image system (DVIS) memory at video rates, and during the next target preparation or exposure the frame (or part of it) could be transferred into tape in 60 s or less. One full field contained 256 vertical lines (MTF = 0.5), and each line had 512 pixel records (MTF = 0.2). The plate scale was 0''.48 per horizontal pixel.

The camera was calibrated by pointing the telescope at a uniformly illuminated section of its dome which was then exposed at six different levels of brightness. This procedure was repeated four times to derive an average calibration with increased signal to noise. The measured camera calibration was then checked, with the *b* filter removed, on the red-giant and horizontal branch stars in the globular clusters M2 and M15. These clusters contain horizontal branch and red-giant stars with *V* magnitudes between 13.0 and 17.0. We found a linear relation between the logarithm of our calibrated intensity and the Arp (1965) *V* magnitude for observations made without our filter. We have too few stars in common with the M15 photometry compiled by Sandage (1970) to calibrate the camera independently with these data. Our calibrated intensity was an average over 15 affected pixels per star. The 1 σ deviation from our calibration was 0.04 mag for each of five exposures between 3 and 32 s.

Vidicon pictures of NGC 6624 were made on each day beginning at 268.08 and including 272.08 UT in 1975. On each day the observations lasted for 0ᵈ08 (2 hours). Single frames made of NGC 6624 with the *b* filter lasted 512 s, with 52 s between exposures. An average of seven of these were made per night. Exposures made without the *b* filter were of 4, 8, or 16 s duration, with 52 s between exposures.

b) *Infrared Observations*

The Marshall Space Flight Center *JHKL* photometer (Johnson and Mitchell 1962) was used to observe the center of NGC 6624 (region R). The photometer was placed at the Cassegrain focus of the 1.5 m telescope at the Mount Lemmon Observatory of the Lunar and Planetary Laboratory. These infrared observations were made for a period of 2 hours beginning at days 268.08 UT and 269.08 UT in 1975. The fluxes were obtained by comparing observations at the cluster center with sky measurements at the cluster edge. Consequently, the fluxes from region R may be systematically low due to cluster stars in the diaphragm near the cluster edges. However, the optical measurements indicate that these stars are 10 to 20 times fainter than region R, so that the error should be quite small.

The 8 to 13 μm (*N*) observations were made at 269 UT in 1975 at the Cassegrain focus of the 1 m telescope of the European Southern Observatory in Santiago, Chile. The detector was 1.5 K gallium-doped germanium bolometer with 15'' diaphragm.

c) *X-Ray Observations*

The X-ray observations were carried out with the Mullard Space Science Laboratory's instrumentation aboard the OAO-C (*Copernicus*) satellite. The X-ray detector has six independent channels in its bandpass of 2.8 to 8.6 keV. Observations of 3U 1820−30 were made between days 269.20 and 269.31 UT in 1975, with one frame of data taken every 86.5 s. The exposure time per frame was 62.5 s, with a 24 s dead time between frames. The satellite passed through the South Atlantic Anomaly between 269.24 and 269.27 UT; therefore, during this period the X-ray detector was not operable due to local particle radiation. This turnoff took place during the predicted occurrence of a giant X-ray burst at day 269.25 ± 01 UT based on the Clark (1976) period and the Grindlay and Heise (1975) epoch. The burst (No. 7) after this computed burst was observed with the correct 0ᵈ18 period.

d) *Radio Observations*

The measurements at 90 GHz (3.5 mm) were made during 32.58 UT in 1976 at the 36 foot telescope of the National Radio Astronomy Observatory,[1] using the cooled 80 to 120 GHz dual-channel receiver. Using a beam-switching technique, we observed simultaneously with both channels and without image rejection so that both sidebands were accepted. The observations represent approximately 10 minutes of integration during a predicted giant X-ray burst.

