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COLOR MAPS OF X-RAY GLOBULAR CLUSTERS

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ABSTRACT

We map the $U-B$ color of the central regions of six globular clusters. The clusters examined include all five relatively unobscured clusters containing high-luminosity X-ray sources: NGC 1851, NGC 6441, NGC 6624, NGC 6712, and M15, as well as 47 Tuc, which contains a low-luminosity source. We have offset and matched the seeing of the input CCD frames to avoid the usual problems of shading and ringing. This technique proves to be a very efficient way of identifying both red giants and anomalously blue objects even in the saturated cores of dense clusters. We have detected a probable counterpart for the X-ray source in NGC 6712. AC 211, the optical counterpart for the source in M15, is also clearly seen, and a region of enhanced blue emission near the X-ray error circle in 47 Tuc is observed. Lower limits are set for the magnitude of the optical counterparts of the X-ray sources in the other clusters. These color maps also provide a new method of searching for color gradients in clusters which is less prone to contamination by chance groupings of giants than the usual aperture photometry. We find that the clusters are redder toward the center, but that the color gradient can be adequately explained by crowding effects. No evidence is found, therefore, that the central cusps in M15 and NGC 6624 are significantly bluer than their surrounding clusters.

Subject headings: clusters: globular — X-rays: binaries — X-rays: sources

I. INTRODUCTION

Understanding of the high-luminosity globular cluster X-ray sources has grown steadily over the 14 years since they were first discovered by Giaconni *et al.* (1974). There are now 10 high-luminosity X-ray sources ($L \gtrsim 10^{36}$ ergs s^{-1}) known to be associated with globular clusters. All of these, except the one in M15, have been observed to emit X-ray bursts (Grindlay 1986). This implies that they are low-mass X-ray binaries with neutron star primaries. This hypothesis is strengthened by the location of these objects, which is close to, but not precisely at, the centers of the clusters. Grindlay *et al.* (1984) determined statistically that the mass of these objects is between 0.9 and 2.0 $M_\odot$. Such binaries are likely to form in globular clusters due to tidal capture (Fabian, Pringle, and Rees 1975). Recently, the discovery of an 11 minute binary period for X-ray source in NGC 6624 by Stella, Priedhorsky, and White (1987), and an 8.5 hr period for the source in M15 (Naylor *et al.* 1986; Ilovaisky *et al.* 1986, 1987; Hertz 1987) has prompted more detailed consideration of the possible origins of these systems (Verbunt 1987; Bailyn and Grindlay 1987).

The location of these sources in the dense cores of globular clusters has made the identification of their optical counterparts difficult at best. Auriere, Le Fevre, and Terzan (1984) have identified the blue star AC 211 as the optical counterpart of the X-ray source in M15. This identification has recently been confirmed by the discovery of similar (presumably orbital) periodicities in AC 211 (Naylor *et al.* 1986; Ilovaisky *et al.* 1986, 1987) and in the X-ray source (Hertz 1987); it should be noted that the latter result is insignificant if the period is not known *a priori* from the optical results. The luminosity reported for AC 211 by Auriere, Le Fevre, and Terzan (1984) of $M_V = -0.4$ and $U-B \approx -1.4$ is brighter than similar field X-ray sources, for which van Paradijs (1983) reports $M_V = 1.2 \pm 1.1$ However, Ilovaisky *et al.* (1987) have recently found that this star has regular luminosity variations of 1.6 mag, with M_V ranging from $-0.6 \lesssim M_V \lesssim 1.0$. Aside from this source, no optical counterpart for a globular cluster X-ray source has been discovered, although a possible optical counterpart to the low-luminosity source in NGC 5824 has been found (Grindlay 1987).

We report here the results of a search for optical counterparts to the X-ray sources in all of the relatively unobscured clusters with *Einstein* HRI positions (for which 90% confidence radii are $\sim 3''.5$; Grindlay *et al.* 1984): 47 Tuc (NGC 104), NGC 1851, NGC 6441, NGC 6624, NGC 6712, and M15 (NGC 7078). The data set consists of CCD images (*UBV* and *RI* in some cases) of the clusters obtained at CTIO and KPNO in connection with the core structure survey of Lugger *et al.* (1987). Rather than perform photometric reductions on the many individual stars near the location of the X-ray sources (even crowded field reduction packages such as DAOPHOT fail to provide accurate results under conditions as crowded as those in the cores of globular clusters), we have chosen to prepare maps of the $U-B$ color of the central regions of the clusters.

Using these color maps, we have found a candidate for the optical counterpart of the source in NGC 6712, which would not have been possible to discover through crowded field photometry. We have also found a blue region near the X-ray source in 47 Tuc, although this might well be a chance super-

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position. Upper limits on the colors and magnitudes of possible optical counterparts are reported for the other three clusters. We also explore the use of such color maps in determining color gradients in globular clusters. This method should be less susceptible to chance groupings of bright stars than aperture photometry, as done for example by Hanes and Brodie (1984). We find that while such gradients do exist, and vary from cluster to cluster, they can be explained by crowding effects. We then place crude limits on the excess populations of blue objects such as CVs which have been postulated to be concentrated in the centers of dense clusters (Ostriker 1985). This question will be addressed in detail in a subsequent paper in which we will examine data taken from M15 and NGC 6624 at the CFHT in subarcsecond seeing conditions.

Section II describes the data set, and § III the reduction procedure. In § IV we report the results of the search for optical counterparts to the cluster X-ray sources, and § V discusses the search for color gradients. In § VI we discuss limits which might be placed on excess numbers of blue objects which may exist in the central regions of the clusters.

II. THE DATA

The observing procedures used are described by Lugger *et al.* (1987). Briefly, the data consist of CCD frames obtained with the CTIO 4 m telescope in 1985 May (NGC 6624 and NGC 6712), 1985 January (NGC 1851 and 47 Tuc), and 1986 August (NGC 6441), and the KPNO No. 1 0.9 m in 1984 May (M15). The image scale is $0\farcs60$ per pixel for the CTIO frames, and $0\farcs48$ per pixel at KPNO. All of the observations were taken under photometric or near photometric conditions (see below for calibration procedure) with seeing disks of $\lesssim 1\farcs5$. The point spread functions we created with DAOPHOT typically had FWHM radii of $\sim 1\farcs2$, (the largest FWHM being $1\farcs42$ for the U frame of NGC 1851), confirming our estimation of the seeing.

III. REDUCTIONS

Both X-ray identifications and core structure were studied by searching for color anomalies and gradients. The basic data were color maps, created by dividing the U frame by the B frame. Thus they are essentially images in $U-B$. Before the division was made, however, the two CCD frames had to be matched in several ways. This process was greatly facilitated by carrying out standard DAOPHOT crowded star field reductions (Stetson 1987) on the outer portions of each frame. In the outer parts of the frame the star images were crowded enough to require DAOPHOT, but not so crowded that meaningful results were difficult to obtain, as was the case in the cores of the denser clusters.

Performing DAOPHOT reductions gave us several necessary results. First, the creation of a point spread function allowed an accurate comparison of the size of the images in the various frames. There were two cases in which the image size varied significantly between the U and the B frames (M15 and NGC 1851), most likely due to wavelength-dependent atmospheric effects, but also possibly due to changes in focus or filter. For these clusters, a two-dimensional Gaussian smoothing was applied to the sharper frame (in both cases the B frame) such that the seeing in the frame was degraded to that in the initially "fuzzier" frame. While this obviously resulted in a loss of information from the sharper frame, it eliminated the problem of "donuts" in the divided image. (These artifacts arise in dividing two frames with different seeing; in the center of a star, the frame with better seeing dominates, while at the edges, the frame with worse seeing records more light. When the frames are divided this results in an annular image.)

In general, the color of the sky background was different from that of the diffuse light from the cluster. Sky subtraction was therefore an important part of the procedure. Without it, pixels with relatively few counts ("holes" in the cluster) were more contaminated by sky than other pixels and tended to appear closer to the sky color, which was generally considerably bluer than the cluster. Thus without sky subtraction, these "holes" appeared in the color map as blue regions; since the sky becomes more apparent at larger radii, significant radial color gradients are artificially introduced. To determine the sky levels in each frame, we used the technique discussed by Djorgovski (1987). We measured the median intensity of two 50×50 pixel boxes at the corners of the frame furthest from the center of the cluster. For five of the clusters, the sky levels determined from the two boxes were the same to within a few percent. For NGC 6712, the presence of the on-chip amplifier in one corner (which created significantly hotter pixels in the U frame) prevented the comparison from being made. Since the center of the cluster was positioned at the other end of the chip, the presence of the on-chip amplifier should have no effect on data from the center of the cluster.

DAOPHOT also provided accurate centroids for star images near the edges of the frames. From these stars offsets between the two frames were determined in the following form:

$$x_B = Sx_U + Ty_U + V\ , \quad y_B = Wx_U + Yy_U + Z\ . \qquad (1)$$

The parameters S, T, V, W, Y, and Z were determined by a least-squares fitting procedure in each direction; the residual for each of the ~ 10 stars was less than 1/10 of a pixel. The division of the frames was then made as follows. For each pixel in the denominator (B) frame, the appropriate offset was performed in the numerator (U) frame. Since in general the offset does not fall in the exact center of a pixel, an appropriately weighted average of the four nearest pixels in the numerator frame was used for the division. This procedure eliminated the ridge-like artifacts that would otherwise be present in the color maps.

