THE ASTROPHYSICAL JOURNAL, 473:L31–L34, 1996 December 10

HUBBLE SPACE TELESCOPE OBSERVATIONS OF THE POST–CORE-COLLAPSE GLOBULAR CLUSTER NGC 6752: A SEARCH FOR CATACLYSMIC VARIABLES

CHARLES D. BAILYN AND ERIC P. RUBENSTEIN
Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101; bailyn@astro.yale.edu, ericr@astro.yale.edu
SHAWN D. SLAVIN, HALDAN COHN, AND PHYLLIS LUGGER
Department of Astronomy, Indiana University, Swain West, Bloomington, IN 47405; sdslavin@indiana.edu, cohn@indiana.edu, lugger@indiana.edu
ADRIENNE M. COOL
Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720; cool@astro.berkeley.edu
AND
JONATHAN E. GRINDLAY
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; josh@cfa255.harvard.edu.
Received 1996 June 20; accepted 1996 September 25

ABSTRACT

We report the results of *HST* WFPC2 observations of the core of NGC 6752. We identify two candidate cataclysmic variables (CVs) from their strong narrowband Hα emission, periodic variability, and, in one case, a UV excess. We interpret the variability of these stars as being double-peaked, ellipsoidal light curves, in which case the orbital periods are 5.1 and 3.7 hr. The CV candidates fall at the edge of the error circle of one of the known X-ray sources in the cluster.

Subject headings: binaries: general — globular clusters: individual (NGC 6752) — novae, cataclysmic variables — white dwarfs — X-rays: stars

1. INTRODUCTION

Large numbers of cataclysmic variables (CVs) should be present in globular clusters. The same processes which produce the overabundance of accreting neutron stars in globular clusters should produce large numbers of CVs as well (e.g., di Stefano & Rappaport 1994). Two nova explosions have been observed in globular clusters (Shara & Drissen 1995 and references therein), which implies a significant underlying population of CVs. Finally, the large observed and inferred populations of low-luminosity globular cluster X-ray sources (LLGCXs) have often been identified as CVs (Hertz & Grindlay 1983).

Optical identifications of this purported large population of cluster CVs have been slow to materialize (Livio 1996). This is largely because CVs are optically faint, and the large stellar densities of globular clusters make them difficult targets, particularly in the cores of dense clusters where they should be most prevalent. However, recent work with the *Hubble Space Telescope* has led to the identification of a number of CV candidates (e.g., Paresce, De Marchi, & Ferraro 1992; Paresce & De Marchi 1994; Shara & Drissen 1995). In particular, Cool et al. (1995) identified three stars as candidate CVs on the basis of strong narrowband Hα flux and UV excesses. Those stars were found to be consistent with the locations of three LLGCXs previously identified by Cool et al. (1993) using the *ROSAT* high-resolution imager (HRI). Recently, spectroscopy with the *HST* Faint Object Spectrograph has confirmed that these stars have spectra similar to those of magnetic CVs (Grindlay et al. 1995).

Here we report *HST* observations of the core of NGC 6752 similar to those carried out by Cool et al. (1995) which resulted in the identifications of the candidates in NGC 6397. We identify two candidate CVs. One of these stars may be associated with one of the X-ray sources identified by Grindlay & Cool (1996). Additional *HST* observations have identified both candidates as periodic variable stars.

2. DATA AND ANALYSIS

We have obtained two sets of observations of the core of NGC 6752 with the *HST* WFPC2 instrument. One set consisted of images taken through the F439W (B), F675W (R), and F656N (Hα) filters. The principal aim of this program was to obtain candidates for CVs and optical counterparts of X-ray sources in the manner described by Cool et al. (1995). The other set was a series of over 300 exposures in the F555W (V) and F814W (I) filters taken over a period of 20 hr when the cluster was in the continuous viewing zone. Because of data transmission limits, only data from the PC chip were recorded in the V and I observations. The principal aim of this program was to search for short-term variability. Here we describe only the results pertaining to the CV candidates discovered with the B, R, and Hα data; a detailed discussion of the V and I data is given by Rubenstein & Bailyn (1996). Both sets of data were obtained on 1994 August 18 and 19. The numbers and exposure times of the images obtained in both programs are listed in Table 1.

