THE ASTROPHYSICAL JOURNAL, 408:L89–L92, 1993 May 10

CANADA-FRANCE-HAWAII TELESCOPE OBSERVATIONS OF GLOBULAR CLUSTER CORES: BLUE STRAGGLER STARS IN M3 (NGC 5272, GC 1339+286)

MICHAEL BOLTE[1,2]
Lick Observatory, University of California, Santa Cruz, CA 95064

AND

JAMES E. HESSER[1] AND PETER B. STETSON
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council, 5071 West Saanich Road, Victoria, BC, Canada V8X 4M6

Received 1992 December 15; accepted 1993 February 24

ABSTRACT

We have obtained a complete inventory of stars brighter than the main-sequence turnoff inside 5 core radii (r_c) in M3, which reveals a blue straggler star (BSS) population in the central regions of this intermediate-density cluster. The data are derived from CCD frames with FWHM < 0.″6 obtained with HRCam at the Canada-France-Hawaii Telescope. In the $2' \times 2'$ region surveyed, the BSSs are marginally more centrally concentrated than giants in the same V-magnitude range. The specific frequency of BSSs inside 5 r_c is $\sim$2.8 and $\sim$3.9 times lower than that measured in the outskirts of M3 and in the low-density cluster NGC 5053, respectively. This result suggests that the production of BSSs through direct stellar collisions or the formation of hard binaries is not significant for central stellar densities up to that of the core of M3. Rather, we may be seeing the effects of a higher destruction rate for primordial binaries in the core of M3 compared with its outer regions, or compared with the lower density cluster NGC 5053.

Subject headings: binaries: general — globular clusters: general — stars: kinematics

1. INTRODUCTION

With the words, "The third feature which differs in the two clusters [the second cluster being M92] is the presence in M3 of the globular-cluster main sequence brighter than $M_V = +3.5$," Sandage (1953) drew attention to the enigmatic, sparse, luminous extension of the globular cluster main sequence populated by objects now known as blue straggler stars (BSSs). In seminal studies, Nemec & Harris (1987) and Nemec & Cohen (1989) discovered populations of BSSs in the low-density globulars NGC 5466 and NGC 5043. They demonstrated that the BSSs are more centrally concentrated than subgiant and giant stars in those clusters, as would be expected from dynamical mass segregation were the BSSs more massive than the average cluster member. Subsequently, BSSs have been discovered in nearly all globular clusters for which observations include regions near the cluster cores (e.g., Coté, Richer, & Fahlman 1990; Sarajedini & Da Costa 1991; Paresce et al. 1991; Bolte 1992; Yanny & Guhathakurta 1993). In another landmark study, Mateo et al. (1990) demonstrated that some of the BSSs in NGC 5466 are eclipsing and W Ursae Majoris binaries, significantly increasing the number of known BSS close binaries over the single object in ω Centauri (Da Costa, Norris, & Villumsen 1986; Margon & Cannon 1989). Thus the empirical evidence that at least some fraction of the globular cluster BSSs are multiple and of a type thought likely to undergo mass exchange or mergers is now compelling. Nemec (1989) and Leonard (1989) provide thorough reviews, and more recent references may be found in, e.g., Fusi Pecci et al. (1992) or Sarajedini & Da Costa (1991).

BSSs are found in a wide variety of environments, including open clusters, the Galactic field (e.g., Stetson 1991) and dSph galaxies (e.g., Olszewski & Aaronson 1985), and it seems likely that no single explanation will serve for all of them. However, the recent work in globular clusters strongly implicates dynamical processes in the formation of some BSSs and, conversely, a possible role for BSSs in the dynamical evolution of globular clusters (see Hut et al. 1992a). In spite of the ever-increasing numbers of globular cluster BSSs being discovered, our understanding of possible correlations between the presence of BSSs and structural properties of globular clusters is essentially nonexistent. Until recently the list of clusters in which BSSs have been discovered was almost exclusively composed of low-density systems (i.e., those for which it is possible to measure sufficiently faint stars to define the main-sequence turnoff [MSTO] inward to the cluster center). There is clearly a danger that our view of the occurrence of BSSs as a function of environment is strongly affected by this observational selection bias. To the extent that the projected spatial distribution of BSSs follows the cluster light, observations near the centers of clusters will often be required to discover these apparently rare objects. The fact that observations in the cores of the two nearest, high-concentration clusters, NGC 104 (47 Tuc) with the *Hubble Space Telescope* (*HST*) (Paresce et al. 1991; Yanny & Guhathakurta 1993) and NGC 6397, with high-resolution ground-based images (Lauzeral et al. 1992; Aurière, Ortolani, & Lauzeral 1990), detected populations of BSSs underscores the distorted nature of our view to date.

