A DYNAMICAL SIGNATURE OF MULTIPLE STELLAR POPULATIONS IN 47 TUCANAE

Harvey B. Richer[1], Jeremy Heyl[1], Jay Anderson[2]

as of March 8, 2013

ABSTRACT

Based on the very broad width of its main sequence, 47 Tucanae is suspected of containing multiple stellar populations. In this contribution, we divide the main sequence of 47 Tuc into four color groups which presumably represent stars of various chemical compositions. The kinematical properties of each of these groups is explored via proper motions and a strong and smoothly varying signal emerges of differing proper motion anisotropies and median proper motion with differing main sequence color; the bluest main sequence stars exhibit the largest proper motion anisotropy which becomes undetectable for the reddest stars. In addition, the proper motion distributions of the various color groups are highly dissimilar. A simiilar analysis for SMC stars, which are located in the background of 47 Tuc on our frames, also exhibit some anisotropy but show none of the variations with color in their proper motion distributions exhibited by the 47 Tuc stars. We discuss implications of these results for possible formation scenarios of the various populations.

Subject headings: globular clusters: individual (47 Tuc) — stars: Population II, Hertzsprung-Russell and C-M diagrams, kinematics and dynamics

1. INTRODUCTION

Previous to about 1980, the general paradigm for globular star clusters was that they were simple stellar populations, that is all stars had uniform chemical composition and were all the same age. However, since that time, numerous spectroscopic studies have shown that many of these clusters exhibit chemical composition variations among their stars likely caused by H-burning via the hot CNO cycle (see Gratton et al. 2004 for a nice review). Recent imaging observations with the Hubble Space Telescope (HST) that produced exquisitely precise photometry has extended this picture to many if not all clusters (see Piotto 2009 for a recent review). However, what is currently lacking is detailed insight into the manner of formation of the various stellar populations in such a cluster. Key input could potentially come from the observation of different dynamics or spatial distributions of the various populations.

The main sequence of 47 Tuc is much broader than observational error alone can explain. This was first pointed out by Anderson et al. (2009) and examined in some detail by Milone et al. (2012) who suggest that the CMD width could be explained as a second-generation population, making up 70% of the total, enriched in both He and N, depleted in C and O with C+N+O constant.

Vesperini et al. (2013), using N-body simulations, have explored the behavior of first generation and second generation stars in a multi-population cluster. In general they find that complete mixing of the two populations does not occur until the cluster is well advanced dynamically; that is when it has lost upwards of 70% of its mass due to two-body relaxation. 47 Tuc, with a half-mass relaxation time of 3500 Myr (Harris 2010), has barely arrived at a state of dynamical relaxation. We can thus expect that its various populations will not yet be well-mixed and that it might be possible to observe either kinematic and/or spatial differences amongst its various stellar populations. Such an observation could well provide critical clues to the multiple population scenario.

In § 2 below we briefly mention the observations relevant to the current study and follow this in § 3 with an exploration the proper motion kinematics of cluster stars yielding strong evidence for differences amongst stars of differing main sequence colors (chemical compositions). § 4 presents a search for radial differences and § 5 discusses possible formation scenarios for the various stellar populations based on their currently observed motion and distributions.

2. THE DATA

Our team was awarded 121 HST orbits in Cycle 17 to image 47 Tuc (GO-11677). The main science goal was to obtain photometry with the ACS F606W and F814W filters that would go deep enough to study the entirety of the white dwarf cooling sequence. A detailed discussion of the observations and data reduction can be found in Kalirai et al. (2012) and Anderson et al. (2008) respectively. Briefly stated, the photometry and proper motions were determined using a total of 754 exposures that were reduced and collated. For the purposes of the present paper it is important to point out that thirteen different roll angles of the telescope were used to acquire the complete data set so there was no preferred axis of the CCD camera which might bias our proper motion results. The total number of exposures include both those from our new HST data together with archival observations. The transformation from each image frame into a reference frame was made using reference-frame stars, then average positions, proper motions and photometry were determined for each star.

Figure 1 displays the proper motion (PM) diagram for all stars in our frames. The 47 Tuc PM distribution was centered around (0,0) with the distribution centered at (4.5,1.5) for the Small Magellanic Cloud (SMC) which

[1] Department of Physics & Astronomy, University of British Columbia, Vancouver, BC, Canada V6T 1Z1; richer@astro.ubc.ca, heyl@phas.ubc.ca
[2] Space Telescope Science Institute,Baltimore MD 21218; jayander@stsci.edu

lies in the background of 47 Tuc. We wanted to have as complete a sample as possible for both 47 Tuc and the SMC with a minimum of contamination. For this reason our PM cut was very generous (about 10σ in each case) with an additional cut in the CMD. From these PM samples we constructed the color-magnitude diagram (CMD) for 47 Tuc (Figure 2). In the present paper we use for 47 Tuc a CMD derived from photometry on individual ACS images in the F606W and in the F814W filters. Images were not combined preserving as much as possible the original resolution in the data (Anderson et al. 2008).

