Astrophysics Preprint Series

IASSNS-AST 94/41

July 1994

82 9437

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Accepted by *The Astrophysical Journal Letters*

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¹ Based on observations with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555

ABSTRACT

We describe images of the center of the dense globular cluster M30 obtained with the Hubble Space Telescope Wide Field/Planetary Camera-2. Data taken in the F336W, F439W, and F555W filters (approximately U , B , and V) yield a color-magnitude diagram with photometric errors of $1\sigma = 0.05$ mag for stars with $V < 17.5$, and $1\sigma \sim 0.1$ mag at $V = 20$, which is 1.5 mag fainter than the main-sequence turnoff. Simulations show that the star identifications are essentially complete for stars with $V < 19.5$, even in the densest regions of the cluster. The projected radial distribution of stars can be represented by a power law distribution: $N(r) \sim r^\alpha$, with slope $\alpha = -0.4 \pm 0.15$, into radii less than $0''.4$ (0.015 pc). The radial profile is also consistent with a flat core of any radius smaller than about $1''.5$ (0.05 pc), but inconsistent with any core radius larger than $2''.5$ (0.09 pc).

A total of 30 blue straggler candidates within $20''$ of the cluster center have been identified from the three-color data. Their radial distribution is strongly centrally concentrated when compared to the horizontal branch, red giant branch, or main sequence stars in the cluster. The abundance of blue stragglers (relative to red giants and subgiants) within $r \lesssim 20''$ of the center of M30 is $f_{\text{BS}} = 0.19 \pm 0.04$, about twice as high as in other dense clusters.

Subject headings: globular clusters: individual (M30) - techniques: image processing - stars: kinematics - stars: blue stragglers

1. INTRODUCTION

With the angular resolution obtainable with the repaired Hubble Space Telescope (HST), it is possible to directly compare models for core collapse and for stellar concentrations around a black hole with observations. The relevant length scales are a few percent of the half-mass radius, or about 0.1 pc for typical globular clusters. The resolution of HST ($\sim 0''.1$) corresponds to 0.005 pc at the distance of typical Galactic globular clusters. Thus, even in crowded fields, it is possible to directly probe the scale over which core collapse is thought to occur and the scale over which a black hole affects the stellar distribution. Due to their proximity, Galactic globular clusters provide an insight into the dynamics of dense stellar systems that is complimentary to images of the nuclei of external galaxies, which have been observed to have central cusps in their light profiles on 0.5 pc scales (Lauer et al. 1994a, 1994b).

2. OBSERVATIONS

A set of eight Wide Field/Planetary Camera-2 (WFPC-2) images of the center of M30 (NGC 7099) were obtained on one orbit on 31 March 1994: 4×4 s with the F555W filter, 2×40 s in F439W, and 2×100 s in F336W. The exposure times were chosen so that the brightest stars in the core did not saturate. We have not transformed the instrumental F336W, F439W, and F555W magnitudes to Johnson U , B , and V magnitudes since our analysis relies only on the relative colors of stars. While the F439W and F555W magnitudes are similar to B and V , respectively, there may be color terms as large as 0.2 mag between F336W and U (Burrows et al. 1993). In the rest of this letter, we use the terms U , B , and V interchangeably with the WFPC-2 filter designations. The zero points of the WFPC-2 magnitudes were adjusted so there is rough agreement ($\lesssim 0.1$ mag) with the ground-based UBV measurements of Dickens (1972); they are also consistent with the pre-flight

WFPC-2 calibration (Burrows et al. 1993).

Each WFPC-2 image consists of a mosaic of four 800×800 CCD frames—a PC CCD with a scale of $0''.044 \text{ pixel}^{-1}$ and three WF CCDs with scales of $0''.10 \text{ pixel}^{-1}$ (Burrows et al. 1993). The center of M30 was placed near the center of the PC CCD. In this letter, we discuss only the $34'' \times 34''$ PC image.

Figure 1 shows a halftone reproduction of the a $9'' \times 9''$ portion of the median of the four PC V images centered on the cluster center (‘+’; see section §4). M30 is at a distance of 7.4 kpc and has a reddening of $E(B - V) = 0.05$ (Djorgovski 1993). The average surface density of stars with $V < 19.5$ in Figure 1 is 4.81 arcsec^{-2} , which corresponds to 3712 pc^{-2} ; the high angular resolution of HST images is crucial for the study of such dense regions. Previous ground-based observations of M30 indicated the presence of a bright central unresolved light source (Williams & Bahcall 1979). Ultraviolet observations by Caloi et al. (1984) suggested that this central source had colors consistent with a bright red giant, i.e., it was not excessively blue.