The strategy used to find CV candidates in the B, R, and Hα data has been described by Cool et al. (1995). Essentially, we searched for Hα bright objects on or bluer than the main sequence. The deep images were combined using the "crreject" algorithm in the IRAF data reduction package. The data were then analyzed using our own implementation of the "assisted aperture" photometry algorithm described by Yanny et al. (1994). Briefly, we use the DAOPHOT-II/ALLSTAR package (Stetson 1992) to create a point-spread function, and then automatically perform aperture photometry on each star,

TABLE 1

EXPOSURE LOG

Filter	Exposure (s)	Number
F439W	70	1
F439W	700	2
F675W	18	1
F675W	180	2
F656N	120	1
F656N	1200	5
F555W	2	18
F555W	26	117
F555W	80	27
F814W	3	18
F814W	50	108
F814W	160	27

after having subtracted all near neighbors. The results are shown in Figure 1, which is a color-color diagram in H$\alpha - R$ versus $B - R$. In Figure 1 2778 stars with R magnitudes ranging from ≈1.5 mag above the main-sequence turnoff to ≈4.0 mag below the turnoff are shown.

Two stars, labeled 1 and 2 in Figure 1 and the finding chart given as Figure 2, immediately stand out. We have carefully inspected the images of these stars, and they are normal in all frames of all three colors—no cosmic rays, bad pixels, or nearby bright stars appear to have affected them. In contrast, the unusual colors of a third candidate (not shown in Fig. 1) proved on inspection to be an artifact of the overlap of the star and the diffraction pattern of a nearby giant. We have searched prerepair F220W FOC data for these stars. Star 2 lies too close to a nearby subgiant for accurate magnitudes to be obtained. However, star 1 shows an $m_{220} - R$ color which indicates a substantial UV excess (see Fig. 4 in Cool et al. 1995 for comparison to the sources in NGC 6397).

Table 2 summarizes the colors and magnitudes of the two candidates. We have converted the optical broadband colors to the Johnson system, following the prescription of Holtzman et al. (1995). However, we note that accurate aperture correc-

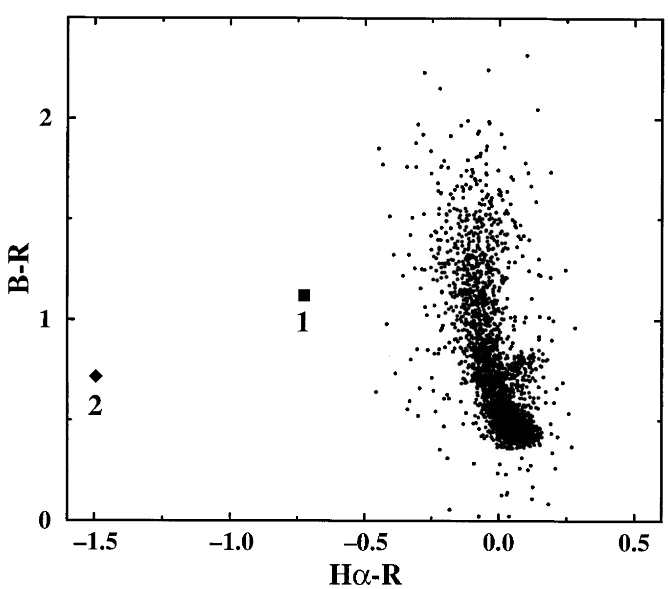

FIG. 1.—$B - R$ vs. H$\alpha - R$ color-color diagram of stars found in the PC image of the core of NGC 6752. The CV candidates are indicated.

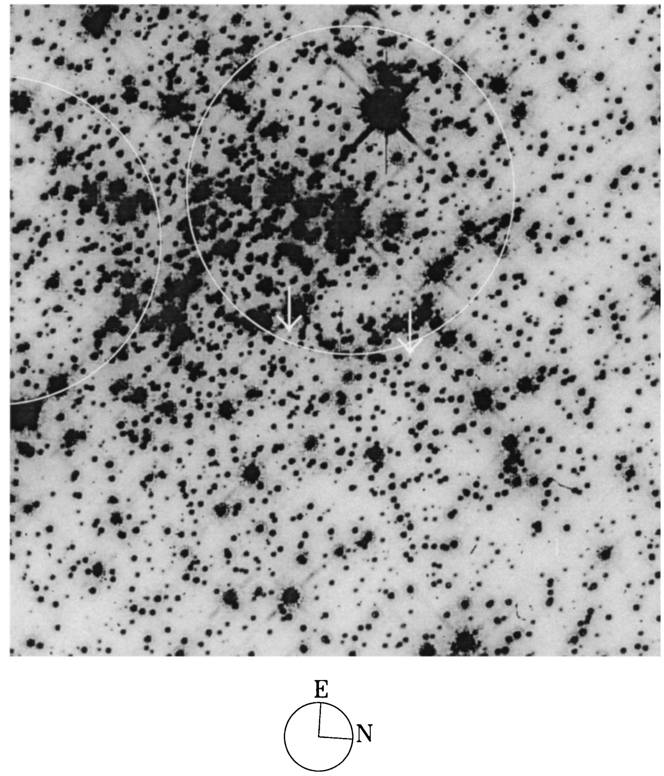

FIG. 2.—Portion of F675W PC image of the center of NGC 6752. The image covers 26′ × 26′. CV candidate 1 is marked by the left arrow, and candidate 2 by the right arrow. Error circle at left of the image is for *ROSAT* source A (Grindlay & Cool 1996), while the more central error circle is for source B.