The calibration of the resulting color maps was carried out by using standard extinction coefficients ($k'_{UB} = 0.27$ for CTIO and $k'_{UB} = 0.30$ for KPNO) together with standard stars taken on the same nights as the data to determine the zero-points C and D, defined such that

$$U-B = C + D[(u-b) - k'_{UB}X]\ , \qquad (2)$$

where $U-B$ is the true color, $u-b$ the instrumental color uncorrected for extinction, and X the air mass. Note that we assume the secondary extinction coefficient was equal to zero, which is consistent with the data from our standard stars. Given the transformation coefficients C and D, the relation between $U-B$ colors and the ratios of CCD counts could then be determined by the following expression:

$$\log \frac{N_U}{N_B} = \log \frac{t_U}{t_B} - 0.4\,\frac{(U-B)-C}{D} + k'_{UB}X\ , \qquad (3)$$

where $N_{U,B}$ are the numbers of counts in the U and B frames, respectively, and $t_{U,B}$ are the exposure times of the U and B frames. In the 1985 May CTIO run, enough standard stars were measured that we could determine extinction coefficients empirically. For the night of 1985, May 12/13, which was photometric throughout, good agreement with the standard CTIO values given above was found. On 1985 May 13/14 and Jan 17/18, use of the above coefficients yielded magnitudes correct to within ± 0.04 with a few exceptions, for which the conditions were presumably not photometric. An appropriate color bar has been added along the side of each map (see Figs. 1*a*–1*f* [Pl. 2–7]).

IV. SEARCH FOR OPTICAL COUNTERPARTS

The color maps resulting from the above procedure are shown in Figures 1*a*–1*f*, as are the *B* frames of the same regions of the clusters. In each plate, an error ellipse equal to 3 times the 1 σ errors given by Grindlay *et al.* (1984) for the position of the X-ray source is shown. It should be noted that this does not necessarily correspond to a 3 σ error (since the systematic errors in the HRI positions are $\sim 1''$–$2''$, and thus the errors will not have a purely Gaussian distribution) and that we have not considered the astrometric errors ($\lesssim 1''$) incurred in locating the center of the error ellipse on our maps. Each plate shows the *B* frame and the color map for the central 100 × 100 pixel region of the cluster. Color bars have been added to the color maps for calibration: in all cases the color range is from $U-B = 1.4$ on the bottom to $U-B = -0.4$ on the top. However, the contrast levels chosen vary from cluster to cluster to show the features studied to best advantage. We have analyzed these results to look for especially blue stars within the error ellipses which might be optical counterparts of the X-ray sources. The results of this effort are described below for each cluster.

a) NGC 6712

NGC 6712 is unusual for a cluster with a high-luminosity X-ray source because it has a large core radius ($\sim 40''$) and a low central density. Grindlay (1985, 1986) has suggested that the presence of a high-luminosity X-ray source in this cluster (presumably the result of tidal capture) indicates that NGC 6712 is currently in a state of postcollapse expansion. The low M/L ratio determined for the central regions of the cluster by Grindlay *et al.* (1987) would suggest a relatively small population of neutron stars, making the formation of an X-ray binary even less likely. The low central density of the cluster allows giants to be resolved all the way into the central core of the cluster (Sandage and Smith 1966). Thus we might expect to see a faint very blue object more easily in the center of this cluster than in the others.

Such indeed proves to be the case. At the north-west corner of the error ellipse for the X-ray source are several of the bluest pixels in the entire cluster. This object can be clearly seen in Figure 1*e*. The only significantly bluer pixels are those associated with the UV–bright sdO star discussed by Remillard, Canizares, and McClintock (1980). Also, in the southwest corner of the frame is a particular star which saturated in the *B* exposure, giving rise to artificially blue pixels. There are three other regions as blue as that in the error ellipse elsewhere in the frame (the most prominent of which is at the far eastern edge of the frame). The blanked out areas of the map correspond to regions which have less than twice the sky brightness; they have been arbitrarily set to the color of the sky and are therefore much bluer than the cluster, which has $E_{B-V} \approx 0.6$ (Webbink 1985).

There are $\sim$9000 pixels which were not set to the sky brightness as described above. Some 12 of these pixels fall inside the plotted error ellipse. Any given object therefore has a 0.0013 chance of falling within the error ellipse. Thus the chance probability that one of the four bluest objects in the frame will fall inside the ellipse is 0.5%.

The presence of nearby, brighter stars, and fluctuations in the background level of the cluster prevented us from identifying the candidate in the *U* and *B* images of the cluster directly, although K. Cudworth (private communication) reported that *B* and *V* plates taken at Las Campanos in subarcsecond seeing conditions confirm the presence of a faint blue star at this position. Despite the failure of standard photometric techniques in our data, we were able to place limits on the magnitude and color of the blue object. We used DAOPHOT to subtract stars of various magnitudes and colors from the center of the blue spot (performing the appropriate offset so that the centers of the stars corresponded). We then divided the subtracted frames in the manner described above, and examined the resulting color map. We found that if the subtracted star was faint and/or red enough, the region of our proposed optical counterpart remained bluer than any other pixels in the central 15 × 15 pixel region of the cluster. Conversely, if the subtracted star was very bright and blue, then, when it was subtracted, either the area near the counterpart became redder than any of the other pixels in the central region or the count rate became lower than the other pixels. In this way we determined the allowed range of color and magnitude depicted in Figure 2 for the blue object. The asterisk in Figure 2 denotes the position in the color-magnitude diagram of an object with properties identical to that reported by Auriere, Le Fevre, and Terzan (1984) for AC 211 (the optical counterpart for the X-ray source in M15 with $U = 14.7$, $B = 16.1$) if it were placed in a cluster with the distance and reddening of NGC 6712. The position of our proposed optical counterpart (subject to an absolute astrometric accuracy of $\sim 0\farcs5$ and a relative uncertainty in the centroid of the blue spot of $\sim 0\farcs3$) is

$$\alpha_{1950} = 18^{\mathrm{h}}50^{\mathrm{m}}21\fs13 \; ; \quad \delta_{1950} = -8°46'3\farcs8 \; .$$

We note that it is well within the error ellipse for the X-ray source, being offset by $1\farcs0$ from the X-ray position. Given the presence of relatively luminous, very nearby stars, this object will be extremely difficult to observe spectroscopically from the ground; its faintness ($M_B \gtrsim 20$) may also prevent successful observations of this object with the Hubble Space Telescope.

b) M15

The star AC 211, which has recently been confirmed as the optical counterpart of the X-ray source in M15 by the detection of identical X-ray and optical orbital periods (Naylor *et al.* 1986; Ilovaisky *et al.* 1986, 1987; Hertz 1987), is clearly seen. The central pixel of that star, situated 2″ directly to the east of the plotted error ellipse, is the bluest spot in the central portion of the map. The somewhat bluer areas in the outer regions of the cluster correspond to the positions of very faint blue horizontal branch stars (Bailyn *et al.* 1987; Buonanno *et al.* 1984) in relatively uncrowded environments. We had only moderately good seeing conditions, much worse than Auriere *et al.* (1984) or Ilovaisky *et al.* (1987). The data from M15 are included here to demonstrate that a blue object can be discovered in a color map under conditions when it would be very difficult to find the object by performing photometric reductions on the *U* and *B* frames separately. Our astrometric measurements show that the position of the bluest pixel agrees to within $0\farcs3$ with the position given by Auriere, Le Fevre, and