With the substantial evidence that BSSs are at least sometimes the result of significant mass transfer or the merging of binary systems, BSSs take on significance as the most visible tracer of a binary population in clusters and as empirical test

[1] Visiting Astronomer, Canada-France-Hawaii Telescope Corporation. The CFHT is operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii.
[2] Hubble Fellow, NASA/STScI.

particles for the evolution of binary systems embedded in the grainy potential of a star cluster. In the higher density cluster cores, BSS numbers may provide the first observational constraints on collision cross sections for single and multiple stars.

Consequently, we have begun a systematic survey at the Canada-France-Hawaii Telescope (CFHT) with the active optics device HRCam (McClure et al. 1989). We report here results for M3, a cluster with central density intermediate between the low-concentration clusters already studied from the ground and the very high core density cluster 47 Tuc (NGC 104) studied with *HST*. The data we have obtained can be used for many more astrophysical investigations once the photometric analyses are complete. However, various tests indicate that even at this stage the results on BSSs in M3 are robust and interesting.

2. OBSERVATIONS AND DATA REDUCTION

The data were acquired on the night of 1992 May 24/25 at CFHT under photometric conditions and with excellent seeing. Observations were made through V and R (" Mould ") filters with the SAIC1 CCD, which has 1024 × 1024 pixels, each 0ʺ13 on a side. To achieve a dynamic range sufficient to measure the brightest giants and main-sequence stars, we took a series of 15 V and 13 R exposures of 25 s duration each over an interval of less than 2 hr. While B and R would have been a more logical choice for our program, no low–read-noise CCDs with blue sensitivity were available. A small shift along columns was made between exposures, and the frames were registered and averaged in three sets of five in V and three sets of four plus a single frame in R. The FWHM for point sources on the averaged frames ranged from 0ʺ44 to 0ʺ63. One of the V frames is shown in Figure 1 (Plate L7), while Figure 2 (Plate L8) shows a section before and after convolution with a Gaussian to degrade the image to FWHM = 1ʺ1. The importance of subarcsecond imaging for working in the centers of clusters is clear.

Point-spread function (PSF) photometry has been performed using a new code developed by P. B. S. This code, called ALLFRAME and based in large part on DAOPHOT and ALLSTAR algorithms (Stetson 1987, 1989), makes optimum and simultaneous use of all information contained in all data frames. The first pass of ALLFRAME, upon which the results reported here are based, included a list of 15,000 stars and used a preliminary PSF for each field. After subtracting the PSFs scaled and positioned at each of the stars, the resulting frames were remarkably free of unfitted objects right to the very center of the cluster.

For our purposes, an instrumental color-magnitude diagram (CMD) is adequate. We have used the V-magnitude measured for stars near the center of M3 by Aurière & Cordoni (1983) to bring the V scale of our CMD *roughly* in line with the standard Johnson V system. A systematic trend in the color of giant-branch stars at any magnitude with the Y position in the frame was discovered; we have not yet tracked down the source of this gradient, but possibly it is due to our having selected relatively fewer PSF stars in the more crowded upper regions (see Fig. 1). This trend was empirically removed from the data used in this analysis, but does not affect the number of BSSs found or any of our conclusions.