III. RESULTS

a) *Optical and Infrared Data*

We report in Table 1 our optical measurements on the position of region R and compare these to previously reported X-ray and optical positions. This tabulation gives the measured position of region R and the wavelength region in which the position was determined. The last column gives the source of the observations. We are grateful to H. Spinrad for kindly lending us a 4 m red plate of region R so that we could measure a position to check against the one determined from vidicon pictures. All the positions, including the

[1] The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

POSITION OF REGION R

Position α(1950)	δ(1950)	Wavelength Band	Source
18:20:27.54 ± 0.08	−30:23:14.2 ± 0.4	098 + RG610	Spinrad 1976
18:20:27.9 ± 0.3	−30:23:16 ± 5	4650 Å	SEC vidicon
18:20:27.7 ± 0.3	−30:23:11 ± 5	*V* filter	Bahcall 1976
18:20:28.8 ± 4	−30:23:08 ± 60	1–10 keV	Jernigan *et al.* 1975

measurement with the SEC vidicon, are in agreement within the errors (1 σ) given. It appears that the measurements made with the Spinrad 4 m plate give the smallest errors. If the stars that populate region R have varying colors, then we might expect slight position shifts of the centroid of R, depending on the filter used. There appear to be no such shifts exceeding the error limits in Table 1.

The optical and infrared *JHKLN* photometry of region R is listed in Table 2. This table lists the wavelength band over which the observations were made, the average flux in this band, the date, and the source of the observations. The optical and infrared fluxes have been corrected for reddening, using a value of $A_v = 1.8$ mag of extinction (Liller and Liller 1975) and $E(\lambda - V)/E(B - V)$ taken from Aannestad and Purcell (1973). Our observations without the filter give a maximum visual magnitude for region R of 12.5, which is consistent with the measurements of Bahcall (1976). The optical fluxes given are an intensity average over the pixels within a $3'' \times 3''$ area near the cluster center. Errors given are statistical sampling errors for the optical observations (see King 1966*a*).

In Figure 1 we show a position-position map of the surface brightness of NGC 6624, uncorrected for reddening, as obtained from SEC vidicon photometry. The brightness is given in the units of magnitudes arcmin^{-2}, and the statistical sampling errors, which are approximately 10 times the instrumental errors, have been estimated from King (1966*a*). From this figure we find that the region of maximum surface brightness has an area of $\sim 4''$. In addition, the brightness contours are slightly elliptical ($e \sim 0.4$), with the major axis aligned east-west. Bahcall's (1976) core radius determined from star counts at angular distances greater than 6″ from the cluster center is also shown on Figure 1.

The time variations of the optical brightness of region R were studied in both the unfiltered and 4650 Å SEC vidicon data. We chose to look at region R through the 4650 Å filter because in six of the eight optical counterparts of compact galactic X-ray sources, a variable optical emission feature near 4650 Å has been observed to correlate well with variations in X-ray flux (McClintock, Canizares, and Tarter 1975). Figure 2 shows the average brightness of the source between 2 and 4 hours UT on 1975 September 29 as determined by an average of the 4650 Å vidicon data over a $3'' \times 3''$ area centered on the brightness peak. This time period is concurrent with pulse No. 6 based on the Clark (1976) period and the Grindlay and Heise (1975) epoch. This X-ray burst was not observed, since the satellite was in the South Atlantic Anomaly, but pulse No. 7 was seen as predicted (Grindlay and Heise).

b) *X-Ray Data*

The measured flux of the X-ray source 3U 1820−30 between 2.8 and 8.6 keV is given in Table 2. Using a distance of 5 kpc, we find that this flux implies an integrated luminosity of $4.2 \pm 0.2 \times 10^{36}$ ergs s^{-1}. The flux reported here is near the minimum of fluxes observed for this source by OSO-7 (Canizares and