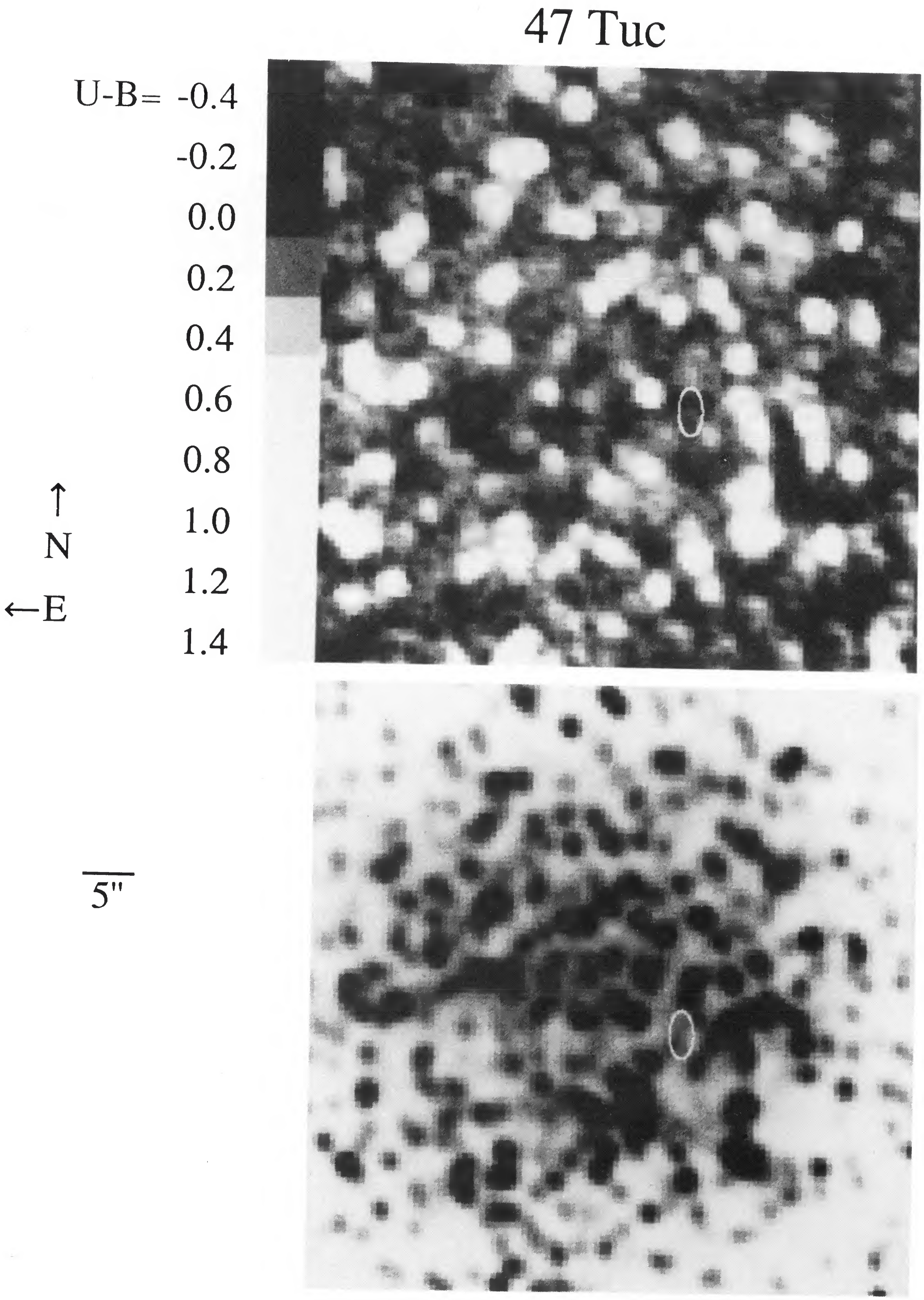


FIG. 1a

FIG. 1.—Color maps (*top*) and *B* frames of the globular clusters studied. Centers of the regions shown coincide with the centers of the globular clusters as given in Grindlay *et al.* (1984). Error ellipses for the X-ray sources, constructed as described in the text are given.

NGC 1851

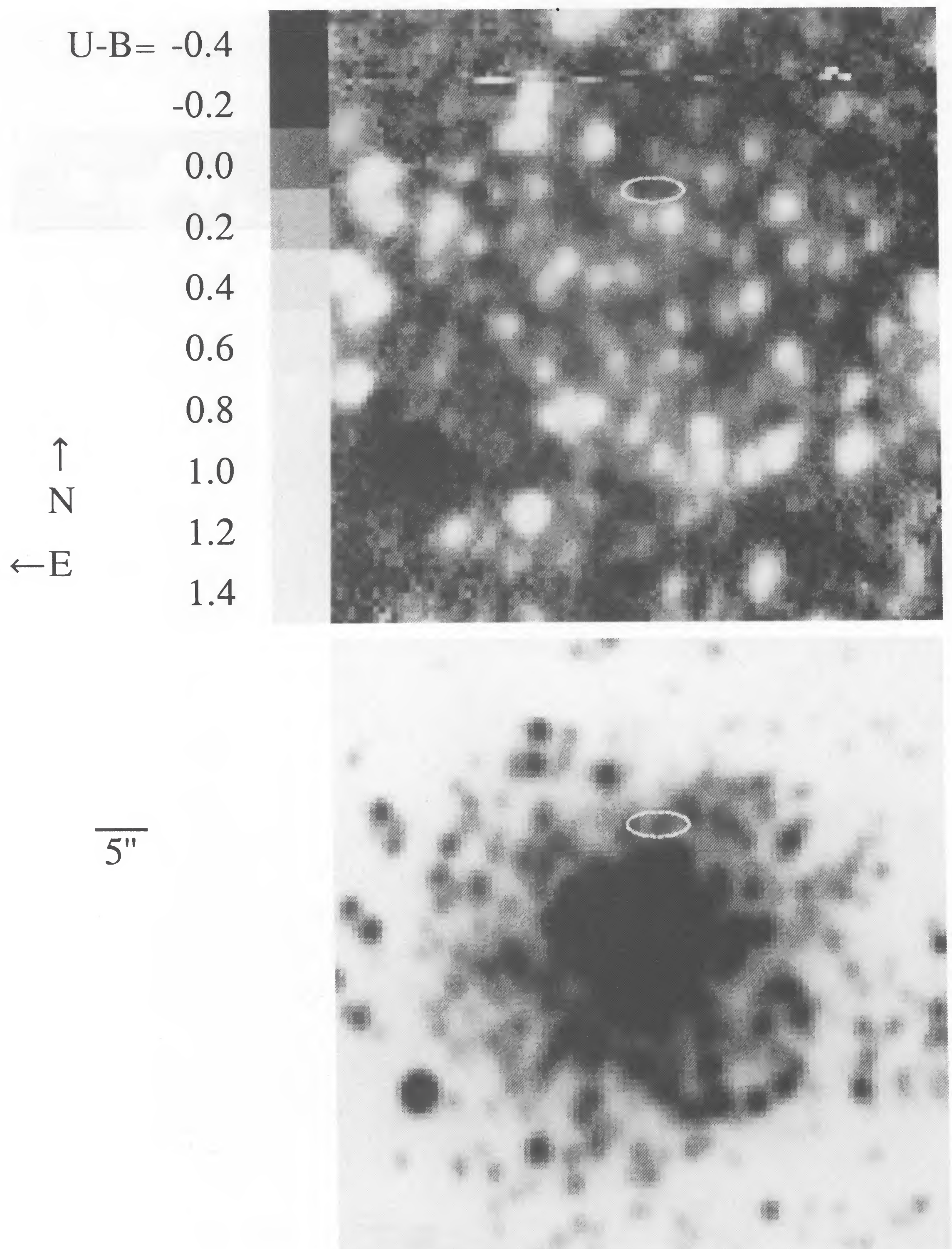


FIG. 1*b*

BAILYN, GRINDLAY, COHN, AND LUGGER (*see* **331**, 305)