3. RESULTS

3.1. *BSS Candidates*

The panels of Figure 3 show the CMD for stars which we measured on all seven frames (three V and four R) with the different panels showing objects with color errors smaller than the indicated cutoffs. The photometric standard error for each star in each magnitude represents a compromise between the error estimated from the goodness of the profile fit in each frame and that estimated from the frame-to-frame repeatability. The color errors are simply the quadratic sum of the errors in V and R.

The definition of the BSS region in the CMD is slightly arbitrary. At the faint end there is potential for confusion with MSTO stars that have large enough errors to scatter them into the BSS region or with photometric binary stars near the MSTO which, for stars of equal mass, will be up to 0.75 mag brighter than single stars and may therefore be counted as " yellow " stragglers. At the bright end, particularly in the color $V-R$, which loses sensitivity to $T_{\rm eff}$ for stars hotter than the instability strip, the blue extension of the horizontal branch droops to faint enough magnitudes to become confused with the brightest and bluest BSSs. We have chosen a conservative definition of the BSS region shown as the polygon in the Figure 3 panels. With this definition, the values for the diagnostic ratios of §§ 3.2 and 3.3 are fairly independent of the color-error selection. The analyses that follow are based on the data shown in Figure 3*c*.

We made a qualitative, but sensitive, check of each of the candidate BSSs to ensure that they were relatively blue objects on the data frames. The R-band frame with the highest image quality was coaligned and subtracted from the best seeing V-band frame after adjusting the "sky" levels to the same value. The pixels at the positions of red giant branch (RGB) stars had large positive residuals in the subtracted frame, while pixels at the positions of objects bluer than -0.45 in instrumental color had negative residuals. We examined the subtracted frame at the positions of all objects identified in the CMD as BSSs to ensure that the pixels had negative values. Seven objects were eliminated from our original candidate list on the basis of this test; in all cases the rejected stars were in the faint, red corner of the BSS region. The final list of BSS candidates contained 46 objects.

3.2. *Spatial Distribution of BSSs*

Nemec & Harris (1987) and Nemec & Cohen (1989) show that BSSs are more centrally concentrated than other populations in the clusters NGC 5053 and NGC 5466. Subsequent studies in other clusters have generally supported this conclusion, although it is often difficult to make a strong case (e.g., Sarajedini & Da Costa 1991; Bolte 1992). The spatial distribution of BSSs carries important, though potentially ambiguous, information regarding their origin (see the discussion in § 4).

We compare the number of BSSs with projected positions on the sky inside a circle with radius 25ʺ (1 r_c; Webbink 1985) centered on our estimate of the cluster center [pixel (485,689) in Fig. 1] with the number of BSSs that fall outside of 1 r_c. We then form the same ratio (the number inside 1 r_c to the number outside) for other populations. Table 1 shows the ratios for BSSs subgiants and giants that fall in the same V-magnitude range as the BSSs, red giant stars brighter than V = 16.75, and horizontal-branch (HB) stars. This sort of comparison is usually made between BSSs and the giants and subgiants in the same V-magnitude range to avoid the possibility that the counting incompleteness as a function of position in the cluster varies with V. However, the photometry is complete in our frames from the tip of the giant branch to at least a magnitude fainter than the faintest of the BSSs. From the values in Table 1, the subgiants and giants fainter than V = 16.75 appear to be