tions were difficult to obtain in this very crowded field. We therefore expect systematic calibration errors of up to 0.2 mag. Both sources vary on timescales of a few hours, as noted below. The B, R, and m_{220} magnitude, which were taken over a relatively short amount of time, may therefore deviate from the mean by as much as 0.2 mag. The I and V magnitudes, however, reflect averages over many images taken over a 20 hr

TABLE 2

CV CANDIDATES

Parameter	Star 1	Star 2
R.A. (J2000)	$19^h10^m51^s.27$	$19^h10^m51^s.18$
Decl. (J2000).....	−59°58′53″	−59°58′49″
B[a]	21.0	21.5
V[b]	20.55	20.89
R[a]	19.9	20.8
I[b]	19.29	19.70
H$\alpha - R$[a]	−0.7	−1.5
$m_{220} - R$[a]	0.9	...
M_V[c]	7.31	7.65

[a] Given the short duration of the B and R observations, and the known variability of the sources, these values may deviate from the mean by as much as 0.2 mag, in addition to calibration errors of similar size, and photometric errors of ≈0.1 mag.

[b] These are mean values over the medium-length exposures listed in Table 1. The principal sources of error are calibrations to the Johnson system (estimated at ≈0.2 mag); the relative magnitudes are accurate to ≈0.02 mag.

[c] Distance and reddening from Peterson 1993.

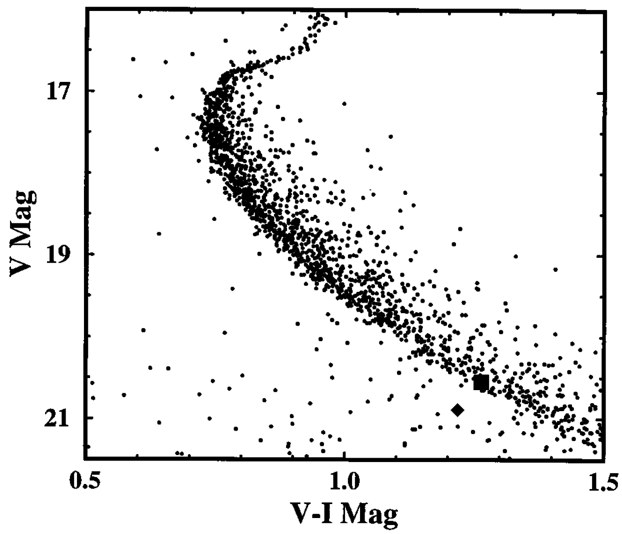

FIG. 3.—$V-I$ color-magnitude diagram of NGC 6752, with CV candidates marked.

period, so they should represent a true mean magnitude for 1994 August 18 and 19.

A similar procedure was applied to the three fields observed with the B, R, and Hα filters and the wide-field (WF) chips. While these fields do not cover the cluster center, they fall within the central few core radii, and therefore might be expected to contain relatively massive objects like CVs. No compelling candidates were discovered. However, the WF data were less sensitive to CVs than the PC data, because of the increased crowding caused by the larger pixel scale. We quantified this effect in two ways. First, we reanalyzed the PC images after performing 2×2 block summing to simulate the resolution of the WF. Second, we added artificial CVs to the WF images. Both methods indicated that the PC is sensitive to CVs about 1.5 mag fainter than can be detected in the WF data. We find that we would recover a CV like candidate 1 in the WF images about 70% of the time, but that we would detect a CV as faint as candidate 2 $\lesssim$ 10% of the time.