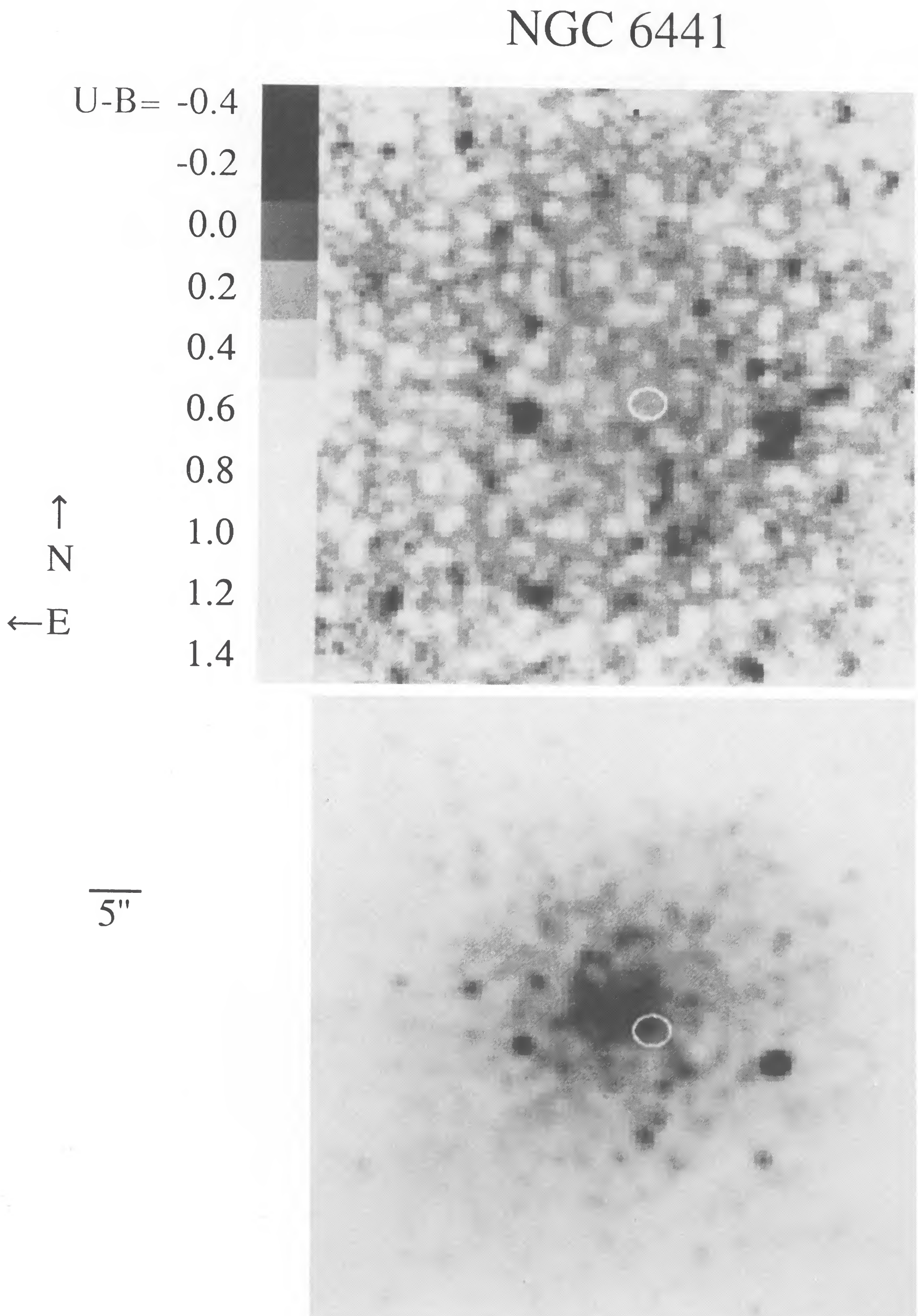
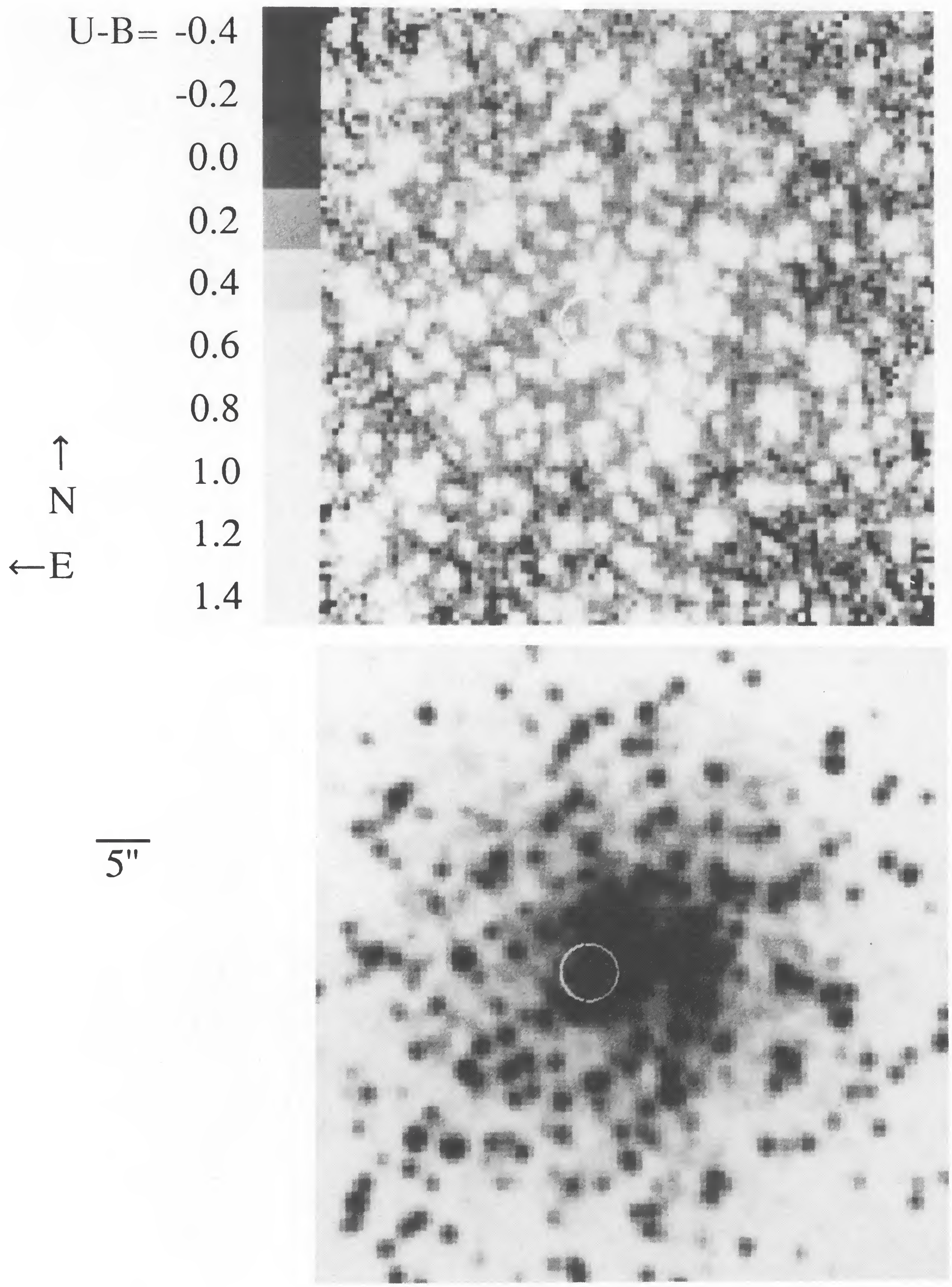


FIG. 1c

NGC 6624



BAILYN, GRINDLAY, COHN, AND LUGGER (*see* **331**, 305)

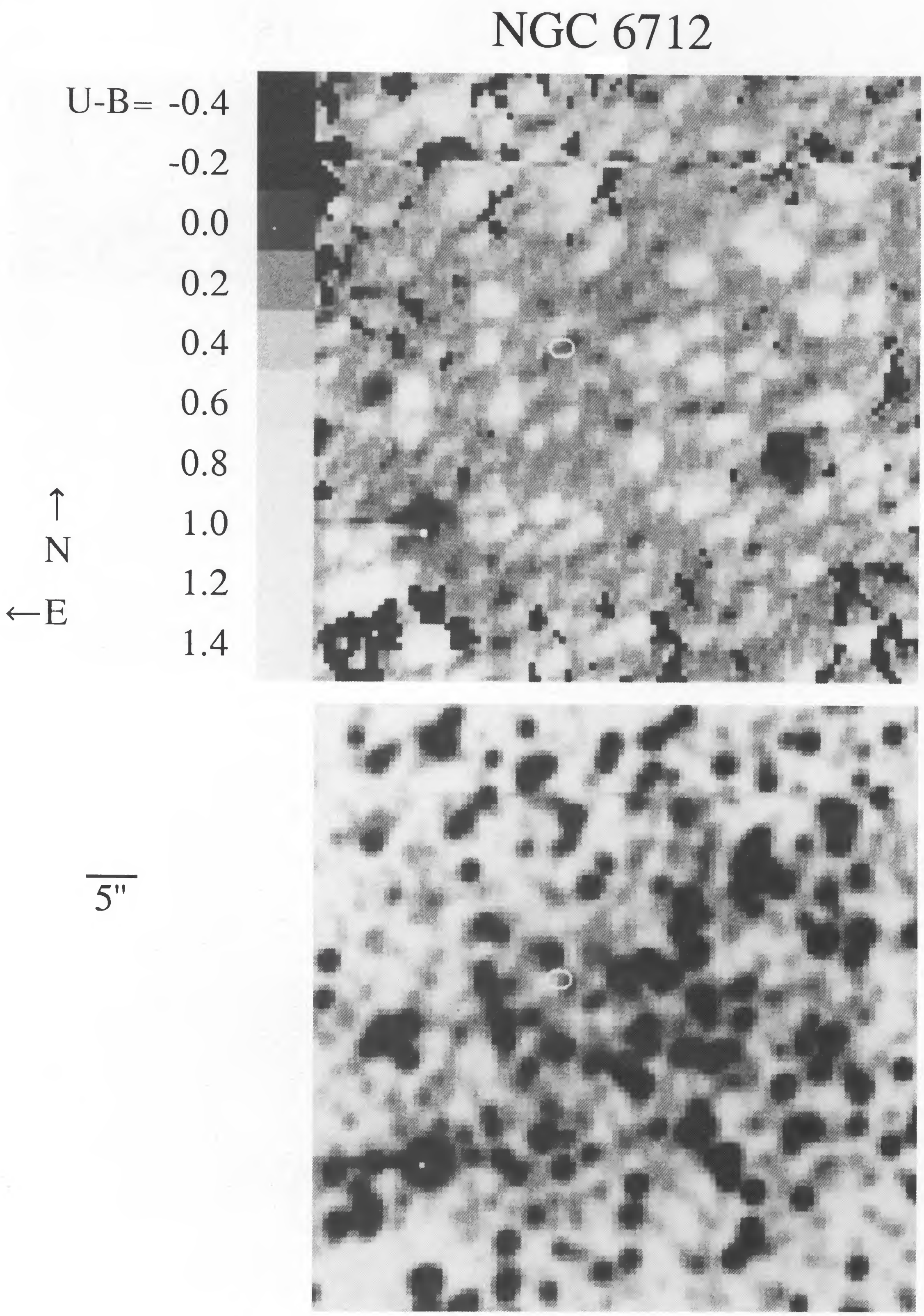


FIG. 1*e*

BAILYN, GRINDLAY, COHN, AND LUGGER (*see* **331**, 305)