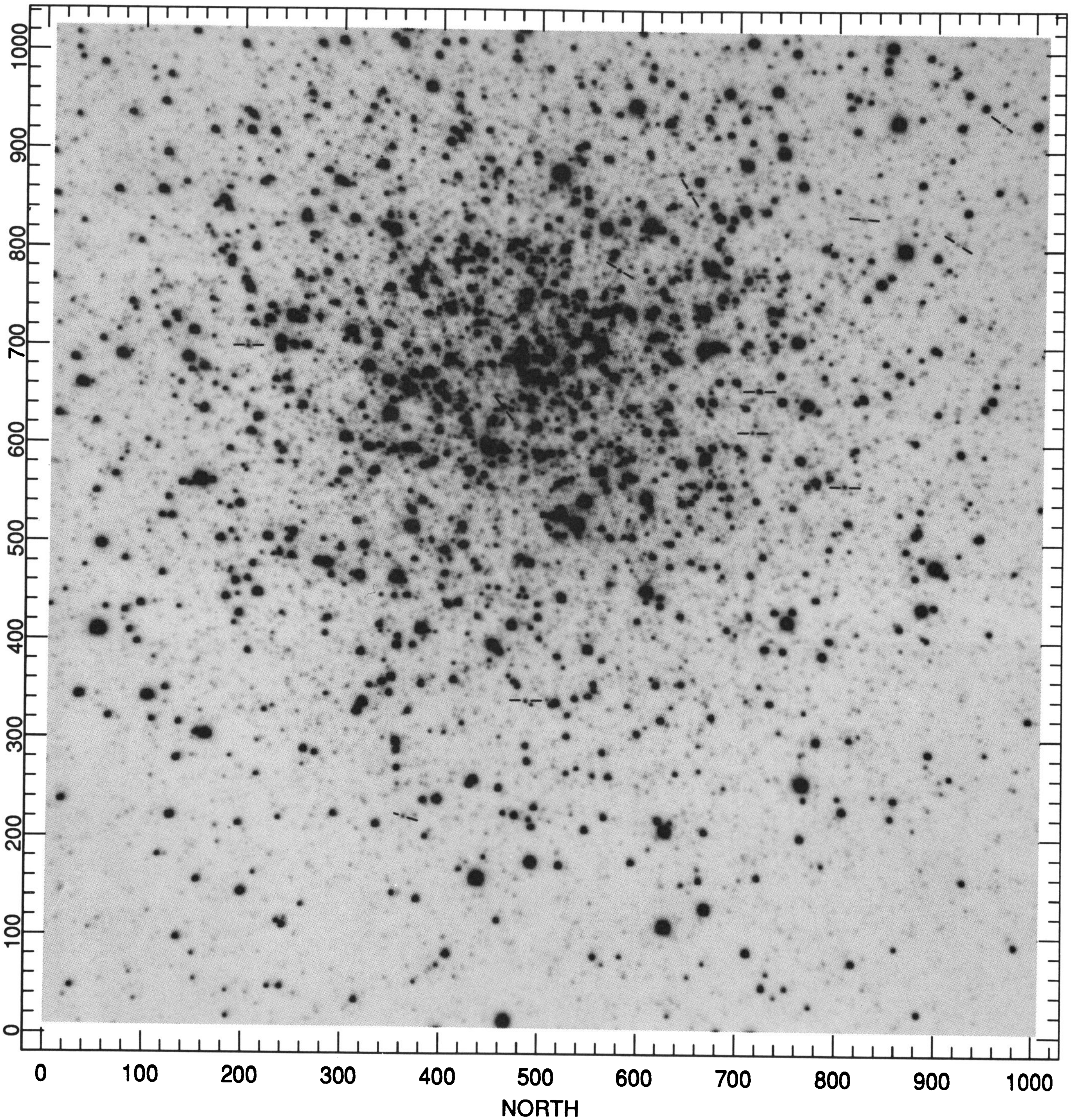

FIG. 1.—Median of five HRCam *V* frames of the center of M3. The FWHM for stars is 0″.44; the faintest stars visible are ~2 mag below the main-sequence turnoff. Several of the most isolated BSS candidates have been identified between tick marks.

BOLTE, HESSER, & STETSON (see 408, L90)