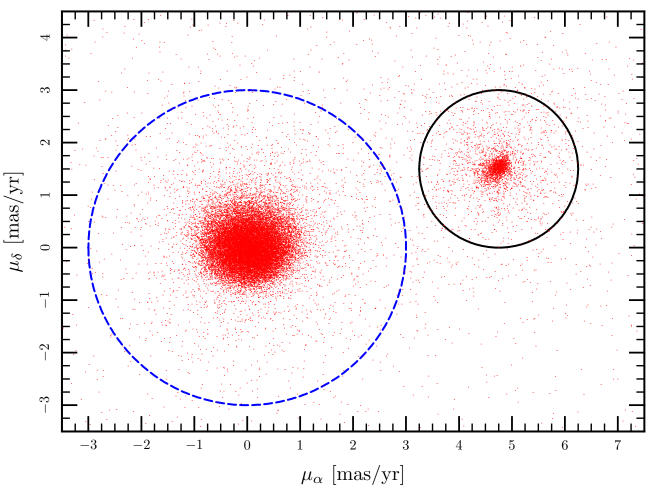

FIG. 1.— PMs of all stars in our frames. The large dashed blue circle encompasses the full 47 Tuc sample. The solid black circle is the boundary of the proper-motion sample for the SMC.

This CMD is meant to contain stars with the highest quality PMs and photometry and hence does not penetrate to extremely faint magnitudes. The left panel of Figure 2 displays the CMD of all stars on our frames. The CMD, however, shows the unusual problem that 47 Tuc poses: in its background is a sizable population of more distant stars that belong to the edge of the SMC. Thus the CMD reveals three major sequences. The reddest one is the cluster main sequence (MS), while the bluest one is its white dwarf cooling sequence. Between them is the SMC MS. This encroachment makes it imperative that the SMC stars be removed from our CMD, by proper motion cleaning. Fortunately the cluster is moving with respect to the SMC by several milliarcseconds (mas) per year, so that over the time span of all available ACS images the differential motion of the two systems amounts to nearly a whole ACS pixel (50 mas). Moreover, since we chose for our observations a field in 47 Tuc that is one of the major calibration fields for the ACS, our field has been imaged hundreds of times over the past ten years. Even though most of those images have shorter exposures, we can use the new deep images to locate in them stars that might otherwise be too faint to measure; with so many images, our proper motions

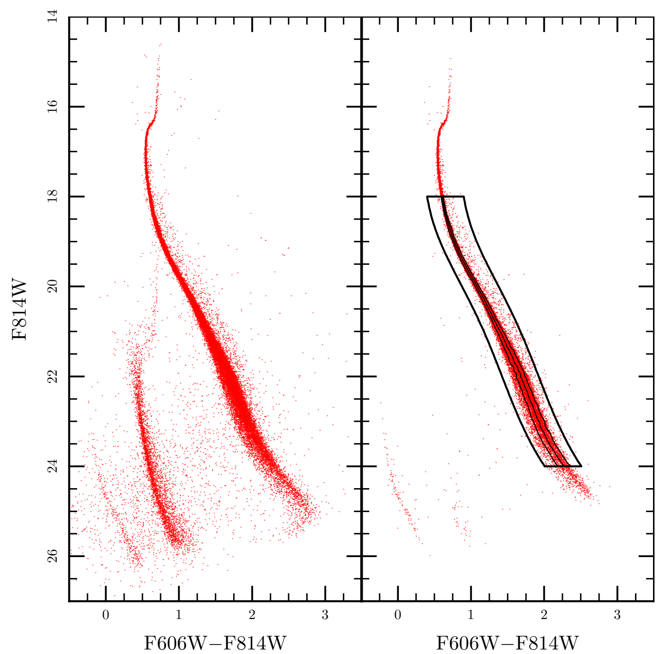

FIG. 2.— CMDs of 47 Tuc. Left: All objects measured in our 47 Tuc field centered at 1.9 half light radii. Right: The same data as in the left panel but now proper motion cleaned to eliminate all but the 47 Tuc stars. Only the main sequence stars within the indicated box are retained for analysis. The light lines in the right panel delineate the color groups outlined in § 3.

are quite well determined.

