THE ASTROPHYSICAL JOURNAL, 453:L21–L24, 1995 November 1

THE PYXIS CLUSTER: A NEWLY IDENTIFIED GALACTIC GLOBULAR CLUSTER

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Received 1995 June 9; accepted 1995 August 17

ABSTRACT

One of the "interesting" objects identified by Weinberger during an eyeball search of sky survey plates for planetary nebulae is a previously unrecognized distant Galactic halo globular cluster. Deep B, R, and I CCD frames of the object to $R = 23$ reveal it to be a cluster of stars some 2′ in core size, with a well-defined main sequence with a turnoff at $R = 22$ and a sparsely populated subgiant branch leading to a stubby red horizontal branch at $R = 18.7$. With a reddening-corrected distance modulus of 18.0, corresponding to a distance of 40 kpc, the Pyxis globular cluster is the latest addition to an exclusive club of distant Galactic satellites. Pyxis is similar in morphological appearance to other outer halo globular clusters and lies tantalizingly close to the plane of the Magellanic Clouds orbit (Jones and coworkers), suggesting it might be a detached cluster of this system.

Subject headings: globular clusters: individual (Pyxis)

1. INTRODUCTION

In a recent paper, Weinberger (1995) produced a catalog of several new interesting objects discovered from a systematic search of film copies of sky survey plates. One of these objects, at $\alpha = 09^h07^m57\overset{s}{.}8$, $\delta = -37°13'17''$ J2000, appeared to just resolve into stars at the plate limit, suggesting it might be a previously unknown distant Galactic satellite. Since there are only a handful of distant Galactic satellites known, any new possible addition is of considerable interest because of the leverage such satellites give to the study of halo dynamics and formation. A search of the known Galactic globular clusters and previously proposed globular clusters (e.g., Djorgovski & Meylan 1993) indicated that this object had not been recognized prior to Weinberger's discovery. As a further check, we examined Lauberts's (1982) ESO/Uppsala survey of the southern sky and found no cataloged "interesting" objects within 20′ of the position given by Weinberger.

We carried out a preliminary investigation of this object using the UK Schmidt Telescope (UKST) B_J and R sky survey plates of the region digitized with the automatic plate measuring facility (APM) in Cambridge (Kibblewhite et al. 1984). The object was readily visible on both digitized plates and clearly resolved into stars, supporting Weinberger's conjecture that it is either a distant star cluster or even a small dwarf spheroidal galaxy. From the plate material, the "size" of the excess group of stars was estimated to be at most 4′ × 4′, which, coupled with the relatively low excess stellar density, strongly suggested the object was a sparsely populated outer halo cluster similar to other distant Galactic halo globular clusters. From the photographic data, the center of the cluster appears to be 10″ to the west and 20″ to the south of Weinberger's position. Since the cluster lies in the constellation of Pyxis, we propose to call it the Pyxis globular cluster.

2. OBSERVATIONS AND REDUCTIONS

To investigate this object further, we obtained deep CCD images in B, R, and I with the du Pont telescope at Las Campanas. The 1024 × 1024 TEK 1 chip was used on the nights of 1995 March 9 and 10 to obtain a series of Pyxis frames. This TEK 1 chip has 24 μm pixels corresponding to $0\overset{''}{.}26$ pixel^{-1} and giving an area on the sky of $4\overset{'}{.}5 \times 4\overset{'}{.}5$, thereby giving good coverage of the majority of the cluster. Total exposure times for B, R, and I were 13,000, 5400, and 2700 s, respectively. Atmospheric extinction coefficients were determined from the apparent magnitude variation of the program stars observed over a wide range of air masses and compared well with standard Las Campanas extinction values. A number of Landolt (1992) standards were also observed on each night. Seeing was very good, with a typical FWHM of the Pyxis frames of around $0\overset{''}{.}75$.