1993ApJ...408L..89B

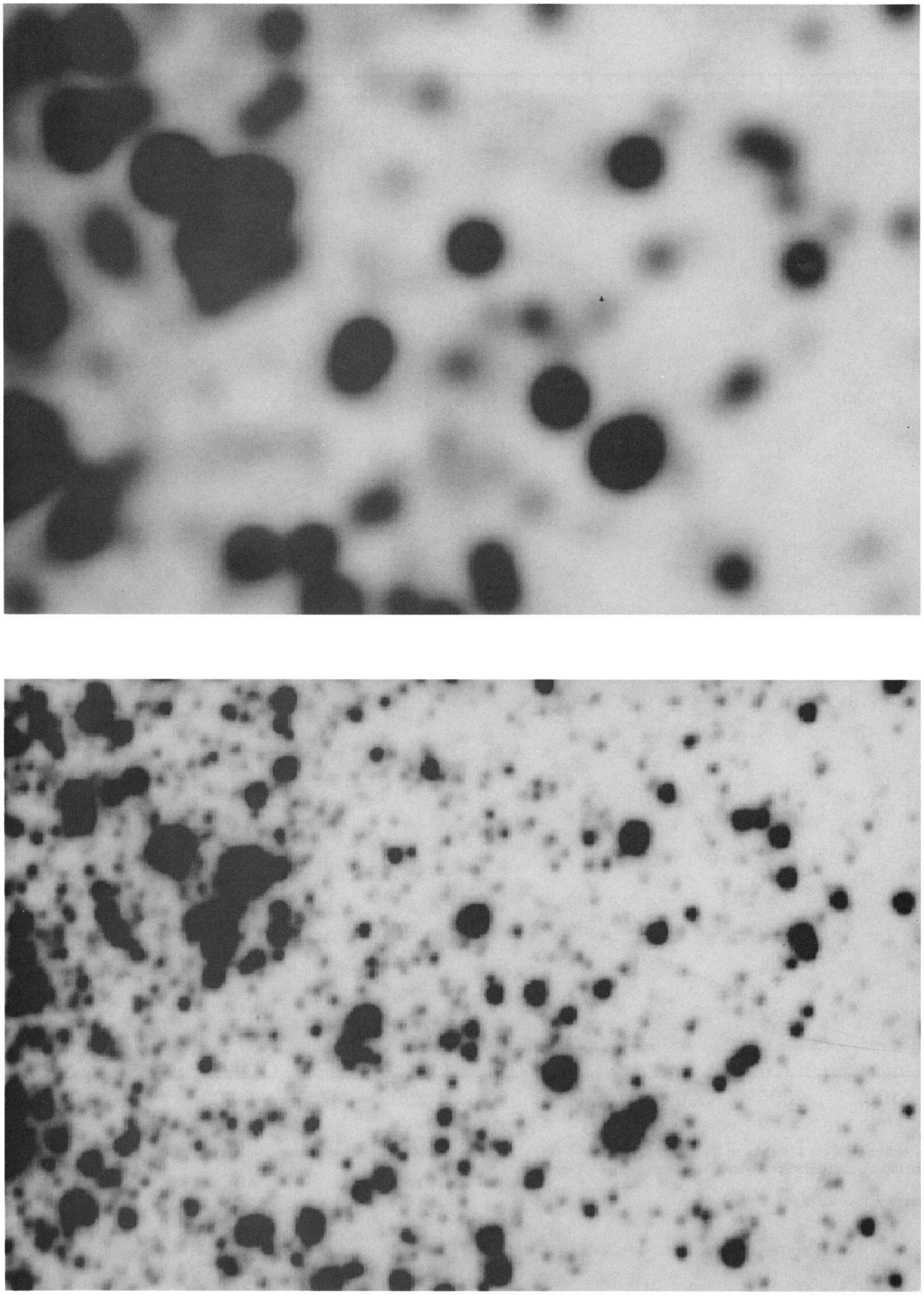

FIG. 2.—Expanded-scale portion of Fig. 1 before and after convolution with a Gaussian to degrade the FWHM to 1″1.

