THE ASTROPHYSICAL JOURNAL, 554:L33–L36, 2001 June 10
© 2001. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE QUEST RR LYRAE SURVEY: CONFIRMATION OF THE CLUMP AT 50 KILOPARSECS AND OTHER OVERDENSITIES IN THE OUTER HALO

A. K. VIVAS,[1] R. ZINN,[1] P. ANDREWS,[2] C. BAILYN,[1] C. BALTAY,[2] P. COPPI,[1,2] N. ELLMAN,[2] T. GIRARD,[1] D. RABINOWITZ,[2] B. SCHAEFER,[3] J. SHIN,[2] J. SNYDER,[1,2] S. SOFIA,[1] W. VAN ALTENA,[1] C. ABAD,[4] A. BONGIOVANNI,[4] C. BRICEÑO,[4] G. BRUZUAL,[4] F. DELLA PRUGNA,[4] D. HERRERA,[4] G. MAGRIS,[4] J. MATEU,[4] R. PACHECO,[4] GE. SÁNCHEZ,[4] GU. SÁNCHEZ,[4] H. SCHENNER,[4] J. STOCK,[4] B. VICENTE,[4] K. VIEIRA,[4] I. FERRÍN,[5] J. HERNANDEZ,[5] M. GEBHARD,[6] R. HONEYCUTT,[6] S. MUFSON,[6] J. MUSSER,[6] AND A. RENGSTORF[6]

Received 2001 February 21; accepted 2001 May 8; published 2001 June 4

ABSTRACT

We have measured the periods and light curves of 148 RR Lyrae variables from $V = 13.5$ to 19.7 from the first 100 deg^2 of the Quasar Equatorial Survey Team RR Lyrae survey. Approximately 55% of these stars belong to the clump of stars detected earlier by the Sloan Digital Sky Survey. According to our measurements, this feature has ~10 times the background density of halo stars, spans at least 37°.5 by 3°.5 in α and δ ($\geq$30 by $\geq$3 kpc), lies ~50 kpc from the Sun, and has a depth along the line of sight of ~5 kpc (1 σ). These properties are consistent with the recent models that suggest that it is a tidal stream from the Sagittarius dwarf spheroidal galaxy. The mean period of the type ab variables, 0.58 days, is also consistent. In addition, we have found two smaller overdensities in the halo, one of which may be related to the globular cluster Pal 5.

Subject headings: galaxies: individual (Sagittarius) — Galaxy: halo — Galaxy: structure — stars: variables: other

1. INTRODUCTION

A well-supported working hypothesis for the formation of the Galactic halo is that its stars and globular clusters were torn from smaller galaxies as they underwent tidal destruction on the way to merging with the Milky Way (see review by Bland-Hawthorn & Freeman 2000). While many features of the halo support this picture, the most direct evidence is provided by the Sagittarius dwarf spheroidal (dSph) galaxy, which is now in the process of tidal destruction in the halo (Ibata, Gilmore, & Irwin 1994; Mateo et al. 1996). Models of the demise of the Sgr dSph galaxy and of other small galaxies have shown that streams of stars from merger events should persist for billions of years in the halo (Johnston 1998; Helmi & White 1999). Until very recently, these streams escaped detection because the old surveys of the halo were too limited in sky coverage or in depth. While a few moving groups of high-velocity stars have been known for a long time (e.g., Eggen 1979), these could be explained by the disruption of star clusters (Eggen 1996), and the density contours of the halo were thought to be smooth on scales of kiloparsecs. The new surveys that map the densities of halo stars over larger areas and to greater depths and ones that detect moving groups of halo stars have revealed large substructures in both density and velocity space, as predicted by the merger hypothesis (Majewski, Munn, & Hawley 1994; Helmi et al. 1999; Morrison et al. 2000; Ibata et al. 2001b). One of the most significant results of these surveys was the discovery of a large clump of candidate RR Lyrae variables (RRs) and A-type stars by the Sloan Digital Sky Survey (SDSS; Ivezic et al. 2000; Yanny et al. 2000). Ivezic et al. and Yanny et al. suggested that this clump is part of the tidal tail of the Sgr dSph galaxy, which is supported by the more recent modeling of the Sgr stream by Ibata et al. (2001a), Helmi & White (2001), and Martínez-Delgado et al. (2001).