The good photometric quality of the nights made it possible to combine the standards of both nights to determine the transformation equations in the fashion described by Grondin et al. (1990). Over 50 standard stars were used for B and R, while only 20 were available for the I magnitudes. The frames of Pyxis were combined and were analyzed with IRAF in a way similar to that described by Grondin et al. (1990). Figure 1 (Plate L3) shows the reduced and combined R frames. At this Galactic latitude ($l = 261\overset{\circ}{.}3$, $b = 7\overset{\circ}{.}0$) foreground contamination from Galactic stars is significant over the whole frame; however, the extra population of fainter stars belonging to the cluster is readily discernible.

3. ANALYSIS OF CLUSTER PROPERTIES

3.1. *Reddening Law*

Reddening as a function of color has been estimated by several groups working on Cepheid calibration. For example,

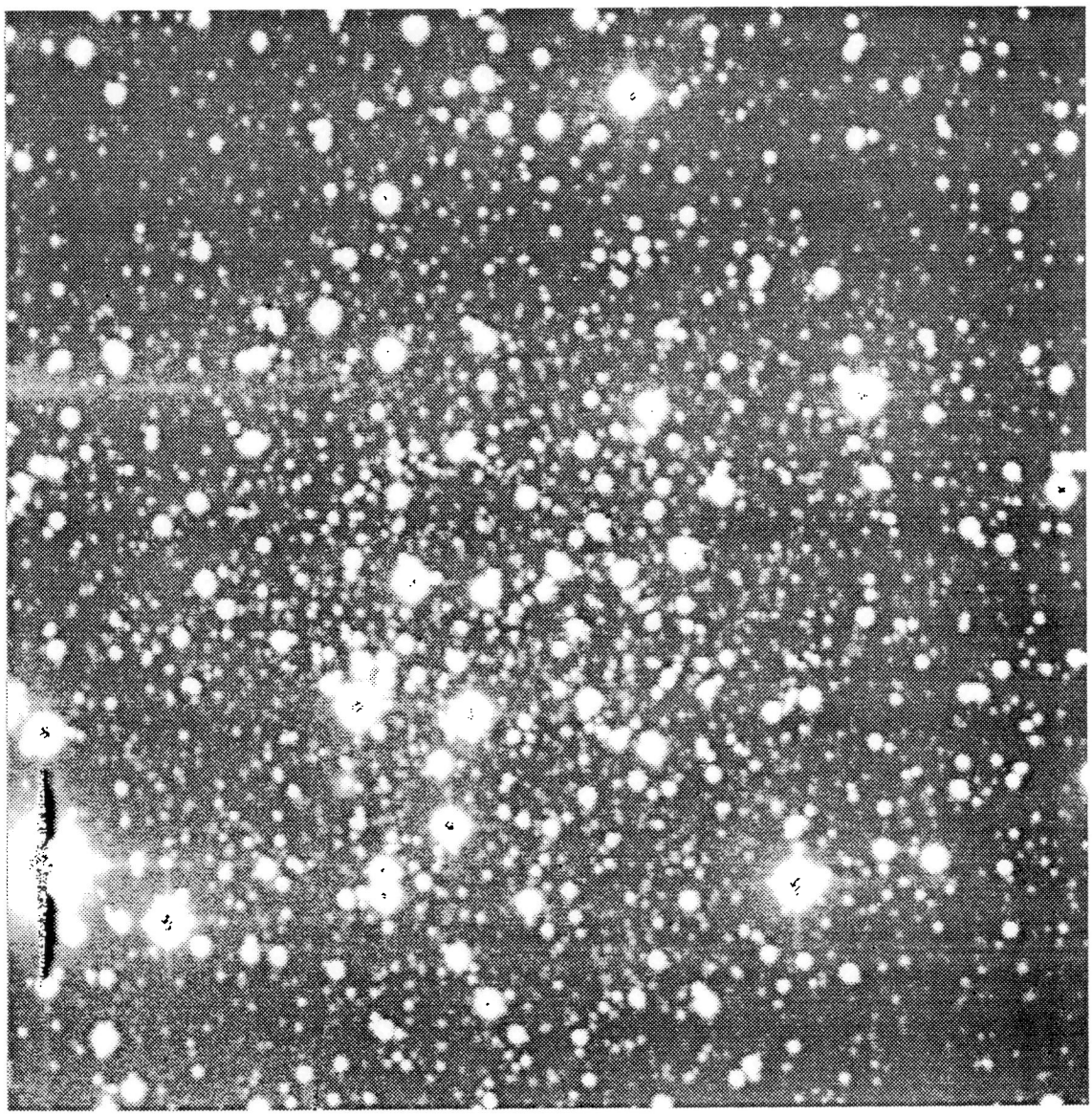