BOLTE, HESSER, & STETSON (see 408, L90)

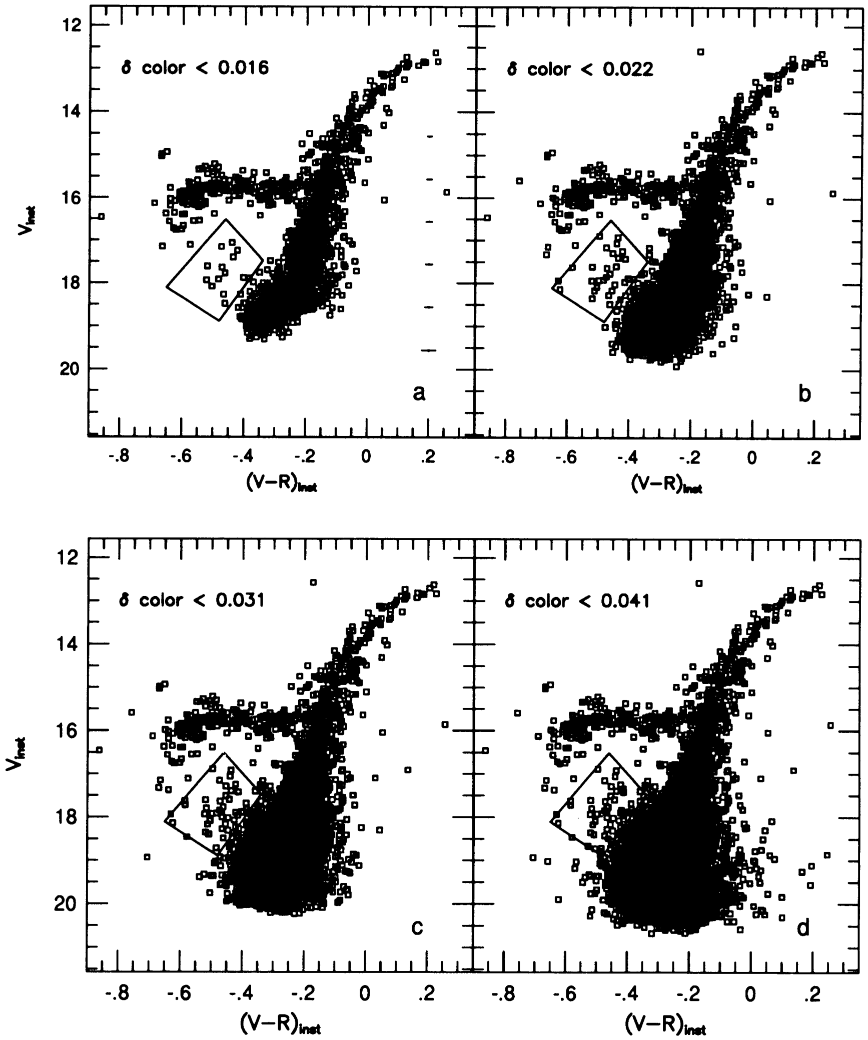

FIG. 3.—Color-magnitude diagrams (CMDs) derived for the center of M3. The different panels show the CMDs with the specified upper limits for measured color error. Inside the polygon is the region from which we have chosen the BSS candidates. Both scales are in the instrumental system, although the V-magnitude scale is *roughly* on the Johnson standard system. The error bars in panel *a* show the approximate color and magnitude errors for the magnitudes where the bars are plotted.

distributed identically to the giants brighter than $V = 16.75$, while the BSSs are marginally more concentrated (at the 1 σ level) and, interestingly, the HB stars are somewhat less concentrated (1.8 σ).

3.3. *Specific Frequency of BSSs*

To minimize the effects of a wide range in cluster total mass when comparing BSS populations, a specific frequency, $F_{\rm BSS}$, normalized by a characteristic cluster size is required. Intercluster comparisons are difficult with the existing published data, because the extent to which the BSS counts are complete is usually not known. The lead of Nemec & Harris (1987) has been followed in most studies, where the BSS counts are compared with the number of subgiant stars that fall in the same magnitude range as the BSSs. This choice is based on the reasonable assumption that incompleteness affects both populations equally. The limitation of such a ratio is that it will be sensitive to the exact magnitude range chosen for the stars considered to be BSSs in a cluster. Unless the luminosity function of BSSs and the stars at the base of the giant branch are parallel, a cluster-to-cluster fluctuation in the ratio of BSSs to giants in the same magnitude range may arise from statistical or systematic differences in the magnitude of the brightest BSS.