The V and I data were analyzed in the following manner (see Rubenstein & Bailyn 1996 for more details). After preparing a summed image, the FIND routine from Stetson's (1987) DAOPHOT2 package was applied to produce a preliminary star list. Sources with shape parameters which differed significantly from those of point sources were deleted from this list, as were sources located within the $\approx$14% of the image dominated by saturated stars and their diffraction patterns. Then, an implementation of the assisted aperture algorithm (the Stellar Photometry System [SPS]) kindly provided by K. Janes and J. Heasley was applied to the star list, producing a master list of 3927 stars. The positions of the stars in the master list were then shifted to match each of the individual V and I frames. We then ran SPS on each individual frame using the master list as input. The recentroiding procedure was turned off for this stage, forcing the positions of the stars to remain fixed. The output was reassembled into a time series for each star in the master list. By taking the average magnitudes for those stars which could be detected in the individual frames, the $V-I$ color-magnitude diagram of 2421 stars shown in Figure 3 was assembled. Since these observations were obtained over a period of 20 hr with interleaved V and I exposures, effects due to short-term

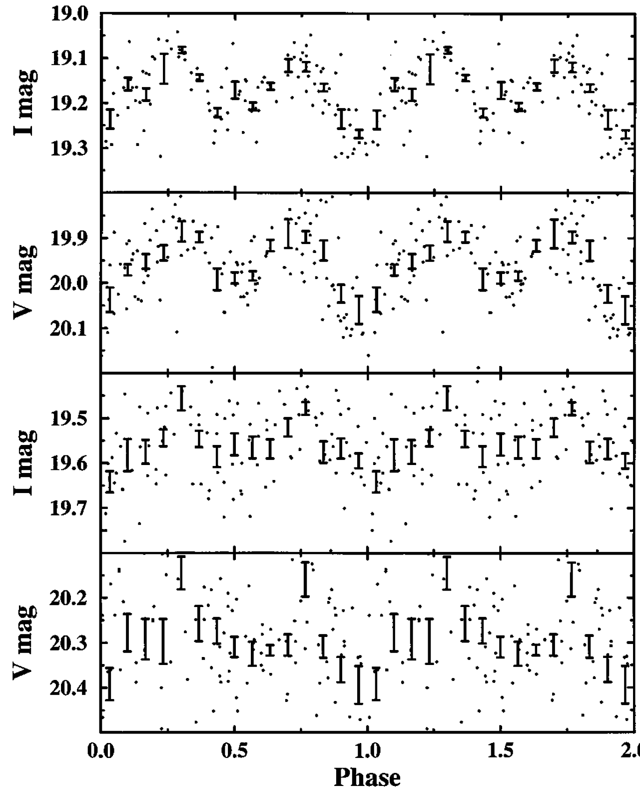

FIG. 4.—Folded time series for the CV candidates. Each time series is comprised of over 100 individual points. We also show the means and standard deviations of the points in 15 equal-sized phase bins. The top two panels show I and V light curves for candidate 1, folded on a period of 5.1 hr; the bottom two panels show I and V light curves for candidate 2, folded on a period of 3.7 hr.

variability should be canceled out, which is not the case in the quoted B, R, and m_{220} magnitudes. A detailed analysis of this color-magnitude diagram is given by Rubenstein & Bailyn (1996). An analysis of the time-series data is in preparation: here we note only that no large-amplitude variables ($\geq$0.4 mag) were found. This indicates that, like M80 (Shara & Drissen 1995), NGC 6752 does not contain bright nova-like variables.

An analysis of the time-series data of the CV candidates demonstrated that they are low-amplitude periodic variables. The Stellingwerf variance statistic test (Stellingwerf 1978) indicated periodic variability on a timescale of $\approx$2.5 hr for star 1 and $\approx$1.8 hr for star 2. To test the significance of the periodic signal, we randomly reassigned magnitudes to times of observations, and recalculated the Stellingwerf statistic. In 1000 trials for each source, no case was found which produced a periodic signal as strong as the one actually observed. Folded, binned light curves are shown in Figure 4. The amplitude and brightness of these variables are consistent with their nondetection in the prerepair *HST* data of Cool (1993) and Shara et al. (1995).

3. DISCUSSION

The *ROSAT* HRI image of NGC 6752 shows two principal components, both within 10″ of the cluster center (Cool 1993; Grindlay & Cool 1996). As shown in Figure 2, stars 1 and 2 fall at the edge of the error circle of the X-ray source identified as "B" by Grindlay & Cool (1996). The dominant error in the large *ROSAT* error circles comes from errors in the absolute pointing of the satellite. Even if these errors are greater than we estimate (which is unlikely, given that a source near the edge of the HRI field of view coincides with the position of a bright SAO star to within 3″), the *relative* positions of the two sources should be accurate to ≈2″. Since the *ROSAT* sources are separated by 14″ and the CVs are separated by 5″, the two CVs cannot both be counterparts of the two brightest LLGCXs, in contrast to the situation in NGC 6397. It is therefore likely that at least one of the LLGCXs has a counterpart fainter than $M_V \gg 7$, although it is also possible that a brighter counterpart is situated within ≤0″.1 of a brighter star or in the diffraction spikes of a saturated giant.