3. ANALYSIS TECHNIQUES AND STELLAR PHOTOMETRY

Bias and flat field corrections were applied to the data as part of the standard pre-processing done at the Space Telescope Science Institute. Cosmic ray events (CRs) were removed from the V -band data by median-filtering the four exposures. Two images with identical exposure were available in each of the U and B bands, and CRs were removed by the following procedure: An image $T_1 = (B_1 - B_2)/B_2$ was created, and pixels above a certain threshold in T_1 (CRs in B_1) were masked out in B_1 . An analogous T_2 image was used to mask B_2 . The images B_1 and B_2 were then averaged excluding masked pixels.

Stars were then identified on the summed $U + B + V$ image using the standard ‘find’ algorithm

of DAOPHOT-II (Stetson 1992). This list was hand-edited to separate blended stars and to remove hot pixels; this resulted in a master star list of about 3500 stars. An iterative procedure was followed using standard DAOPHOT routines: A Point Spread Function (PSF) of radius 20 pixels was generated by averaging together the images of about 30 relatively isolated, bright stars, after removing the neighbors of these stars using the PSF template constructed in the previous iteration. This was done independently for each of the combined U , B , and V images. A series of PSF templates were tried consisting of bi-variate Gaussian, Lorentzian, or Moffat functions plus a matrix of residuals which varied linearly with image position or were fixed; the Moffat function with linearly variable residuals was found to be marginally superior to the other templates. This PSF template was fitted to all stars on the combined U -, B -, and V -band images. The resulting color-magnitude diagram (CMD) shows more scatter in the bright red giant branch than is present in a CMD constructed from direct aperture photometry of stars, even before performing a position-dependent correction to the aperture photometry (see below). It is probable that the undersampling of the PSF prevents the standard DAOPHOT software from making an optimal fit to the peaks of stars.

We obtained aperture photometry of stars using a circular aperture with a radius of 2 pixels ($0''.088$). The sky for each star was determined locally (in a surrounding annulus). Prior to performing aperture photometry for a given star, every neighbor within 40 pixels of the star was removed from the image by subtracting a PSF scaled by its best-fit DAOPHOT magnitude.

To determine the effects of variation in the core of the PSF relative to the total light as a function of filter and field location, we measured the ratio of light enclosed within 2 pixels to that within 20 pixels for a set of isolated stars. This ratio varies systematically from 0.61 in the lower left corner of the CCD image to 0.69 in the upper right corner, corresponding to a 12% variation in the fractional energy enclosed within $r < 0''.09$ of the PSF. The variation with position was similar in

magnitude and sign in the U , B , and V data. This variation is consistent with a PSF that becomes slightly less sharp as one moves outward in radius from the optical axis of HST. A linear fit to the ratios results in an rms variation of less than 0.02; this position-dependent correction was applied to all U , B , and V aperture magnitudes.

Figure 2 shows a $(U - V, B)$ color-magnitude diagram of all stars with $V \lesssim 21$ detected in the U , B , and V filters. The red giant branch (RGB) is remarkably tight; the width of the RGB indicates that the photometric errors are less than 0.05 mag for these stars. The horizontal branch (HB) is quite blue and has the long blue tail expected for a low metallicity cluster: $[\text{Fe}/\text{H}] = -2.13$ (Djorgovski 1993). There are numerous, well-defined blue stragglers (BSs) in the diagram (§5).

Figure 3 (Plate XX) shows a false-color representation of the stars within $20''$ of the center of M30. The color of the dot indicates the stellar type: red = RGB, green = HB, yellow = BS, and white = main sequence (MS); the dot size is proportional to the V magnitude. A green cross marks the center of the cluster.

4. RADIAL DENSITY PROFILE

Counts of luminous stars have been used to determine the projected radial density distribution in the center of M30. Ground-based studies (Djorgovski & King 1984) have classified M30 as a post core collapse cluster, based on its rising surface brightness profile at radii $< 3''$ (0.1 pc). Due to the high angular resolution of HST, one can now use star counts to probe the density at radii $r < 0''.4$ (0.014 pc). Even with the high resolution of HST, however, one must accurately model the incompleteness as a function of limiting magnitude and of stellar density in order to make reliable inferences about the number counts near the cluster center.

et al. 1994), we generated a simulated F555W image of M30 based on an extrapolation of the

observed stellar luminosity function and with a radial profile of slope -0.7 . This artificial image was processed in the same way as the individual HST M30 images.