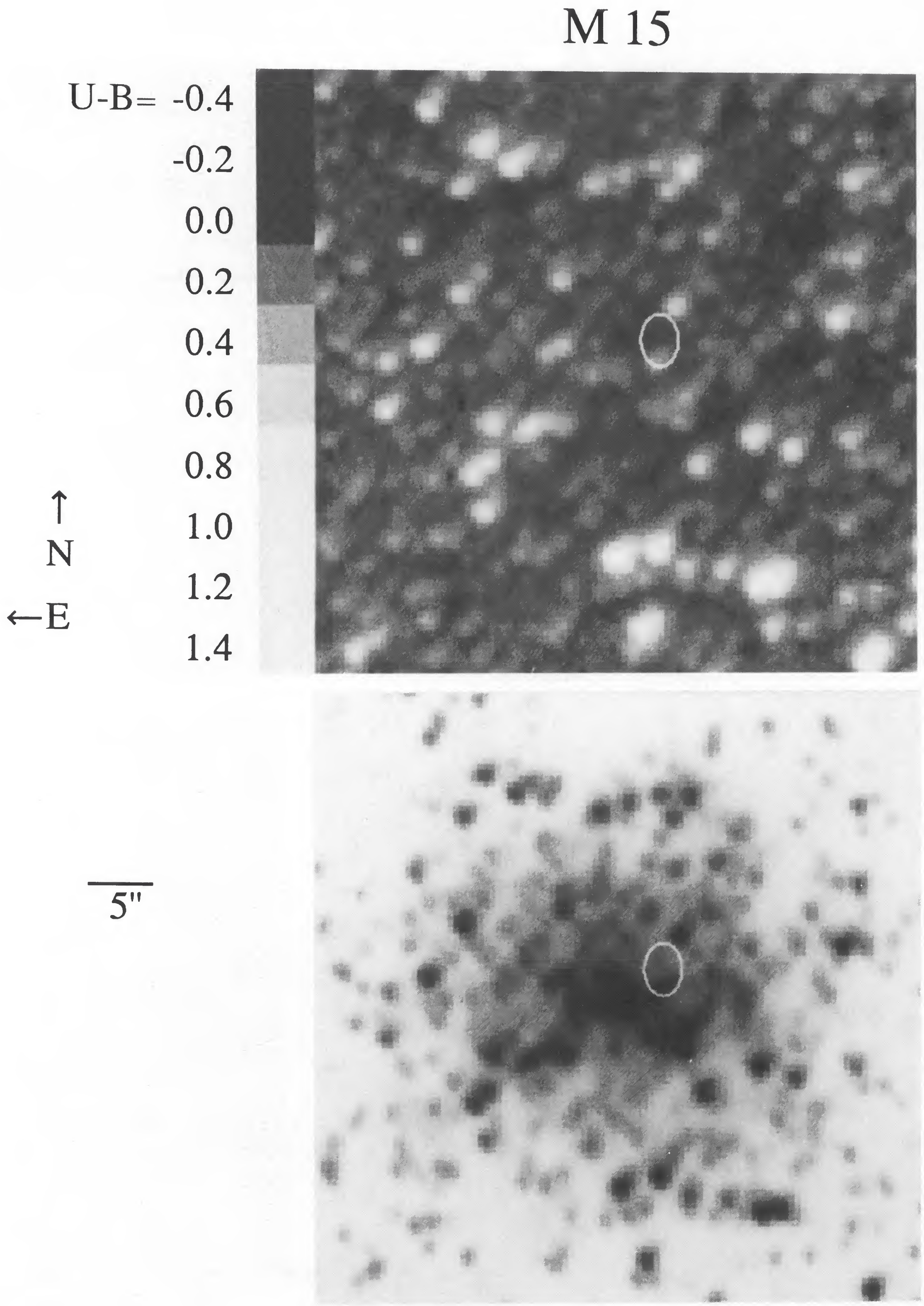


FIG. 1*f*

BAILYN, GRINDLAY, COHN, AND LUGGER (*see* **331**, 305)

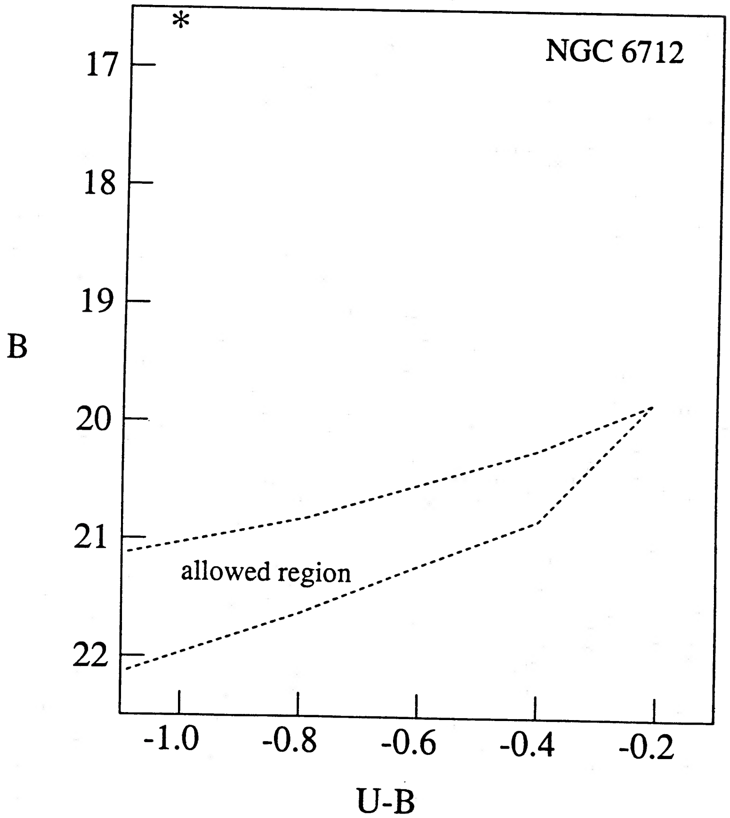


FIG. 2.—Limits on $U-B$ color and B magnitude of the proposed optical counterpart of the X-ray source in NGC 6712. The asterisk represents the position in the diagram of AC 211 (the optical counterpart of the X-ray source in M15 observed by Auriere, Le Fevre, and Terzan 1984 to have $U = 14.7$ and $B = 16.1$) if it were at the distance and reddening of NGC 6712.

Terzan (1984) for AC 211, which indicates that it is slightly outside the error ellipse constructed in the manner described above for the X-ray source. It is not clear why the systematic errors in the HRI position, which presumably are responsible for the misalignment of the X-ray and optical positions of this source, are as large as 2″.

To test the reliability of the procedure described above for placing limits on the magnitude of our proposed optical counterpart to the X-ray source in NGC 6712, we have performed the same calculation for AC 211. The results are shown in Figure 3. The dotted lines represent the limits placed on the magnitude and color of AC 211 from our data. The asterisk, which represents an object with $U = 14.7$ and $B = 16.1$ as reported by Auriere, Le Fevre, and Terzan (1984), falls some distance outside these limits. However, Ilovaisky *et al.* (1987) have recently reported that the U magnitude of AC 211 varies by over 1 mag, from $U = 14.5$ to $U = 16.1$. These limits are represented in Figure 3 by the solid lines. Our limits on the magnitude and color of AC 211 overlap with this region, and our results are therefore not in conflict with previous observations.

c) *NGC 6624*

No optical counterpart was found within the X-ray error ellipse of NGC 6624. We have attempted to place limits on the magnitude and color of the optical counterpart in the following manner. We used DAOPHOT to add stars of a given magnitude and color inside the X-ray error ellipse in the same way in which we subtracted stars from NGC 6712 (we have altered DAOPHOT so that random noise is added as well as the appropriately scaled point spread function). We then divided the frames with the added star, to see if a pixel bluer than any in the surrounding 15 × 15 pixel region could be found. If such a pixel was found, we assumed that a star of the color and magnitude added would have been detected if present. We note that this procedure is not a true limit on the magnitude and color of the source, since what we are doing is adding a *second* source to the cluster. However, the limits obtained do give some indication of what properties an object must have in order to be detected in our color maps.

The results proved to vary greatly depending on where within the error ellipse the star was added, due to the variations in the cluster background. We therefore examined stars added at each of a grid of eight points within the error ellipse. Figure 4*a* shows the limits on the color and magnitude of the optical counterpart obtained from the grid point at which it was easiest to see a potential counterpart, and from the grid point at which such a counterpart was the most difficult to detect. The asterisk again indicates the location in the color-magnitude diagram of a star with the properties reported by Auriere, Le Fevre, and Terzan (1984) for AC 211 if placed in a cluster with the distance and reddening of NGC 6624. We note that even for the grid point at which an optical counterpart would be the easiest to detect, the limit of detectability is $M_B \approx 19$. This is 1 mag brighter than the maximum optical luminosity the source could be expected to have, given the current model for this source of a Roche lobe filling white dwarf orbiting a neutron star (Bailyn and Grindlay 1987).