The location of star 1 on the main sequence in $V - I$ is not typical for a CV. The star is well isolated from its neighbors, so there seems to be no reason to doubt the reality of the Hα and UV excess which identify this star as a CV candidate. The red colors of the counterpart may indicate that there is a significant contribution from a low-mass secondary to the optical emission from the source. If this is the case, the variability might be due to ellipsoidal variations of the Roche lobe filling secondary, as is seen in some field CVs (e.g., Berriman et al. 1983). The relatively red $V - I$ color of candidate 2 suggests that it too may display ellipsoidal variability.

Ellipsoidal variations produce two maxima and minima per orbit, so the orbital periods suggested by the above hypothesis are 5.1 hr and 3.7 hr, respectively. The geometry of the systems are self-consistent in that the Roche lobes are similar in size to a main-sequence star of ≈0.3–0.5 $M_\odot$ (Green, Demarque, & King 1987). If the variability were caused by an eclipse of the accretion disk, the orbital periods would be half what we suggest. But in this case the secondaries would be too small and faint to contribute significantly to the optical emission, and the observed red colors would require an anomalously cool accretion disk.

Table 2 shows that the H$\alpha - R$ and $m_{220} - R$ colors and absolute V magnitude of candidate 1 are similar to those of the candidates in NGC 6397 (Cool et al. 1995), which were subsequently shown by Grindlay et al. (1995) to have CV-like spectra. However, at least one of the CV candidates is not coincident with the *ROSAT* sources identified by Grindlay & Cool (1996). Optical counterparts of the X-ray sources as faint or fainter than our candidate CVs would result in f_x/f_{opt} ratios higher than those observed in NGC 6397. Therefore, it is not certain that the new sources reported here are similar to those in NGC 6397. Clearly spectroscopy of the kind obtained by Grindlay et al. (1995) for the candidates in NGC 6397 is required for a fuller understanding of the sources reported here.

We are grateful to K. Janes and J. Heasley for providing their SPS software. This work was supported by NASA grant NAGW-2469 (C. D. B. and E. P. R.), NAG5-1607 (A. M. C.), a National Young Investigator award from the National Science Foundation to C. D. B., and grant HST-GO-5344 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAG5-26555.

REFERENCES

Berriman, G., Beattie, D. H., Gatley, I., Lee, T. J., Mochnacki, S. W., & Szkody, P. 1983, MNRAS, 1983, 1105
Cool, A. M. 1993, Ph.D. thesis, Harvard Univ.
Cool, A. M., Grindlay, J. E., Cohn, H. N., Lugger, P. M., & Slavin, S. D. 1995, ApJ, 439, 695
Cool, A. M., Grindlay, J. E., Krockenberger, M., & Bailyn, C. D. 1993, ApJ, 410, L103
Di Stefano, R., & Rappaport, S. 1994, ApJ, 423, 274
Green, E. M., Demarque, P., & King, C. R. 1987, The Revised Yale Isochromes and Luminosity Functions (New Haven: Yale Obs.)
Grindlay, J. E., & Cool, A. M. 1996, in preparation
Grindlay, J. E., Cool, A. M., Callanan, P. J., Bailyn, C. D., Cohn, H. N., & Lugger, P. M. 1995, ApJ, 455, L47
Hertz, P., & Grindlay, J. E. 1983, ApJ, 275, 105
Holtzman, J. A., et al. 1995, PASP, 107, 1065
Livio, M. 1996, in ASP Conf. Ser. 90, The Origins, Evolution and Destinies of Binary Stars in Clusters, ed. E. F. Milone & J.-C. Mermilliod (San Francisco: ASP), 312
Paresce, F., & De Marchi, G. 1994, ApJ, 427, L33
Paresce, F., De Marchi, G., & Ferraro, F. 1992, Nature, 360, 46
Peterson, C. J. 1993, in ASP Conf. Ser. 50, The Structure and Dynamics of Globular Clusters (San Francisco: ASP), 337
Rubenstein, E. P., & Bailyn, C. D. 1996, ApJ, in press
Shara, M. M., & Drissen, L. 1995, ApJ, 448, 203
Shara, M. M., Drissen, L., Bergeron, L. E., & Paresce, F. 1995, ApJ, 441, 617
Stellingwerf, R. F. 1978, ApJ, 224, 953
Stetson, P. B. 1987, PASP, 99, 191
———. 1992, in IAU Colloq. 136, Stellar Photometry—Current Techniques and Future Developments, ed. C. J. Butler & I. Elliot (Cambridge: Cambridge Univ. Press), 291
Yanny, B., Guhathakurta, P., Schneider, D., & Bahcall, J. N. 1994, ApJ, 435, L59