Following techniques used in earlier work (Guhathakurta et al. 1992; Yanny et al. 1994), we generated a simulated F555W image of M30 based on an extrapolation of the observed stellar luminosity function, a power-law stellar density distribution with slope -0.7 , and a realistic PSF model. This artificial image was processed in the same way as the individual HST M30 images.

Examination of the difference between the input and output magnitudes of the simulated stars shows that the 1σ photometric errors are about 0.05 mag for $V < 17$ and remain less than 0.1 mag until one reaches $V = 19.5$, which is 1 mag below the main-sequence turnoff. The simulations also yield the completeness fraction, $C(r) = N(V_{\text{output}} < V_{\text{lim}})/N(V_{\text{input}} < V_{\text{lim}})$. Note that while non-detection of faint stars causes $C(r)$ to be less than unity, it may be more than one if V_{output} is systematically brighter than V_{input} . This luminosity bias was seen in simulations (using the aberrated PSF) of the extremely dense cluster M15, and is related to crowding (Yanny et al. 1994); multiple faint overlapping stars near the cluster center tend to be measured as a single bright star. Our simulations of M30 show that these effects are unimportant in the HST dataset for a limiting magnitude $V_{\text{lim}} = 19.5$; the derived value of $C(r)$ is in the range 0.9–1.1 at all radii in the cluster. We restrict our analysis of the M30 star counts to stars with $V < 19.5$, and do not apply any completeness corrections. The approach assumes that there is no strong luminosity segregation in the cluster.

Before measuring the radial density profile for a set of stars, one must accurately determine the center of the cluster. We have used a number-weighted (rather than luminosity-weighted) centroid of stars with $V < V_{\text{lim}}$ within a circle of radius r_{max} . Starting with an initial guess, the centroid of stars within the circle is adjusted iteratively until it converges, which it always does for initial

guesses within 50 pixels of the obvious cluster center. The derived center also appears to be robust when V_{lim} and r_{max} are varied. The 1σ error (δr) in the centroid position is derived by applying the Bootstrap Resampling Method (Efron 1982) to the observed star lists. The estimated error, based on the results of 800 simulated clusters, is $\delta r = 5$ pixels or $0''.2$ using $V_{\text{lim}} = 19.5$ and $r_{\text{max}} = 6''.6$.

The surface density of $V < 19.5$ stars in M30 is plotted as a function of radius in Figure 4. The error bars indicate 1σ Poisson errors. The data are well fit by a rising power-law in the range $0''.2 < r < 4''$ with slope -0.37 ± 0.15 (solid and dotted lines). We performed a maximum-likelihood analysis of the stellar distribution comparing it to models with various core-radii and determined that a central, constant-density region with a core radius $r_{\text{core}} \lesssim 1''.5$ (0.05 pc) is also consistent with the data. Any core radius larger than $2''.5$ (0.09 pc), however, is ruled out by the data.

Theories of core collapse suggest that at very small radii, 2% to 10% of the half-mass radius, heating by primordial binaries should stabilize the core (Goodman & Hut 1989; McMillan et al. 1991). Other studies indicate that even if there are not enough binaries to halt collapse, core oscillations will prevent the core radius from shrinking to less than 0.5% of the half-mass radius (Gao et al. 1991). The half-light radius for M30 is $61''.6$ or 2.2 pc (Djorgovski 1993). Thus, one expects the core radius of M30 to be larger than $0''.3$ in the absence of binary stars, and larger than $1''.2$ if they are present in the center. The observed stellar density distribution in M30 is consistent with these lower limits.

A black hole in the center of the cluster would produce a radial distribution for surrounding stars that is a power law with a slope of $\alpha = -0.75$ in projection (Bahcall & Wolf 1976, 1977). A central black hole would also have a strong effect on the radial velocity dispersion of stars within a few arcseconds of the center. The fact that ground-based observations show a velocity dispersion of only 6 km s^{-1} in a central $4''.6 \times 6''$ box (Zaggia et al. 1992) implies that the black hole mass cannot

exceed $M \lesssim rv^2/G = 10^3 M_\odot$.

5. BLUE STRAGGLERS

The CMD in Figure 2 shows different stellar populations in M30 that are distinguished on the basis of relative colors and brightnesses: a red giant branch, horizontal branch, main sequence, and a clear concentration of blue straggler stars brighter and bluer than the main-sequence turnoff ($B < 18.75$, $U - V < +0.25$). The criteria used to define RGB, HB, MS, and BS stars are indicated by dashed lines in Figure 2. Only MS stars brighter than $B = 20.25$ are considered, so the sample is free of differential incompleteness.