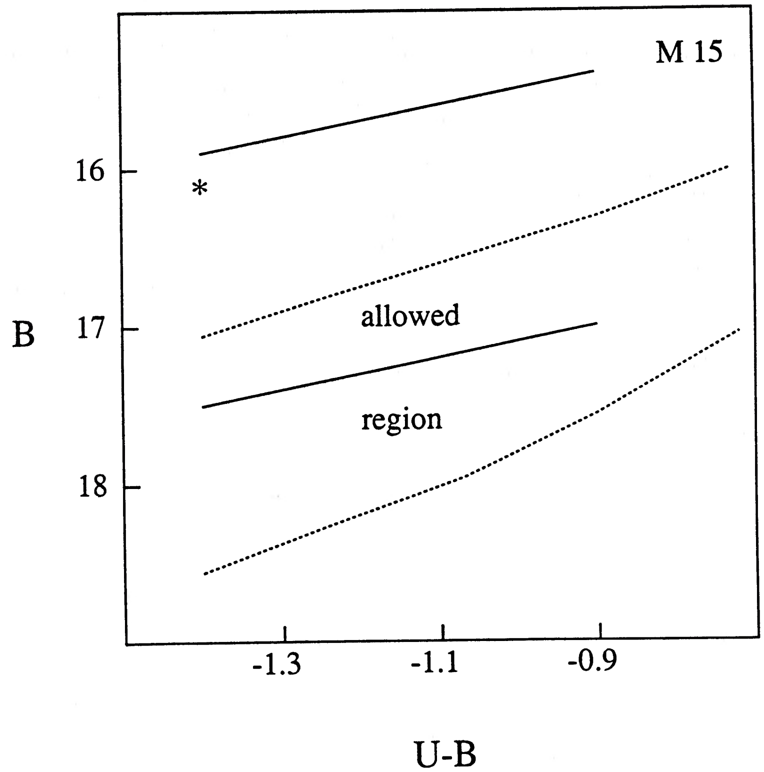


FIG. 3.—Limits on the $U-B$ color and B magnitude of AC 211 as observed in our data in a similar manner as the proposed counterpart of the X-ray source in NGC 6712 (*dashed lines*). Asterisk denotes the colors and magnitude of AC 211 as observed by Auriere, Le Fevre, and Terzan (1984), and solid lines show the limits on the U magnitude of AC 211 found by Ilovaisky *et al.* (1987).

d) NGC 1851

The X-ray source in NGC 1851 is unusual for a high-luminosity globular cluster source because it is far away from the center of the cluster, being displaced almost two core radii to the north of the center (Grindlay *et al.* 1984). This should make any optical counterpart easier to detect, since it lies in a less densely populated region. Nevertheless, we find no evidence for a blue object in or near the error ellipse. A *UV*–bright giant similar to the one in NGC 6712 is clearly visible in the southeast corner of the $U-B$ color map. This object is the UV–bright giant discussed by Vidal and Freeman (1975), and may be the source of the reported UV flux observed with *IUE* from this cluster (Grindlay 1985).

We have placed limits on the color and magnitude of a possible optical counterpart for this X-ray source in a manner similar to that for NGC 6624. We added blue objects to both the B and U frames in eight locations within the error ellipse. The criterion for "detecting" an artificially added counterpart was that it should be bluer than any pixel within 15 pixels of either the X-ray position or the center of the cluster (not counting those pixels associated with the UV giant). The limits for the magnitude and color of an optical counterpart are presented in Figure 4*b*.

e) NGC 6441

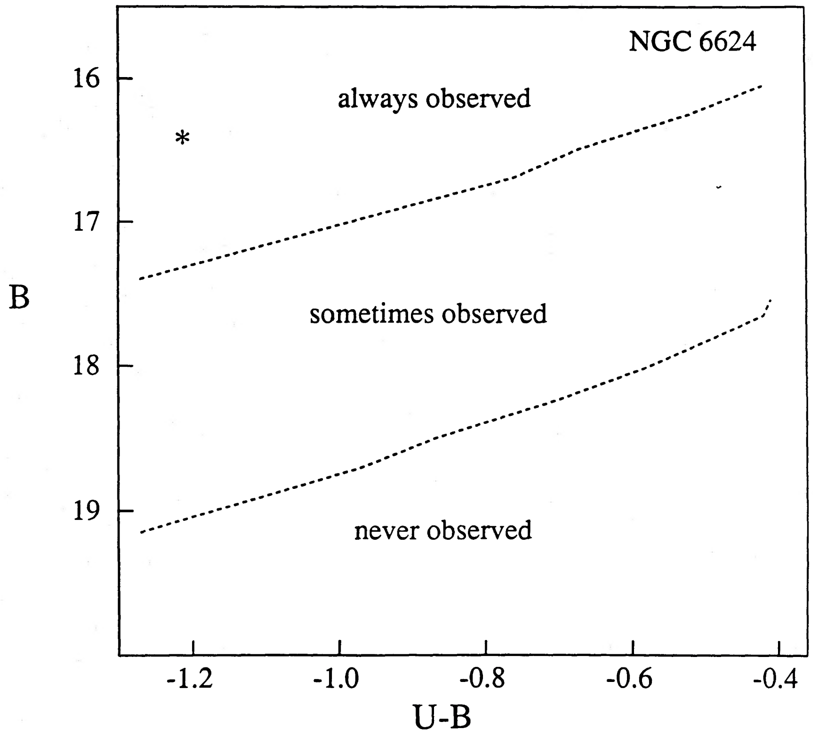
NGC 6441 is a difficult cluster to observe, due to the presence of a nearby 5th magnitude star. The scattered light from this star is evident on both the U and the B CCD images obtained for this cluster, and it results in a gradient in the background light across the cluster. For this reason the $U-B$ color map (Fig. 1*c*) appears generally redder at the bottom and bluer at the top.

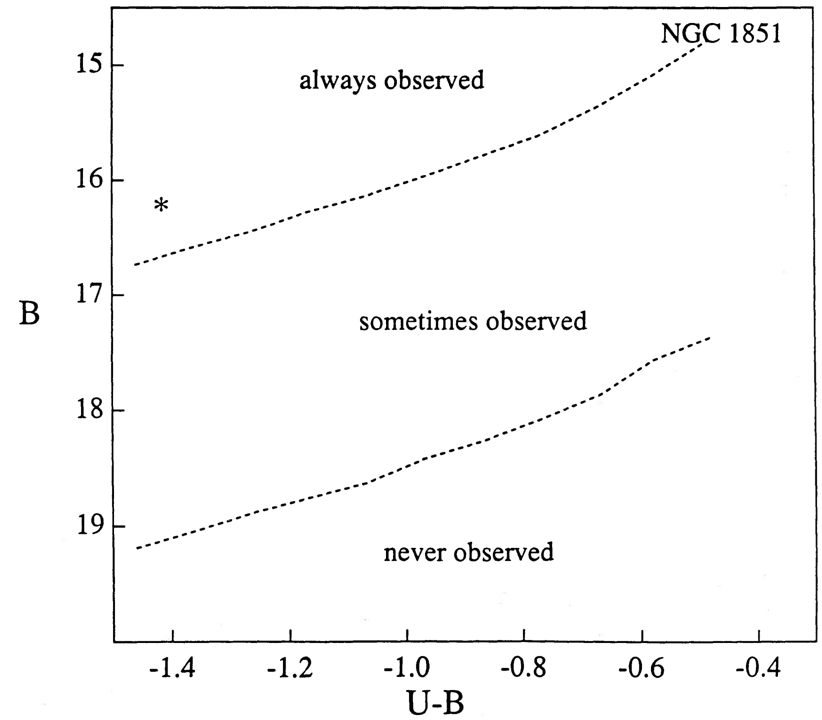
The color map also shows that the cluster has an excess of blue stars compared to the other clusters discussed here. There are two stars which appear to be similar to the UV–bright giants in NGC 6712 and NGC 1851, and also several other, dimmer blue stars. There are also many red giants apparent in the outer regions of the color map. Examination of the U and B frames confirms that the red and blue stars evident in the color maps exist in the original frames and are not artifacts of the dividing procedure.

Despite the many individual stars visible in the outer regions of the color map, the central regions of the cluster show a more uniform color than the other clusters we examined. The variations in color within 15 pixels of the position of the X-ray source are not extreme. Thus we have been able to use the procedure discussed for NGC 6624 to place limits on the magnitude and color of a potential optical counterpart for the X-ray source. Our results are presented in Figure 4*c*.

f) 47 Tuc

The X-ray source in 47 Tuc is of a different character than the other sources studied in this paper, in that its luminosity is considerably lower ($L \approx 10^{34.5}$ ergs s^{-1}). This places it below the luminosity gap (Hertz and Grindlay 1983) and between the "high" and "low" luminosity globular cluster sources. This source may therefore be associated with a CV with a white dwarf primary, rather than with a neutron star primary (although it could be a neutron star transient source in quiescence). It is included in this survey because the existence





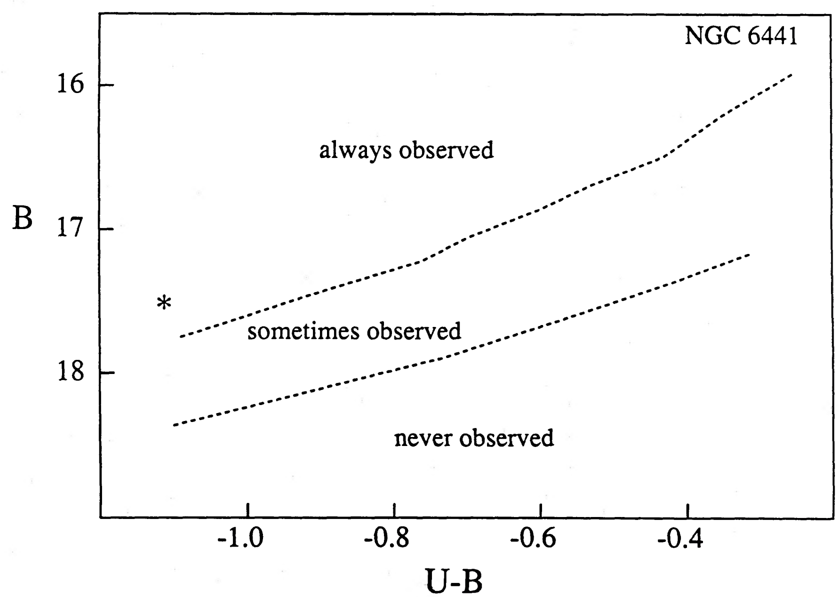


FIG. 4.—Limits on the $U-B$ color and B magnitude of any optical counterpart of the X-ray sources in (*a*) NGC 6624, (*b*) NGC 1851, and (*c*) NGC 6441. The asterisk, as in Fig. 1, represents the position in the diagrams of AC 211 if it had the distance and reddening of the cluster in question. The color-magnitude diagrams are divided into three regions corresponding to colors and magnitudes for which added stars could be detected anywhere within the X-ray ellipses, colors, and magnitudes for which added stars could be detected in some parts of the error ellipses, and colors and magnitudes for which added stars could not be detected anywhere in the error ellipses.

of an *Einstein* HRI position (Hertz and Grindlay 1983) enables us to put much stronger limits on its location in the cluster than is true for most other low-luminosity sources.