FIG. 1.—This combined *R*-band CCD frame of the Pyxis cluster covers an area of 4.′5 × 4.′5. East is at the bottom and north is to the left. The cluster shows up as a clear excess of fainter stars centered near the middle of the frame.

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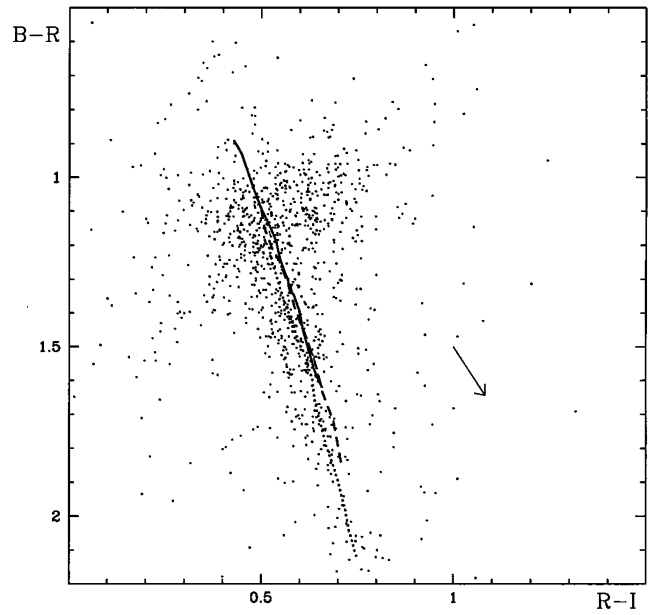

FIG. 2.—Two-color *BRI* diagram of the Pyxis cluster. Overlaid as solid, dashed, and dotted lines are Yale isochrones for metallicities of [Fe/H] = −2.4, −1.4, and −0.75, respectively, at a fixed reddening of $E(B-V) = 0.23$. The arrow denotes the reddening vector direction.

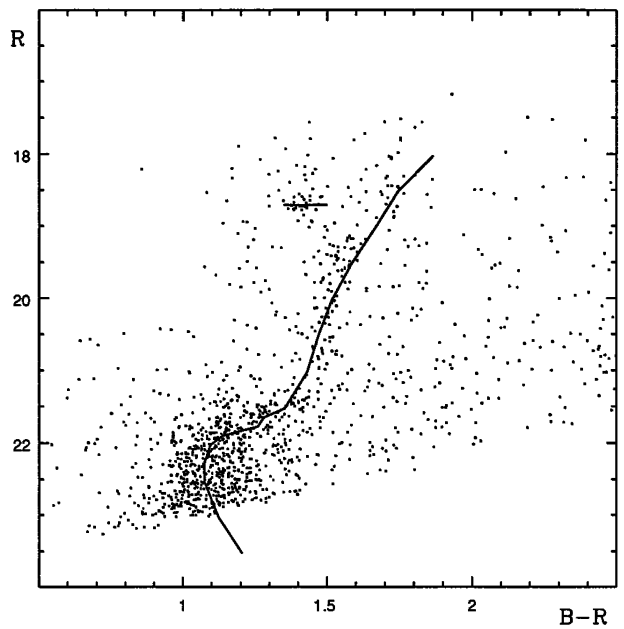

FIG. 3.—Pyxis cluster *BR* color-magnitude diagram with a Yale isochrone superposed. Parameters used for the fit are a metallicity [Fe/H] = −1.1, an age of 13 Gyr, a reddening of $E(B-V) = 0.19$, and a true distance modulus of 18.0. The short horizontal line marks the position of the red horizontal branch.