We would like a comparison population that (1) has a fixed magnitude range with respect to some CMD feature, (2) contains as many stars as possible to reduce the Poisson noise in the comparison sample, (3) can be specified independently of cluster metal abundance, and (4) is insensitive to small errors in determining the V-magnitudes of the sample. The third point addresses the fact that some CMD features, such as the magnitude level of the horizontal branch or the point where the subgiant branch intersects the base of the giant branch, may be functions of cluster metallicity. Consideration of the fourth

TABLE 1

RELATIVE DEGREE OF CENTRAL CONCENTRATION FOR DIFFERENT POPULATIONS

Region	$N_{\rm BSS}$	$N_{\rm SGB}$	$N_{\rm HB}$	$N_{\rm RGB}$ ($V \leq 16.75$)
$r \leq 1\, r_c$	19	293	76	170
$r \geq 1\, r_c$	27	574	200	347
Ratio	0.70 ± 0.20	0.51 ± 0.04	0.38 ± 0.05	0.49 ± 0.05

point leads us to reject for the comparison sample any stars fainter than the main-sequence turnoff (TO), where the steep luminosity function would convert a small error in setting the V-magnitude of the comparison population into a large change in the number of main-sequence stars counted.

We have adopted a comparison sample whose boundaries may be related to either of two naturally occurring fiducial marks in cluster CMDs: the HB and the TO. In most cases the two definitions will be equivalent, but under actual circumstances it may sometimes be more practical to adopt one definition or the other. First, we define the comparison sample as consisting of all the cluster stars in the CMD brighter than 2 mag below the level of the HB at the instability strip ($V_{\rm HB}^{+2}$). We use the lower envelope of stars on the HB between -0.52 and -0.20 in our instrumental color as a fiducial. Equivalently, we define the comparison sample as consisting of those stars brighter than $V_{+0.05} - 2.63$ mag (see VandenBerg, Bolte, & Stetson 1990). Either method gives a comparison sample of all cluster stars brighter than $V = 17.80$ in our data and, restricting our sample to only those objects with color errors less than 0.031 mag, gives 1382 RGB and HB stars in the sample. Our specific frequency is $F_{\rm BSS} = 0.033 \pm 0.005$, where the error assumes Poisson statistics for the individual sums propagated through the division.

Of the published studies of globular cluster BSSs, only that of Paez, Straniero, & Martinez Roger (1990) from the outer regions ($\sim 15\ r_c$) in M3 and that of Nemec & Cohen (1989) for NGC 5053 give sufficient data to generate the ratio of BSSs to RGB + HB stars in the way we have defined the RGB + HB sample: $F_{\rm BSS} = 9/94 = 0.09 \pm 0.03$ and $F_{\rm BSS} = 24/168 = 0.14 \pm 0.03$, respectively. The specific frequency of BSSs within 5 r_c of the center of M3 is a factor of 2.8 ± 1.2 smaller than that seen in the outer regions of the same cluster and a factor of 3.9 ± 1.1 smaller than that seen in the center of NGC 5053.

4. DISCUSSION

It is premature to speculate too deeply on the origin of these results, but the indication that $F_{\rm BSS}$ is smaller in the higher density region suggests a few possible interpretations. If we assume that BSSs are the result of mass exchange or merging in primordial binaries, then our result is qualitatively consistent with the picture presented by Renzini, Mengel, & Sweigart (1977; see their Fig. 6) in which the fraction of the initial binaries which are "hard" and survive cumulative dynamical interactions decreases as the stellar density increases. In fact, according to numerical simulations (Hills 1984), binary–single-star interactions for the central density of M3 do not significantly deplete the pool of primordial binaries with separations small enough that mass transfer will occur when the primary evolves off the main sequence. For the simple picture of a decreasing pool of nonionized binaries surviving to evolve into BSSs to work quantitatively will probably require the higher collision cross sections of binary-binary interactions (Leonard & Fahlman 1991; Leonard & Linnell 1992; Hut, McMillan, & Romani 1992b). With the consideration of binary-binary interactions, the distribution of BSSs is determined by a complex interplay between the density dependence of the collision rates, the sinking of binaries and their merger products to the cluster center via two-body relaxation, and the ejection of merger products from the central regions via their recoil velocities.