We find that the bluest pixel within 15 pixels of either the core of the cluster or the X-ray source lies just outside the error ellipse. We do not believe that this reflects any unusual systematic effect arising from this particular pixel, since several neighboring pixels are also relatively blue. However, other regions in the center of the cluster have almost the same color as that of this bluest pixel, and are bluer than the neighboring pixels. It may be that the presence of this blue region near the X-ray error box is a chance superposition. We can determine the chance probability that the bluest pixel within 15 pixels of the center of the cluster should lie as close to the X-ray position by noting that ~ 32 pixels are as close or closer to the error ellipse as the blue spot. Thus the coincidence probability is $32/(15^2\pi)$ or $\sim 5\%$. Given that we are examining a number of clusters, it is not at all surprising that such a chance superposition would occur.

V. SEARCH FOR COLOR GRADIENTS

We have also used the color maps to search for color gradients, in NGC 1851, and in NGC 6624 and M15, which have been shown to have cusps, i.e., the density profile never flattens out in the central regions (Hertz and Grindlay 1985; Djorgovski and King 1986; Lugger *et al.*, 1987). Such cusps are thought to be indicative of postcollapse clusters and might be expected to be bluer than the rest of the cluster due to the formation of large numbers of tidal capture binaries (Grindlay 1985; Ostriker 1985). For each of these clusters we have examined the distribution of colors in the central 30 × 30 and 90 × 90 pixel regions. A gradient in the stellar populations of the clusters resulting in a color gradient in the cluster should in principle be apparent in a different distribution of colors between the 30 × 30 and 90 × 90 pixel regions. Since these distributions reflect the *area* which displays a certain color, rather than the total magnitude in the two colors, this procedure will be less prone to contamination by chance groupings of luminous red giants in the central regions of the cluster, a problem which has plagued attempts to measure color gradients in clusters by aperture photometry (e.g., Hanes and Brodie 1984). However, crowding effects may result in apparent changes in color, as described below.

Our results show that such radial gradients do exist, and vary from cluster to cluster. However, they can be completely explained by crowding effects. A color gradient due to crowding would be expected if the rare bright stars (red giants in the case of a globular cluster) are a different color than the more numerous dimmer stars which make up the background cluster light. A crowded field should have proportionally more pixels dominated by bright stars than an uncrowded field, and thus the distribution of a crowded field would be skewed toward the color of the rare bright stars. We therefore expect the inner regions of the cluster to be redder than the outer regions. This was found to be true in all clusters except M15 (see Figs. 5*a*–5*c*), which is well known to have an extremely blue horizontal branch (Buonanno *et al.* 1984; Bailyn *et al.* 1987), and thus the differences in color between the giants and the underlying cluster light should indeed be less than for other clusters. As noted above, blue regions corresponding to the positions of these blue stars can be seen in the outer regions of the color map, along with red regions corresponding to normal giants, and these two kinds of stars might be expected to cancel each other out to some extent in the most crowded regions of the cluster.

We have calculated the significance of the difference between the various regions by performing a two-sided Kolmogorov-Smirnoff test on the histograms of number of pixels versus color ratio. The probability that two observed distributions are drawn from the same population is

$$P = Q\left[\left(D\,\frac{N_1 N_2}{N_1 + N_2}\right)^{1/2}\right], \tag{4}$$

where D is the maximum deviation of the two normalized cumulative distributions, N_1 and N_2 are the number of independent samples in each of the two distributions, and

$$Q(x) = 2\sum_{j=1}^{\infty} (-)^{j-1} e^{-2j^2x^2}\,. \tag{5}$$

Since the seeing disk is larger than 1 pixel, each pixel is not an independent resolution element in our data. Therefore the K-S test results were calculated using a smaller number for N than the number of pixels. Given that the seeing was approximately twice the size of a pixel, we believe that 4 pixels per resolution element is appropriate. As can be seen in Table 1, however, the 90 × 90 pixel box is significantly different in color from the 30 × 30 box for NGC 6624 and NGC 1851, even if the resolution is considered to be reduced still further. It should be noted that the 90 × 90 box *contains* the 30 × 30 box. Thus the significance of the difference between them is in fact greater than that reported in Table 1. We hope to be able to examine smaller areas still (for which there were insufficient resolution elements to obtain meaningful results in the data reported here) using observations of M15 and NGC 6624 recently obtained at the CFHT in subarcsecond seeing conditions (Bailyn *et al.* 1988).

The interpretation of the color gradients as crowding effects was confirmed by creating artificially crowded regions for each of the clusters. The mean number of counts per pixel for the crowded inner region was determined, and then similarly sized regions further from the cluster center (appropriately sky subtracted) were added until the mean counts per pixel of this artificially crowded region matched that of the central region. Regions containing the UV–bright star in NGC 1851 were *not* coadded, since this bright blue object significantly skewed the resulting color distribution. We then performed two-sided KS tests like those described above between the color distributions of the artificially crowded frames and the true central regions of the cluster. No significant differences were found.

TABLE 1

COMPARISON OF 30 × 30 and 90 × 90 PIXEL CENTRAL REGIONS OF CLUSTERS

Cluster	Pixels per Resolution Element	Chance probability of Same Distribution
NGC 6624	4	2.8×10^{-13}
	9	3.9×10^{-6}
	16	1.2×10^{-3}
NGC 1851	4	5.2×10^{-13}
	9	7.1×10^{-6}
	16	1.5×10^{-3}
M15	4	2.5×10^{-2}
	9	0.29
	16	0.64