We construct our sample in two steps. The first step is to identify the location of the main sequence ridge line of 47 Tuc in the CMD. The left-hand panel of Figure 2 depicts the CMD for all the stars in our frame. The right-hand panel depicts only those stars whose proper motions lie within the long-dashed, blue circle in Figure 1. This proper-motion cleaned CMD allows us to roughly determine the main-sequence ridge line and define a colour and magnitude selected sample of stars whose magnitudes lie within the black box and whose proper motions lie within the large, long-dashed blue circle in Figure 1. In this way we do not exclude stars with unusually high proper motions from our cluster sample and eliminate non-cluster stars with color cuts. The solid black circle in Figure 1 is the boundary of the PM sample for the SMC. We define and use a color cut for the SMC sample in a similar manner.

3. PROPER MOTION KINEMATICS

We divide the 47 Tuc MS into four groups in color from bluest to reddest. We first sort the MS stars from brighest to faintest in F814W and divide this sorted sample into thirty non-overlapping groups of 400 stars. For each group of stars we determine the median F606W − F814W color as well as the standard deviation of the distribution as estimated by the Q_n statistic (Rousseoeuw & Croux 1991). As in Heyl et al. (2012) we use this statistic as a robust estimator of the standard deviation of a distribution, and we will denote its value by $\hat{\sigma}$. The right panel of Figure 2 displays the four color groups along the MS of 47 Tuc as a function of apparent magnitude.

Thus we have defined the width through $\hat{\sigma}$ and the center of the main sequence through the median as a function of F814W. By spline interpolation we determine the values of the width and median at the value of F814W for each star in the sample and assign each star to one of four color groups. The first group lies greater than one standard deviation blueward of the median. The second group lies blueward of the median yet within one standard deviation. The third group lies redward of the median yet within one standard deviation. The fourth group lies more than one standard deviation redward of the median. The proper motions of all of the stars lie within the large circle in Figure 1, and their magnitudes lie within the box in Figure 2. The ridge line of the main sequence typically lies within the second group. The fourth group contains some binary stars with nearly equal mass components. Binaries with more unequal mass components lie closer to the main-sequence ridge line. Chemical abundance variations can also affect the color of single stars resulting in a spread in color. Our data are not sufficient to determine whether a particular stellar object is a single star with a peculiar chemical abundance, a binary or an optical double. These four color groups, indicated on the 47 Tuc CMD in the right panel of Figure 2, presumably represent stars of differing chemical composition or binarity that can now be explored kinematically.

In Figure 3 (top) we plot the proper motion dispersions in the radial and tangential directions with respect to the cluster center for the four groups. In calculating these dispersions we have added an additional cut in the estimated proper-motion error. We only use the stars whose errors are less than the median proper-motion error at their apparent magnitude. The error bars in the dispersions denote 90% confidence regions as determined by bootstrapping the sample. If the stars are moving isotropically, the dispersions in these two orthogonal directions should be the same. Clearly they are not. The anisotropy is largest for the bluest stars and reduces to no discernible anisotropy for the reddest ones. This signature remains after dividing the main sequence into brighter and fainter groups.

Furthermore, the middle panel of Figure 3 depicts the median tangential proper motion of each group relative to the mean proper motion of the main sequence stars. Again we see that the redder stars move differently than the blue stars. According to Figure 3 of Anderson and King (2003), the rotation of 47 Tuc is toward negative values in the tangential direction in this diagram – at about −0.23 mas/yr. Hence the bluest stars move more slowly than average in the direction of the rotation of the cluster in the plane of the sky.

As a sanity check we carried out a similar analysis on the SMC stars. Again we divide the MS of the SMC into four color bins. Of course, since the MS of the SMC is much bluer than that of 47 Tuc, the SMC groups have different color ranges compared to those in 47 Tuc. We have restricted our sample here to lie below the turnoff of the SMC (fainter than F814W= 22) and brighter than 24 in F814W. In 47 Tuc we measured the PM dispersions along the radial and tangential axes of the direction to the cluster center. This makes no sense for the SMC because the proper motion ellipse of the SMC is rotated by 45 degrees relative to that of 47 Tuc. In this case we measure the dispersions along (blue squares) and perpendicular to (green triangles) the long axis of the proper motion distribution seen in Figure 1. These are illustrated in the bottom panel of Figure 3.