We suggest that the simplest interpretation of our result is that BSSs are formed in lower density environments, such as the center of NGC 5053, old open clusters, and the field through mass-exchange or angular-momentum loss and coalescence in primordial binaries. At the density of the center of M3, binary *disruption* mechanisms have begun to dominate and have impeded the formation of BSSs, whereas the primordial binaries have survived and continue to form BSSs in the cluster outskirts. At still higher densities, binary *formation* and collision mechanisms may take over, producing the centrally concentrated populations of BSSs in the dense cores of clusters like 47 Tuc and NGC 6397.

We would like to acknowledge gratefully the vision and expertise of the "HRCam team," Dennis Derdall, Murray Fletcher, Walter Grundmann, Robert McClure, Rene Racine, William Rambold, Harvey Richardson, Jim Stilburn, and Robert Wooff. This instrument is essential to the cluster core imaging program. Hugh Harris made some useful suggestions which improved this work, as did the anonymous referee.

REFERENCES

Aurière, M., & Cordoni, J.-P. 1983, A&AS, 52, 383
Aurière, M., Ortolani, S., & Lauzeral, C. 1990, Nature, 344, 638
Bolte, M. 1992, ApJS, 82, 145
Coté, P., Richer, H. B., & Fahlman, G. G. 1991, AJ, 102, 1358
Da Costa, G., Norris, J., & Villumsen, J. 1986, ApJ, 308, 743
Fusi Pecci, F., Ferraro, F. R., Corsi, C. E., Cacciari, C., & Buonanno, R. 1992, AJ, 104, 1831
Hills, J. G. 1984, AJ, 89, 1811
Hut, P., et al. 1992a, PASP, 104, 981
Hut, P., McMillan, S., & Romani, R. W. 1992b, ApJ, 389, 527
Lauzeral, C., Ortolani, S., Aurière, M., & Melnick, J. 1992, A&A, 262, 63
Leonard, P. J. T. 1989, AJ, 98, 217
Leonard, P. J. T., & Fahlman, G. G. 1991, AJ, 102, 994
Leonard, P. J. T., & Linnell, A. P. 1992, AJ, 103, 1928
Margon, B., & Cannon, R. 1989, Observatory, 109, 82
Mateo, M., Harris, H. C., Nemec, J., & Olszewski, E. W. 1990, AJ, 100, 469
McClure, R. D., et al. 1989, PASP, 101, 1156
Nemec, J. M. 1989, in IAU Colloq. 111, The Use of Pulsating Stars in Fundamental Problems in Astronomy, ed. E. G. Schmidt (Cambridge: Cambridge Univ. Press), 215
Nemec, J. M., & Cohen, J. G. 1989, ApJ, 336, 780
Nemec, J. M., & Harris, H. C. 1987, ApJ, 316, 172
Paez, E., Straniero, O., & Martinez Roger, C. 1990, A&AS, 84, 481
Paresce, F., et al. 1991, Nature, 352, 297
Olszewski, E., & Aaronson, M. 1985, AJ, 90, 2221
Renzini, A., Mengel, J. G., & Sweigart, A. V. 1977, A&A, 56, 369
Sandage, A. 1953, AJ, 58, 61
Sarajedini, A., & Da Costa, G. S. 1991, AJ, 102, 628
Stetson, P. B. 1987, PASP, 99, 191
———. 1989, ALLSTAR User's Manual
———. 1991, AJ, 102, 589
VandenBerg, D. A., Bolte, M., & Stetson, P. B. 1990, AJ, 100, 445
Webbink, R. F. 1985, in IAU Symp. 113, Dynamics of Star Clusters, ed. J. Goodman & P. Hut (Boston: Reidel), 541
Yanny, B., & Guhathakurta, P. 1993, preprint