Schmidt (1976) gives $E(R-I) = 0.82E(B-V)$, and Dean, Warren, & Cousins (1978) quote $E(V-I) = 1.25E(B-V)$. In the *B*, *R* domain these relations translate to $E(B-R) = 1.43E(B-V)$. Nandy published several papers on reddening laws in different Galactic directions (e.g., Nandy 1968) and came to the general conclusion that the form of the reddening law was well approximated by $\delta m_{\rm abs} \propto \lambda^{-1}$ over the wavelength range 4000–10000 Å, and was independent of direction to first order. Taking the extinction in the *V* band to be $3.20E(B-V)$ (e.g., Laney & Stobie 1994) then leads to an extinction coefficient of $2.77E(B-V)$ for the *R* band. The maps of Burstein & Heiles (1982) do not extend inward of Galactic latitudes of 10°; however, the Pyxis cluster at $l = 261.^{\circ}3$, $b = 7.^{\circ}0$, lies in a region of lower than average Galactic absorption with only slowly varying contours of extinction. Extrapolating from the Burstein & Heiles (1982) maps, we estimate the extinction to be $E(B-V) \sim 0.23$ with a likely error of ±0.04. In the next section we use the *BRI* data, together with Yale isochrone fits (Green, Demarque, & King 1987), to make an independent estimate of the reddening.

3.2. *Comparison with Yale Isochrones*

The reddening and metallicity were determined by first constraining the plausible range of both parameters using the observed cluster stellar locus in the *BRI* plane. In a two-color $B-R, R-I$ diagram, the main locus of the Yale isochrones is independent of both distance and age, and is also independent of helium abundance in the range $0.2 < Y < 0.3$. Furthermore, the position of this locus as a function of metallicity is also essentially invariant with $B-R$ color and only weakly dependent on $R-I$ color. This is illustrated in Figure 2 for a sequence of 13 Gyr Yale isochrones with metallicities −2.4, −1.4, and −0.75 superposed on the Pyxis cluster data points at a fixed reddening of $E(B-V) = 0.23$. The main locus for each metallicity can therefore be used to define an equivalent range of allowed reddening. So, for example, in order to fit the [Fe/H] = −2.4 locus, a reddening of $E(B-V) = 0.15 \pm 0.04$ is required; for [Fe/H] = −1.4 and −0.75, the corresponding reddenings are $E(B-V) = 0.17 \pm 0.04$ and 0.20 ± 0.04, respectively.

If we now examine successful pairings of metallicity and reddening on the *B*, *R* color-magnitude diagram, we find that all Yale isochrones more metal poor than [Fe/H] = −1.4 produce too blue a main-sequence turnoff to fit the data. The same holds in the *R*, *I* color-magnitude plane, whatever the age of the cluster. In the same sense we can rule out metallicities richer than [Fe/H] = −0.75, because they produce main-sequence turnoffs that are too red compared with the cluster data. Consequently, our best estimates of the cluster parameters that fit both color-magnitude diagrams and the two-color locus are a metallicity of [Fe/H] = −1.1 ± 0.3, an age of 13 ± 3 Gyr, a reddening of $E(B-V) = 0.19 \pm 0.04$, and a true distance modulus of 18.0 ± 0.2. This is illustrated in Figure 3, which shows the *B*, *R* color-magnitude diagram overlaid with a Yale isochrone corresponding to [Fe/H] = −1.1.

An alternative estimate of the metallicity can be obtained by measuring the color of the giant branch at the horizontal-branch (HB) magnitude (e.g., Zinn & West 1984). The Pyxis system has $(B-R)_g = 1.7 \pm 0.1$, which, corrected for reddening, gives $(B-R)_{0g} = 1.4 \pm 0.1$ or $(B-V)_{0g} = 0.9 \pm 0.1$. This corresponds to to a metallicity of [Fe/H] = −1.0 ± 0.3, consistent with the metallicity derived from the direct fits to the Yale isochrones, but not independent of it, because of the dependence on the reddening estimate.