TABLE 2

PHOTOMETRY OF REGION R

Wavelength Band	log [mean flux (Jy*)]	Date (UT)	Source
4200–6500 Å	−0.72 ± 0.04	272.08/75	This paper
4580–4760 Å	−1.0 ± 0.04	272.08/75	This paper
0.9–1.3 μm (*J*)	−0.10 ± 0.05	269.08/75	This paper
1.4–1.7 μm (*H*)	−0.05 ± 0.04	269.08/75	This paper
2.0–2.4 μm (*K*)	−0.19 ± 0.04	269.08/75	This paper
3.0–3.7 μm (*L*)	−0.30 ± 0.04	269.08/75	This paper
8–13 μm (*N*)	< +0.3	270.1/75	This paper
2.8–8.6 keV	−4.40 ± 0.02 (low)	268.2/75	This paper
1.0–1.5 keV	< −3.70 (low)	18–21/72	Canizares and Neighbours 1975
1.0–6.0 keV	−4.10 ± 0.1 (low)	18–21/72	Canizares and Neighbours 1975
3.0–10.0 keV	−4.27 ± 0.07 (low)	18–21/72	Canizares and Neighbours 1975
15–40 keV	< −4.78	18–21/72	Canizares and Neighbours 1975
1.0–1.5 keV	−3.45 ± 0.13 (high)	304–311/71	Canizares and Neighbours 1975
1.0–6.0 keV	−3.38 ± 0.01 (high)	304–311/71	Canizares and Neighbours 1975
3.0–10.0 keV	−3.53 ± 0.01 (high)	304–311/71	Canizares and Neighbours 1975
15–40 keV	< −4.9 (high)	304–311/71	Canizares and Neighbours 1975
1.2 keV	−3.0 (burst)	271.4/75	Grindlay and Gursky 1976
3 keV	−2.6 (burst)	271.4/75	Grindlay and Gursky 1976
4 keV	−2.6 (burst)	271.4/75	Grindlay and Gursky 1976
6.5 keV	−2.8 (burst)	271.4/75	Grindlay and Gursky 1976
8 keV	−3.1 (burst)	271.4/75	Grindlay and Gursky 1976
12 keV	−3.5 (burst)	271.4/75	Grindlay and Gursky 1976
3 cm	< −2.3 (low)	269.08/75	Hjellming 1976
3 cm	< −1.2 (burst)	269.08/75	Hjellming 1976
3 mm	< 0.0 (burst)	32.58/76	This paper

* 1 Jy = 10^{-26} W m^{-2} Hz^{-1}.