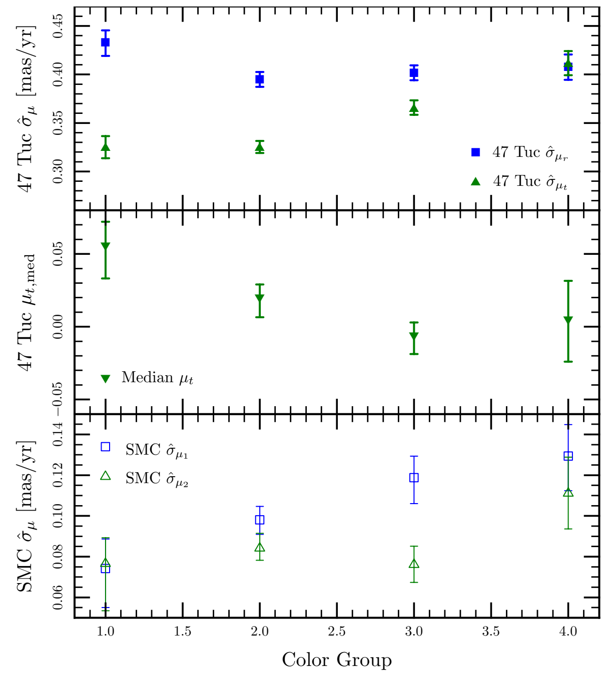

Fig. 3.— The radial and tangential proper motion dispersions as a function of color group (1 is the bluest main sequence group, 4 the reddest) for 47 Tucanae (top) and the SMC (bottom) as well as the median tangential proper motion for 47 Tucanae (middle).

Note that the PMs here are much smaller than for 47 Tuc reflecting mainly its greater distance; it is thirteen times farther from the Sun than is 47 Tuc. In addition, the stellar sample here is much smaller than was available for 47 Tuc (12,199 vs. 1,115). As with 47 Tuc, there is some evidence for anisotropy in these PMs. However, the trend of anisotropy with color group in the SMC is completely different than in 47 Tuc. In 47 Tuc the dispersion along the major (radial) axis of the proper motion only changes modestly while the dispersion along the minor (tangential) axis increases for the redder stars. In the SMC the dispersion along the minor axis of the proper motion ellipsoid changes modestly, and the dispersion along the major axis increases for the redder stars. The distribution is more anisotropic for the redder stars. Due to the size of the SMC sample this trend is only marginally significant.

We quantify these statements by comparing the PM distributions of the various color groups in 47 Tuc to each other and then again for the SMC via KS tests. These data are collected in Table 1. The KS tests give evidence for large differences in the PM distributions among the 47 Tuc color groups but are inconclusive for the SMC.

4. RADIAL EFFECTS

In addition to PM effects, we search for radial differences among the various 47 Tuc color groups. Since 47 Tuc is at best barely relaxed, any discernible signals here could potentially provide important clues to formation scenarios of the populations. In Figure 4 we present the cumulative radial distributions of the four MS color groups of 47 Tuc. The bluest color group is by far the most centrally concentrated of all and this conclusion is

TABLE 1
KS Probabilities for Minor-Axis PM Distributions and the Radial Distributions

Color Groups	47 Tuc	SMC	47 Tuc Radial
1 vs. 2	6.89×10^{-3}	0.688	8.46×10^{-7}
1 vs. 3	3.27×10^{-6}	0.357	1.03×10^{-11}
1 vs. 4	9.96×10^{-7}	0.275	1.47×10^{-4}
2 vs. 3	6.92×10^{-4}	0.371	6.84×10^{-3}
2 vs. 4	1.08×10^{-6}	0.447	8.91×10^{-3}
3 vs. 4	6.96×10^{-3}	0.340	1.52×10^{-3}

statistically highly significant as demonstrated in the final column Table 1. If the spread in color were due to a large contribution of binaries or optical doubles, one would expect that the reddest color bin would be the most centrally concentrated due to mass segregation in the first instance and the increased chance of superposition in the second.