3.3. *Distance*

The distance modulus was estimated essentially independent of the isochrone fits by using the location of the red

horizontal branch. From the 24 red HB stars we find $R_{HB} = 18.71 \pm 0.02$, where the rms uncertainty comes from the dispersion of the apparent magnitudes normalized by $n^{1/2}$. We can translate this value to an absolute magnitude using the relationship given by Walker (1992) for RR Lyrae stars, $M_V(RR) = 0.15[Fe/H] + 0.72$, and the transformation from $B - R$ to $B - V$ [for this color range $B - R \sim 1.54(B - V)$] given by Evans (1988) and derived from synthetic colors of stars generated from the Gunn & Stryker (1983) stellar atlas. For [Fe/H] = −1.1 the absolute magnitude of the red horizontal branch is $M_R = 0.2 \pm 0.1$, where the error solely reflects the uncertainties due to the derived Pyxis cluster parameters and does not allow for the possible 0.3 mag uncertainty in the zero point of the RR Lyrae calibration (Walker 1992). The true distance modulus of 18.0 corresponds to a heliocentric distance of 40 kpc and a Galactocentric distance of 42 kpc. The Galactic coordinates of the Pyxis cluster are (−14.5, −39.3, and +4.9) kpc, assuming a solar distance of 8.5 kpc from the Galactic center. With this position vector the Pyxis cluster lies within a few degrees of the likely orbital plane of the Magellanic Clouds (Jones, Klemola, & Lin 1994), some 34° along the orbit, and is potentially a detached cluster of this system.

3.4. *Age Estimate*

With the other cluster parameters fixed, we directly estimated the age of the Pyxis cluster by fitting Yale isochrones to the B, R and R, I color-magnitude diagrams. Our best age estimate for the cluster is 13 ± 3 Gyr, with due allowance for the errors from the reddening, metallicity, and distance estimates. However, in addition to the uncertainty in derived cluster parameters, this age estimate is sensitive to the normalization of the Yale isochrones with respect to real cluster ages. This introduces an additional spread of ±2 Gyr and brings the total error budget on the age estimate up to ±3–4 Gyr. Of the so-called young outer halo Galactic globular clusters, Pal 12, Rup 106, Arp 2, and Ter 7, only Pal 12 (Gratton & Ortolani 1988; Stetson et al. 1989) appears to have a comparable metallicity (though see Da Costa & Armandroff 1995). Direct fits of Yale isochrones to Pal 12 give an age of 10 ± 3 Gyr. Likewise, direct comparison of the Pal 12 stellar locus with the Pyxis color-magnitude diagrams also suggests that Pyxis is not a "young" globular cluster.

The clear detection of the turnoff (TO) in Pyxis allows us to estimate the cluster age directly from the magnitude difference between TO and the HB, ΔR_{TO-HB}. Fitting a ridge to the cluster locus near TO gives $R_{TO} = 22.0 \pm 0.1$, and therefore $\Delta R_{TO-HB} = 3.3 \pm 0.1$. Buonanno, Corsi, & Pesci (1989) give an average turnoff for Galactic halo globular clusters of $\Delta V_{TO-HB} = 3.55 \pm 0.09$. We can convert our ΔR magnitude into ΔV by noting that the turnoff color is 0.3 mag bluer in $B - R$ than the HB color. This leads to an estimate of $\Delta V_{TO-HB} = 3.2 \pm 0.1$, suggesting that Pyxis may be somewhat younger than the average age of Galactic halo globulars.