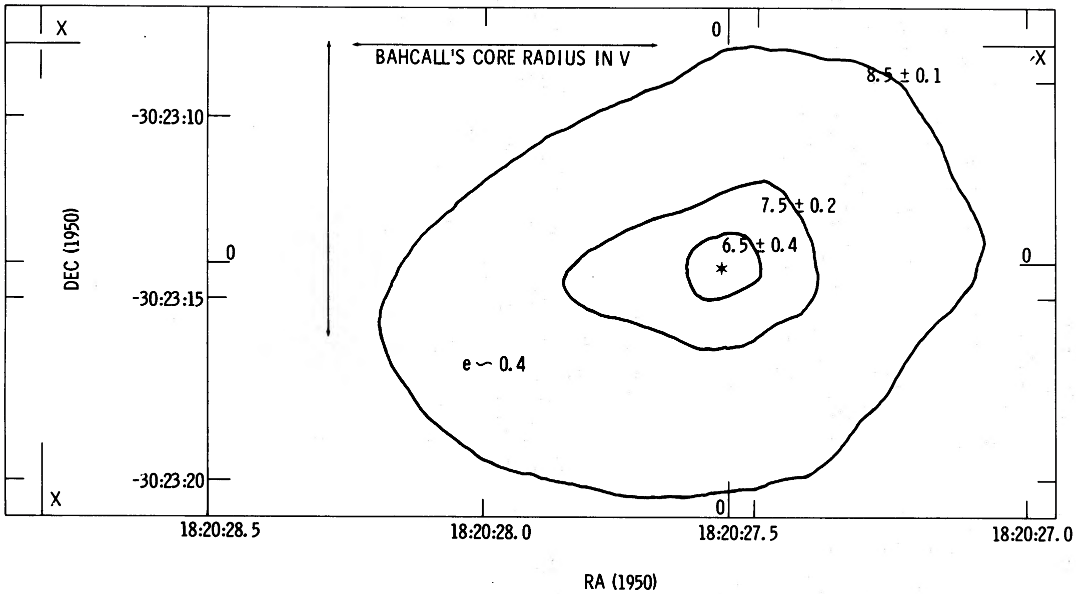

FIG. 1.—Position-position map of the brightness of region R of NGC 6624 measured by the SEC vidicon without the 4650 Å filter. The fluxes are in units of magnitudes arcmin^{-2}. The core radius of Bahcall's region R is also shown. The optical position as listed in Table 1 is marked by an O. The X-ray position, accurate to only $\pm 60''$, is marked by a cross.

Neighbours 1975). We detected no significant change in X-ray flux during the entire observing period (0^{d}06 total). A power spectrum analysis shows no peak-to-mean flux modulations exceeding 20% for all periods between 3 and 40 minutes. During our observations, the source was unusually inactive and faint, with none of the flaring activity reported by Canizares and Neighbours.

We have also made a spectral analysis of the X-ray flux. If we fit an optically thin, thermal bremsstrahlung spectrum (with an energy-dependent Gaunt factor) to the emission, we find that the temperature of the plasma is $T \geq 6.5$ keV, with a χ^2 minimum of 0.35 per degree of freedom occurring at 11.5 keV for a 3-parameter fit. In addition, we have assumed the X-ray flux is attenuated by the factor exp $[-N_H\sigma(E)]$ as it passes through the interstellar medium, where N_H is the column density of cold absorbing matter in the direction of the source and $\sigma(E)$ is the energy-dependent cross section tabulated by Charles, Culhane, and Tuohy (1973). Our analysis shows that the column density of cold absorbing matter toward 3U 1820−30 is $N_H = 8(+4, -3) \times 10^{22}$ atoms cm^{-2}, a result which is significant to 2 σ. In the determination of the error,

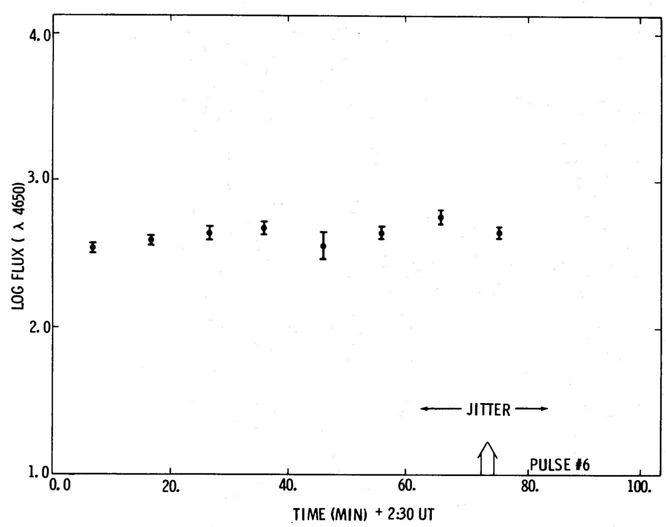

FIG. 2.—Time variations of the optical flux of region R as measured in the 4650 Å filter. The time of a computed pulse, and the jitter (or 1 σ error) in the time of that pulse, are also shown. This is pulse No. 6 after the first pulse seen by Grindlay and Heise (1975).

we have used the formulation of Lampton, Margon, and Bowyer (1976). If the source has solar metal abundances, the emission measure is $E = \int N_e^2 dV = 4.2 \times 10^{59}$ cm^{-3}. A power-law analysis of the emission yields a χ^2 minimum of 0.35 per degree of freedom for a slope of -1.95 ± 0.55 and a column density of $N_{\rm H} = 10 \pm 7 \times 10^{22}$ atoms cm^{-2}.