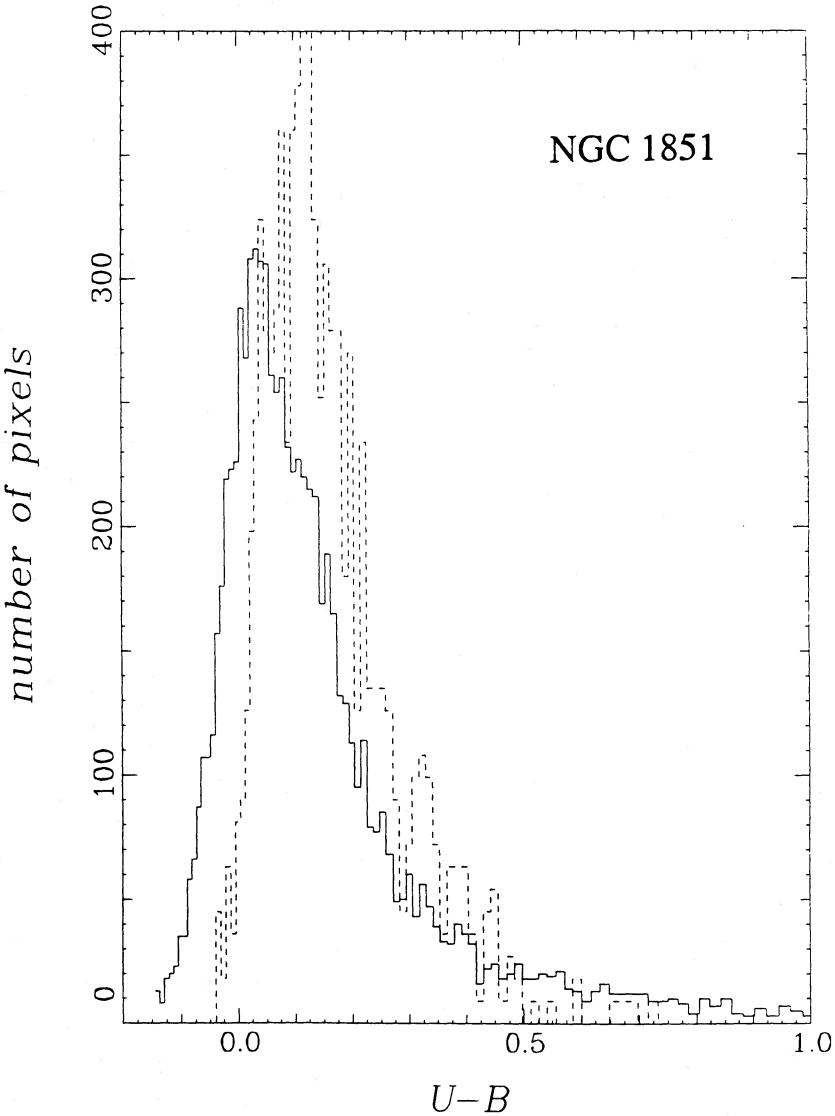


FIG. 5*a*

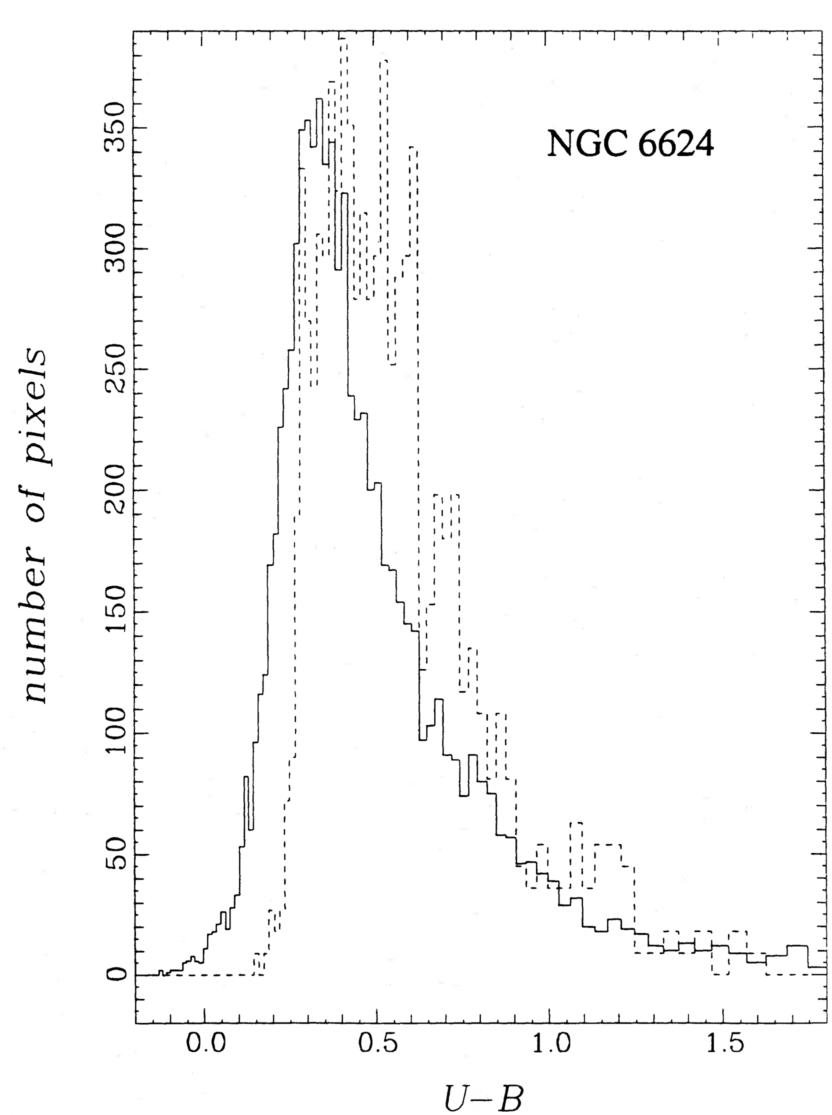


FIG. 5*b*

FIG. 5.—Distributions of the colors of the central 30 × 30 pixel box (*dotted line*) and 90 × 90 pixel box (*solid line*) in the globular clusters (*a*) NGC 1851, (*b*) NGC 6624, and (*c*) M15. The *y*-axis for the 30 × 30 box has been multiplied by nine. The bins are in equal intervals of the ratio of *U* counts to *B* counts. Note that the two distributions are significantly different for NGC 1851 and NGC 6624.

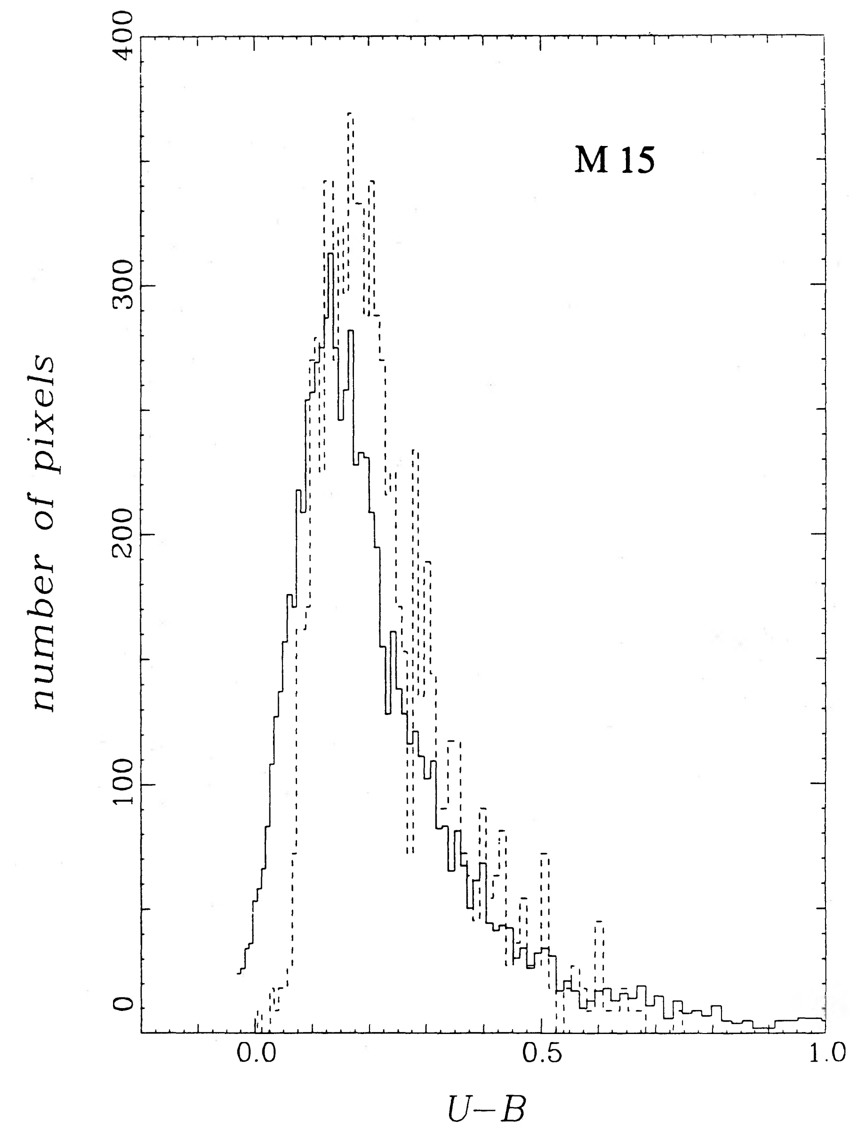


FIG. 5c

VI. DISCUSSION

Since the discovery of the dense central cusps of such clusters as M15 and NGC 6624 (Newell and O'Neil 1978; Djorgovski and King 1984; Hertz and Grindlay 1985; Djorgovski and King 1986; Lugger *et al.* 1987), it has been speculated that these cusps should contain large numbers of tidal capture binaries (Ostriker 1985). This might result in an excess in the number of binaries in which one component overflows its Roche lobe (e.g., cataclysmic variables, CVs). Such binary systems might be expected to be significantly bluer than other globular cluster objects. Several methods of searching for this population of stars are described by Grindlay (1987), who also describes some evidence of increased Hα emission in the central regions of M15.

Our result that the color gradients in these globular clusters can be accounted for by crowding effects enables us to place crude limits on any excess of blue objects in the centers of M15, NGC 6624, and NGC 1851. As before, we compare the central 30×30 pixels of a color map with a similarly sized region with the same total count rate created by coadding several regions farther from the center of the cluster (suitably sky subtracted). This time, however, we also added a smoothly distributed flux to each of the comparison regions. The counts per pixel added to the U and B frames of the comparison region corresponded to a $U-B$ color of -1.0, approximately that expected for a population of CVs. We then divided the resulting artificially crowded frames, and we compare the distribution of colors in this map with that of the true central 30×30 region of the cluster. We experimented with different amounts of the blue flux, and determined how much was needed to produce a 3 σ deviation from the observed color distribution of the true central region. If we assume that the extra blue light is provided by stars with an absolute B magnitude of 5.0, $U-B = -1.0$ and $B-V = 0.0$, the amount of blue flux necessary to induce a 3 σ difference between the color distribution of the central pixels and that of the artificially crowded pixels corresponds to just over 200 stars in NGC 1851 and M15, and 70 stars in NGC 6624.

While these numbers are of the same order of magnitude as the several hundred extra binaries predicted in the central regions of dense clusters (Ostriker 1985), there are several severe difficulties in taking these numbers as representing an upper limit on such an excess population of CVs. Most importantly, since there are 900 pixels in the area we have taken as the central region, and the number of CVs being considered is smaller than this, our assumption that their light is evenly distributed over all the pixels cannot be valid. Also, these stars might well be centrally concentrated within the inner 30 × 30 pixels of the cluster, and for this reason also might not contaminate all pixels equally. Thus the results presented here do not rule out the possibility that a central population of CVs may be emitting large amounts of Hα and UV continuum light in the central cores of these globular clusters. To study this question in detail would require that an appropriate population of CVs with a realistic optical luminosity function (Patterson 1984), distributed properly over the central regions of the cluster, be added star by star to the CCD frames. We are currently examining this problem for comparison with the CFHT data of M15 and NGC 6624 mentioned above.

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