3.5. *Morphology and Absolute Magnitude*

Although the CCD data do not extend far enough to reach the likely cluster tidal radius, we can still use them to make estimates of the center of the cluster, the core radius, and total magnitude. To facilitate morphological studies, the locus of the cluster in the B, R color-magnitude diagram was used to select a cluster-dominated sample of stellar x, y CCD coordinates. The two-dimensional image distribution shows no significant departures from circularity, and we have therefore assumed zero ellipticity in the subsequent analysis. The center of the x, y distribution was determined by fitting a Gaussian profile to histograms of the marginal sums projected along the x- and y-axes. Using the previously measured photographic plates to bootstrap the CCD coordinate system to the plate astrometric grid, with a precision of order 1″, leads to a value for the cluster center of $\alpha = 09^h07^m57\overset{s}{.}2$, $\delta = -37°13'38''$ J2000, with an error of order ±5″ on both axes. With the center defined, it is now straightforward to measure the number density of images as a function of radius, and this is shown in Figure 4. The overlaid curve is a fit of a King (1962) model without a tidal-radius term (i.e., a Hubble law). The best-fit parameters are central density 130 arcmin^{-2}, core radius 1.′3, and background density 10 arcmin^{-2}. There is obviously some uncertainty in the background level even with the use of the color-magnitude locus to remove most of the Galactic stars. However, the value for the core radius is fairly robust with respect to the adopted background level, and we estimate the error in this parameter to be ∼10%. At a distance of 40 kpc the cluster therefore has a core diameter of some 30 ± 3 pc.

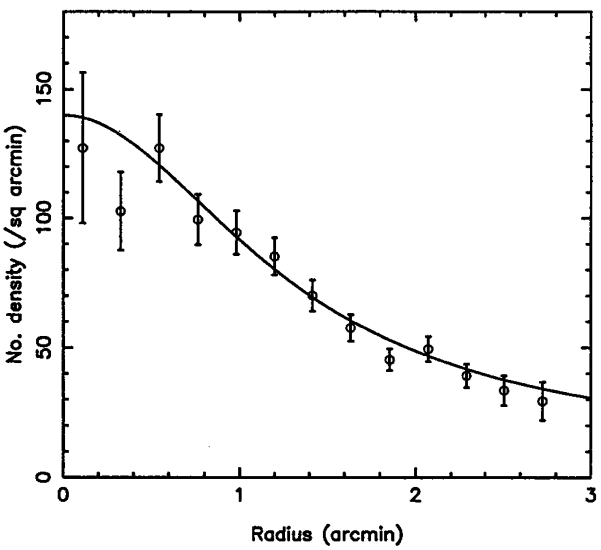

FIG. 4.—Radial surface density profile of the Pyxis cluster with a King (1962) model superposed. See text for further details.

The absolute magnitude of a cluster in such a crowded field as this is difficult to estimate directly; however, we can get an approximate idea of the magnitude by directly comparing the cluster luminosity function with that of comparable clusters, and by making a correction for the area of the cluster not recorded (∼30%) on the CCD frame. Direct comparison of the main-sequence luminosity function near TO with Pal 12 (Gratton & Ortolani 1988) implies that Pyxis is some 1.1 mag brighter than Pal 12 and therefore has an absolute mag of $M_V \sim -5.9$.

4. SUMMARY

The object identified by Weinberger on UKST sky survey film copies is a previously unknown outer halo Galactic globular cluster. The Pyxis cluster appears to be somewhat younger than the majority of halo Galactic globulars, is of intermediate metallicity, and lies some 42 kpc from the

Galactic center. An intriguing possibility is that Pyxis is a detached member of the cluster system of the Magellanic Clouds, since it lies in the plane of their orbit and at a similar distance. With this in mind, it is of note that the color-magnitude diagram of Pyxis is similar to that of the outer halo LMC cluster, ESO 121–SC03 (Mateo, Hodge, & Schommer 1986), which has an anomalous age relative to other LMC clusters and has been postulated to be a captured SMC cluster. A radial velocity is urgently needed to examine the possibility of Pyxis being a Magellanic Cloud cluster captured by the Galactic halo.

We would like to thank the referee for his comments on our manuscript. We are grateful to the UKSTU for lending us the *R* survey plate used in this study, and we acknowledge useful discussions with M. Mateo. This project has been supported financially, in part (S. D.), by the Natural Sciences and Engineering Research Council of Canada.

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