For comparison with our data, Table 2 also lists the X-ray flux measurements from OSO-7 (Canizares and Neighbours 1975) when 3U 1820 − 30 was active (high) and when it was quiet (low), and the observations of the X-ray flux seen in a giant X-ray burst (Grindlay and Gursky 1976).

c) *Radio Data*

During the time of a computed burst, Hjellming (1976) observed region R at 3 cm and found no detectable radio flux. In addition, he saw no radio flux from the steady source around the time of the burst. Our later observations of region R at 3.5 mm during the time of a computed burst also showed no detectable radio flux.

IV. DISCUSSION

In Figure 3 we have plotted the data from Table 2. We have "best" fitted the optical and infrared photometry, in the least-squares sense, to a blackbody at $T = 3400$ K $= 0.293$ eV. As is clear from this figure, the fluxes in the J and K bands fall below the expected blackbody fluxes, which is what we would expect if the stars populating region R were bright cluster red giants. In that case, the low fluxes can be interpreted as CN(J) and CO(K) absorption (Faÿ and Johnson 1973). We expect that these bright red stars are characteristic of the most luminous stars that populate the center of this cluster. To test this hypothesis, we have built a cluster model for NGC 6624 using the self-consistent approach of King (1966*b*). Assuming that the brightest stars in the cluster are distributed according to the density distribution given in this model, we can determine the probability that, upon looking at region R, we see a star in the outside ($10^c \leq r/r_c \leq 1$) or in the inner part ($1 \leq r/r_c \leq 0$) of the cluster, where $c = \log r_t/r_c = 2(W_0 = 8.6)$ is the cluster concentration factor (Bahcall 1976). Integrating the density distribution in a cylinder through the center of the cluster with the cylinder radius equal to the measured core radius, we find that $P(1 \leq r/r_c \leq 10^2) \sim 0.28$ and $P(0 \leq r/r_c \leq 1) \sim 0.72$. We are thus 3 times more likely to observe a star within a core radius of the center than outside this radius. In addition, these models give $\rho_0 = 3.70 \times 10^5\, M_\odot$ pc^{-3} and $\sigma = 8.9$ km s^{-1} for the central mass density and velocity dispersion, respectively, of the cluster. To determine these last parameters, we have used our measured central brightness of $V = 6.55$ mag arcmin^{-2}, assumed that $A_v = 1.8$ mag and $d = 5$ kpc (Liller and Liller 1975), and taken the mass-to-light ratio $(M/L) \sim 1$ in solar units.

Figure 1 shows that the brightness distribution within region R is extended, which implies that more than one star is at the cluster center. If we assume that the intrinsic luminosity of the brightest stars within the cluster is $M_v \sim -2$, then we can estimate that $N \sim$ 3–10 red giants make up region R. Assuming that the characteristic luminosity of these stars is $\log L/L_\odot \sim 4$ (Allen 1973), we can now estimate that the integrated visual luminosity of region R is $L \sim$ 6–8 $\times 10^{37}$ ergs s^{-1}.

Using our previous estimates for P and N, we find that we are seeing about six stars near the center and about two stars near the outer parts of the cluster. Consequently, we expect that the bright red objects we see in region R (see Fig. 3) are the characteristic of the brightest objects found near the center of the cluster. In another globular cluster, NGC 6388, we are also observing light from stars in the central regions. Illingworth and Freeman (1974) have measured a value for the stellar velocity dispersion in the cluster and find that it agrees well with the value computed from King's cluster models. Had they been observing objects mostly in the outer parts of the cluster, they would have seen a stellar velocity distribution weighted toward cluster stars with the lowest relative velocities. They would then have measured a velocity dispersion lower than that given by calculations based on models.