The BS stars in M30 are shown by the yellow dots in Figure 3. It is apparent from this figure that the BSs are concentrated in the central $3''$ of the cluster. To compare the radial distributions of the various stellar types, we plot their cumulative fraction as a function of radius in Figure 5. The BS stars are more centrally concentrated than RGB, HB, and MS stars (99% significance on the basis of a Kolmogorov-Smirnov test). The BS stars may be the end products of recent mergers or stellar collisions; their radial distribution is consistent with them being more massive than post-main-sequence stars. The MS stars are less concentrated than RGB stars (97% K-S significance), possibly because of mass segregation.

Following the prescription of Bolte et al. (1993), we compute the specific frequency of BS stars: $f_{\text{BS}} = N(\text{BS})/N(V < V_{\text{HB}} + 2)$, where $V_{\text{HB}} = 15.1$ in M30. The BS specific frequency in M30 is $f_{\text{BS}} = 0.19 \pm 0.04$ averaged over the PC image ($r \lesssim 20''$); it is higher in the inner $10''$, $f_{\text{BS}} = 0.26 \pm 0.06$, due to the central concentration of the BSs. The abundance of BSs in M30, relative to RGB/subgiant stars, is about twice as high as that seen near the centers of the dense clusters M3 and 47 Tuc (Guhathakurta et al. 1994). Djorgovski and Piotto (1993) make a strong case for the depletion of the bright RGB in the center of M30, and this biases the BS frequency

slightly. We also note that the accurate photometry obtained with WFPC-2 allows one to define the a BS region which extends closer to the subgiant branch than those used in earlier studies; this may have resulted in the identification of a more complete BS sample.

6. SUMMARY

1. We have obtained photometry of stars in the central $r < 20''$ of the dense globular cluster M30, with an accuracy $1\sigma \lesssim 0.1$ mag for stars with $V < 20$, which is 1.5 mag below the main-sequence turnoff. Simulations of the data indicate that the star counts are complete for objects with $V < 19.5$, even at the center of the cluster.
2. The radial profile of the star counts in the central $2''$ of M30 appears to rise as a power law with a slope $\alpha = -0.4$ into $r < 0.4''$. If the cusp in the density distribution is due to the presence of a black hole, it must be less massive than $\sim 10^3 M_\odot$ to avoid conflict with ground-based velocity dispersion measurements. A central constant-density region with core radius $r_{\text{core}} \lesssim 1.5''$ fits the data, and any core radius $r_{\text{core}} > 2.5''$ is inconsistent with the data.
3. As has been noted in several other clusters, M30 contains a centrally concentrated group of 30 blue straggler stars, 10 of which lie within $2''$ of the cluster center.

We acknowledge useful discussions with P. Hut, and thank David Saxe for help with the figures. P.G. would like to thank the Institute for Advanced Study for its generous hospitality. This work was supported in part by NASA through grant number NAG5-1618 and by STScI grant GO-5324.01-93A.

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Figure Captions

1. Greyscale representation of the median of four V exposures (each of 4 s duration) of the central region of M30. The center derived from number-weighted centroid fitting to the stars is marked with a cross. This image is $9''$ (0.32 pc) on a side. The brightest stars in this picture are red giants with $V \sim 15$, while the faintest visible stars are at $V \sim 20$ (1.5 mag below the main-sequence turnoff).
2. A $F439W$ (B) vs $F336W - F555W$ ($U - V$) color-magnitude diagram for more than 3000 stars within the central $20''$ of M30. These are instrumental magnitudes; the photometric zeropoints have been adjusted so the locations of the horizontal branch and bright red giant branch agree with ground-based photometry. The criteria used to select horizontal branch, red giant branch/subgiant, blue straggler, and main-sequence stars are indicated by dashed lines.
3. Color plate of the entire field ($34''$ on a side) of the Planetary Camera data with the color indicating stellar types: red = RGB/subgiant, green = HB, yellow = BS, white = MS. The dot size is proportional to the stellar V magnitude. The green cross marks the center of the cluster shown in Figure 1.
4. The projected density profile of stars with $V < 19.5$ in M30. The error bars show 1σ Poisson errors. The data are well fit by a power law of slope -0.37 ± 0.15 (solid and dotted lines). A core of radius $r_{\text{core}} \lesssim 1''.5$ is also consistent with the star counts.
5. Cumulative radial distribution of stars of various types. The blue stragglers are centrally concentrated relative to the other stellar types; the difference is significant at the 99% confidence level. Main-sequence stars are significantly less concentrated than red giant/subgiant stars.

Fig. 1

Fig. 2

Fig 3 M30

5 arcsec

Fig. 4

Fig. 5