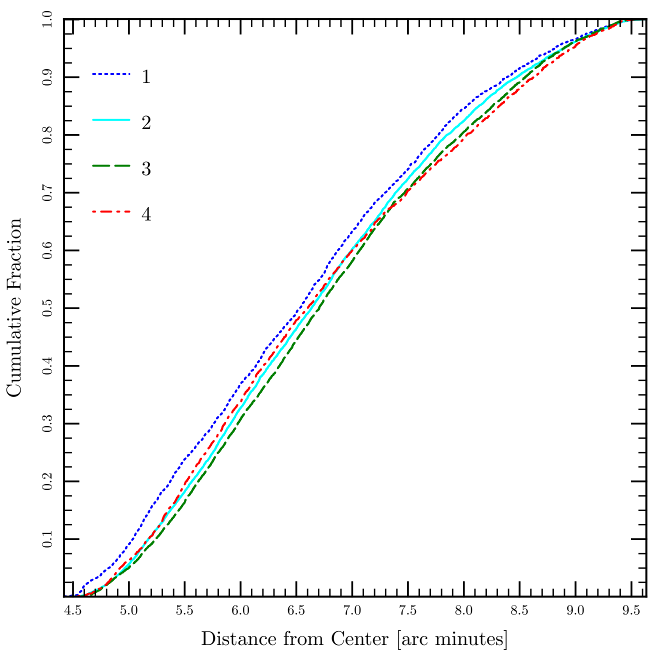

Fig. 4.— The cumulative radial distribution of the four color groups of 47 Tuc main sequence stars.

5. DISCUSSION

What have we discovered in the present analysis?

- The 47 Tuc main sequence stars demonstrate anisotropic PMs that are strongly correlated with their colors. The sense of this result is that the bluest stars possess the most anisotropic motions while the reddest stars exhibit no measurable anisotropy. The SMC stars also exhibit some anisotropy, but this anisotropy is not correlated with the colors of the stars as it is for 47 Tuc.
- The 47 Tuc main sequence stars of differing colors possess cumulative proper motion distributions that are radically different. The cumulative distributions of the proper motions of the color groups in the SMC exhibit no statistically significant variations.
- The bluest 47 Tuc MS stars are more centrally concentrated than the redder stars.

What formation scenarios do these observations suggest?

The distributions of proper motions and positions differ for stars on the red and blue side of the main sequence ridge line of 47 Tuc. These differences contradict the notion that the globular cluster formed monolithically. The possible formation scenarios fall into two separate categories depending on whether one assumes the blue population to be younger or older than the red population. Of course, these age differences are small compared to the age of the cluster, but significant compared to the time over which the stars of 47 Tuc formed.

Milone et al (2012) support the first scenario and argue that the blue cohort exhibits signs of CNO processing and therefore helium enrichment from the earlier red generation. This first red generation would reflect the initial angular momentum of the gas that was to form the cluster. After the most masssive of these stars died and returned CNO enriched gas to the cluster, the second bluer generation form from radially outflowing gas resulting in a proper motion distribution dominated by radial motions. Furthermore, some of the highest angular momentum gas could have been lost before the second star formation epoch, resulting in less angular momentum in the second bluer generation of stars. Finally the chemical enrichment would have been produced by the most massive and most centrally concentrated stars in the cluster, so the blue stars that result would also be more centrally concentrated. This broad-brushstroked scenario is illustrative and not unique, but it does demonstrate how such dynamical measurements could constrain the birth history of the cluster. Detailed numerical simulations including gas dynamics would be required to get a clearer picture.

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. These observations are associated with proposal GO-11677. Support for program GO-11677 was provided by NASA through a grant from the Space Telescope Science Institute which is operated by the Association of Universities for Research, Inc., under NASA contract NAS5-26555. H.B.R. and J.H. are supported by grants from The Natural Sciences and Engineering Research Council of Canada and by the University of British Columbia. J.A., B.M.S.H., J.S.K., R.M.R and M.M.S. were funded by NASA. The authors benefited from useful conversations with Brett Gladman.

REFERENCES

Anderson, J., & King, I. R. 2003, AJ, 126, 772

Anderson, J., King, I. R., Richer, H. B., Fahlman, G. G., Hansen, B. M. S., Hurley, J., Kalirai, J. S., Rich, R. M., & Stetson, P. B. 2008, AJ, 135, 2114

Anderson, J., Piotto, G., King, I. R., Bedin, L. R., & Guhathakurta, P. 2009, ApJ, 697, L58
Gratton, R., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385
Harris, W. E. 2010, arXiv1012.3224
Heyl, J. S., Richer, H., Anderson, J., et al. 2012, ApJ, 761, 51
Kalirai, J. S., Richer, H. B., Anderson, J., et al. 2012, AJ, 143, 11
Milone, A. P., Marino, A. F., Piotto, G., et al. 2012a, ApJ, 744, 58
Piotto, G. 2009, IAU Symposium, 258, 233
Rousseoeuw, P.J. & Croux, N.N. Journal of the American Statistical Association 88, 20, 1991
Vesperini, E., McMillan, S. L. W., D'Antona, F., & D'Ercole, A. 2013, MNRAS, 429, 1913