To the X-ray flux measured during a giant burst, we have also fitted a blackbody distribution. From Figure 3 the pulse data can quite clearly be well represented by a single blackbody at $T \approx 1.7 \times 10^7$ K $= 1.5$ keV. However, there are still far too few X-ray measurements of the steady X-ray source to give an accurate picture of it. Consequently, we have described the steady source by two different distributions of radiation representing opposing assumptions about the X-ray emission region. First, we have fitted the data at low and high luminosity by blackbody distributions at $T \approx 8 \times 10^6$ K $= 0.7$ keV and $T \approx 1.2 \times 10^7$ K $= 1.1$ keV, respectively. During low luminosity, in particular, the flux measurements are uncertain, and a temperature as low as $T \approx 5.8 \times 10^6$ K $= 0.5$ keV cannot be excluded. We have made the assumption that our X-ray data and those of Canizares and Neighbours (1975) are characteristic of this source when it is in its lowest luminosity state. We do not suggest that at both times the source was in the same state. The choice of this distribution clearly requires that the source be optically thick at X-ray wavelengths. Second, we have described the data in terms of thermal bremsstrahlung radiation from an optically thin, fully ionized plasma. In these calculations we have used the free-free Gaunt factor of Karzas and Latter (1961) and a representative temperature of $T \approx 10^8$ K $= 10$ keV. Another possibility is that the X-ray emitting region will show the characteristics of both radiation distributions. In that case, the plasma is optically thin at X-ray frequencies, becoming optically thick ($\tau = 1$) at some lower $\nu = \nu_c$. The observed flux would behave like the thermal bremsstrahlung spectrum until $\nu = \nu_c$, and thereafter fall with the characteristic slope of -2.

We feel that the X-ray photometry so far obtained and shown in Figure 3 is most consistent with an

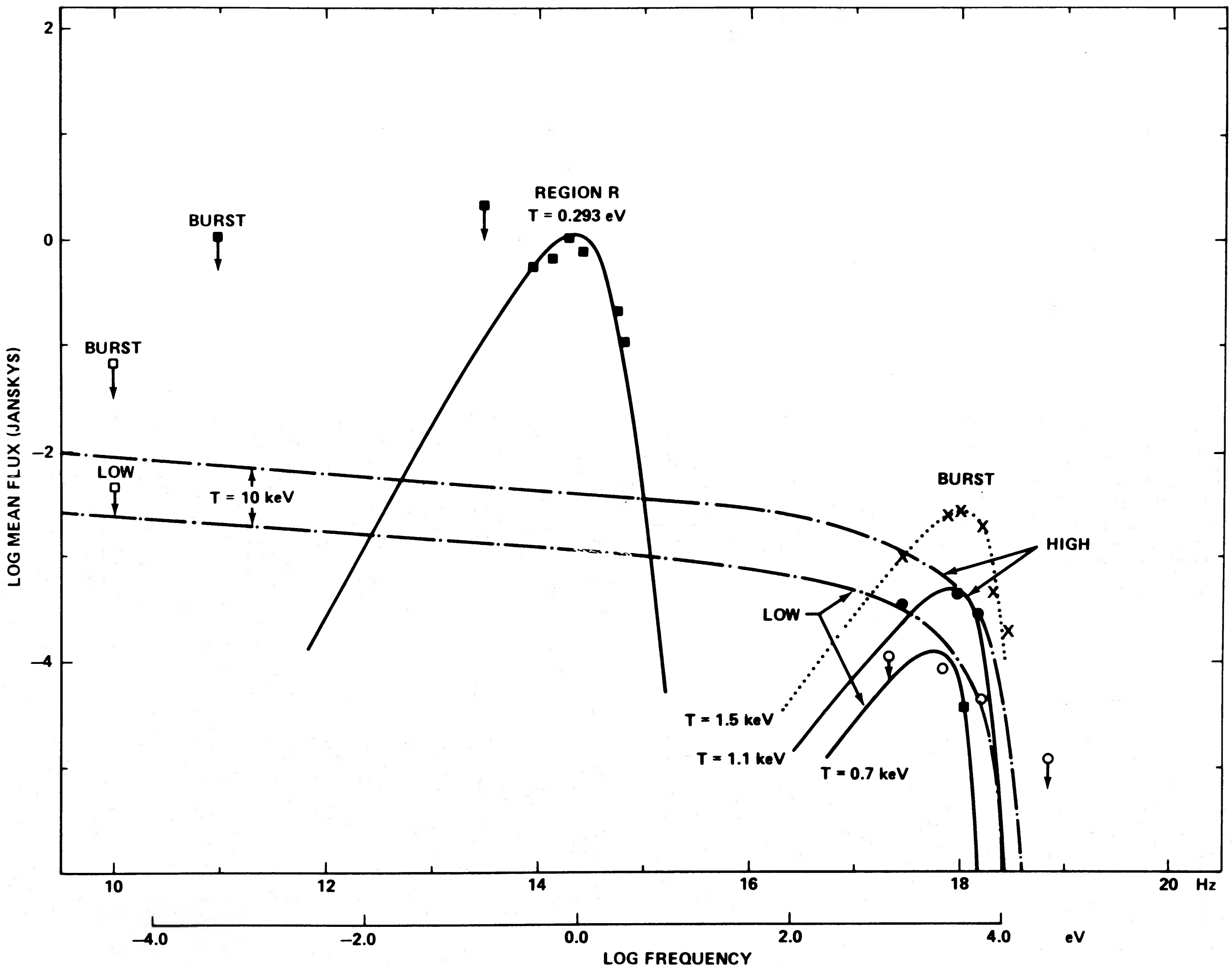

FIG. 3.—The photometric measurements of region R and 3U 1820−30, as given in Table 2. *Filled squares*, data from this paper. *Open circles*, data taken from Canizares and Neighbours (1975) during low luminosity. *Filled circles*, data taken from Canizares and Neighbours during high luminosity. *Crosses*, fluxes taken during a giant burst (Grindlay and Gursky 1976). *Open squares*, the 3 cm upper limits of Hjellming (1976). The optical and pulse data have been fitted to a blackbody alone. The low- and high-luminosity X-ray data have been fitted to both a blackbody at the indicated temperature and an optically thin thermal bremsstrahlung spectrum at $T = 10$ keV.

optically thick source that emits blackbody radiation. This conclusion is reinforced by measurements of the column density of material to the source. As reported, we measured a column density to 3U 1820−30 (assuming the source emits optically thin, thermal bremsstrahlung radiation) of $N_H = 8(+4, -3) \times 10^{22}$ atoms cm^{-2}. That is, a column density of absorbing material of $N_H = 8(+4, -3) \times 10^{22}$ atoms cm^{-2} is required to correct the observed X-ray flux for its fall below the predicted thermal bremsstrahlung spectrum. This value agrees, within $2\ \sigma$, with the column densities $N_H = 2 \times 10^{22}$ atoms cm^{-2} obtained by Canizares and Neighbours (1975), and $N_H = 3 \times 10^{22}$ atoms cm^{-2} obtained by Clark (1976). Our value is not within $2\ \sigma$ of the measurement by Grindlay and Gursky (1976), $N_H = 9(+11, -8) \times 10^{21}$ atoms cm^{-2}. On the other hand, optical measurements of the reddening to NGC 6624 give significantly lower values for the column density $N_H = 2 \pm 0.7 \times 10^{21}$ atoms cm^{-2} (Burstein and McDonald 1975) and $N_H = 4 \times 10^{21}$ atoms cm^{-2} (Liller and Liller 1975). Optical and X-ray evidence therefore suggests that there is absorption within the X-ray source, in violation of the basic assumption used in deriving the X-ray column density that the X-ray emission mechanism is optically thin, thermal bremsstrahlung radiation. We believe that the evidence suggests that the source radiates like a blackbody.

If the source 3U 1820−30 does radiate like a blackbody, then we can account for the increase in X-ray luminosity during a burst by an increase in the temperature of the source without an increase in its size. If the temperature rises from 0.7 keV to 1.5 keV, as shown in Figure 3, then the luminosity of the source would increase by a factor of 20. Such an increase would easily account for the X-ray flux during a burst. In addition, this explanation requires that the spectrum of the burst harden until the flux peaks, behavior that is observed by Grindlay and Gursky (1976). It does not simply account for the further hardening observed in the burst as it decays.

If the source radiates like a blackbody, it is more reasonable to assume that the source has a spherical geometry than that it has a ring or disklike geometry. Were the source a ring or disk, it would then be required that we happen to see it edge-on. Otherwise we would have expected to see a component of optically thin 3 cm radiation, at least at $1\ \sigma$. This was not observed. In addition, there is some evidence that the X-ray source MX 0513−40, associated with the globular cluster NGC 1851, also has a higher column density measured in the X-ray (assuming optically thin, thermal bremsstrahlung radiation) than is measured optically (Clark, Markert, and Li 1975; Arp 1965). This, too, would argue that 3U 1820−30 is not a ring or disklike object seen in a special orientation.

Finally, the X-ray luminosity of the steady source has been seen to rise slowly to maximum (~10 months) and then fall more rapidly than it rose (Canizares and Neighbours 1975). This behavior is just what theoretical calculations predict for a collapsed object accreting matter (Bisnovatyi-Kogan, Zel'dovich, and Nadezhin 1972).

Given the observed steady X-ray flux in a wavelength band $\Delta\nu$ and the distance to the source, we can compute the X-ray luminosity of the source in this band. Given that the source geometry is spherical and that it radiates like a blackbody at temperature T, we can estimate the size of the X-ray emitting region from the relation

$$r = 1.47 \times 10^{23}\left[\frac{L_0(\Delta\nu)}{\int_{\Delta\nu} \nu^3 \exp(-h\nu/kT)d\nu}\right]^{1/2},$$

where $L_0(\Delta\nu)$ is the observed luminosity in the wavelength band $\Delta\nu$ in ergs s^{-1} and ν is the frequency in Hz. Our observed luminosity in the 2.8 to 8.6 keV band is 4.2×10^{36} ergs s^{-1}, and the temperature of the blackbody is $T \approx 8 \times 10^6$ K. This implies that the radius of the emitting region is $r \approx 4.7 \times 10^6$ cm = 47 km. If we ask for the mass of an object that has this value of R as its Schwarzschild radius, we find that $M = 15.8\ M_\odot$. Therefore, our analysis requires that the mass of the collapsed object within 3U 1820−30 is $M \leqslant 15.8\ M_\odot$.

V. CONCLUSIONS

We have observed the globular cluster NGC 6624 and the associated X-ray source 3U 1820−30 at optical, infrared, X-ray, and radio wavelengths. We have found that at the center of the globular cluster, within Bahcall's region R, there is an extended distribution of optical and infrared emission that is fitted quite well by a blackbody spectrum at $T = 3400$ K. These observations suggest that the brightest stars that populate the center of NGC 6624 are luminous red-giant stars. We have found no optical flux variations in the source during a predicted X-ray burst.

We have interpreted the X-ray emission associated with NGC 6624 in 3U 1820−30 as coming from a blackbody whose temperature varies. As Figure 3 demonstrates, however, other interpretations of the X-ray data are possible. We have also found that the time variations of the steady X-ray flux are characteristic of a collapsed object accreting matter. If the X-ray source is a blackbody, then it is most likely a spherical object with a radius of $r \approx 47$ km. The mass of the collapsed core in 3U 1820−30 is then $M \leqslant 15.8\ M_\odot$.

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