We report here the first results of the Quasar Equatorial Survey Team (QUEST) survey for RRs, which will ultimately survey about 700 deg^2 of the sky down to a limiting magnitude of $V \sim 19.7$. By coincidence, the first part that has been completed includes a large fraction of the region searched earlier by the SDSS for RRs. Unlike the SDSS, which consisted of only two epochs of observations separated by 1.99 days, we have observations at 20–30 epochs separated by hours to more than 1 yr. These observations allow us to detect many more RRs than the SDSS and to determine the periods and the light curves of the stars, which ensures that they are indeed RRs and not another type of variable. In addition, we determine the mean magnitudes of the stars from many measurements, which reduces the errors in their distances.

Our results confirm the major conclusion of the SDSS that a large clump of old stars exists in the halo at ~50 kpc from the Sun and show that this clump extends beyond the SDSS region. We also find evidence for two smaller density enhancements, one of which may be related to the globular cluster Pal 5.

2. OBSERVATIONS AND DATA REDUCTION

The observations for this survey were made with the 1 m Schmidt telescope at Llano del Hato Observatory in Venezuela and the CCD camera built by the QUEST collaboration (Snyder 1998). The camera has 16 2048 × 2048 CCDs set in a 4 × 4 array. It has a 2°.3 × 2°.3 field of view, and the pixel size of 15 μm corresponds to a scale of 1″.02 pixel^{-1}. The camera is operated in drift-scan mode, which generates a continuous strip of the sky at a rate of 34.5 deg^2 hr^{-1}. Each row of four CCDs is fitted with a different filter. Because V observations were obtained every night, they were chosen for the search for RRs.

[1] Yale University, Astronomy Department, P.O. Box 208101, New Haven, CT 06520-8101.
[2] Yale University, Physics Department, P.O. Box 208120, New Haven, CT 06520-8120.
[3] University of Texas, Department of Astronomy, Austin, TX 78712.
[4] Centro de Investigaciones de Astronomía (CIDA), AP 264, Mérida 5101-A, Venezuela.
[5] Universidad de Los Andes, Departamento de Fisica 5101, Mérida, Venezuela.
[6] Indiana University, Department of Astronomy, 319 Swain West, Bloomington, IN 47405.

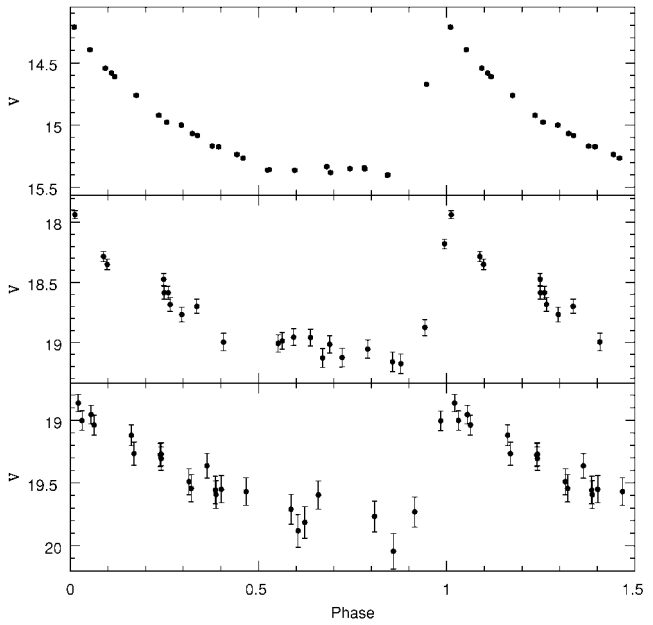

FIG. 1.—Phased light curves of three RRs of different magnitudes. *Top:* Light curve of a star near the bright limit of our survey. *Middle and bottom:* Light curves of stars near the faint limit. As expected, near the faint limit the photometric errors are large but are nonetheless much smaller than the amplitudes of the type ab variables.

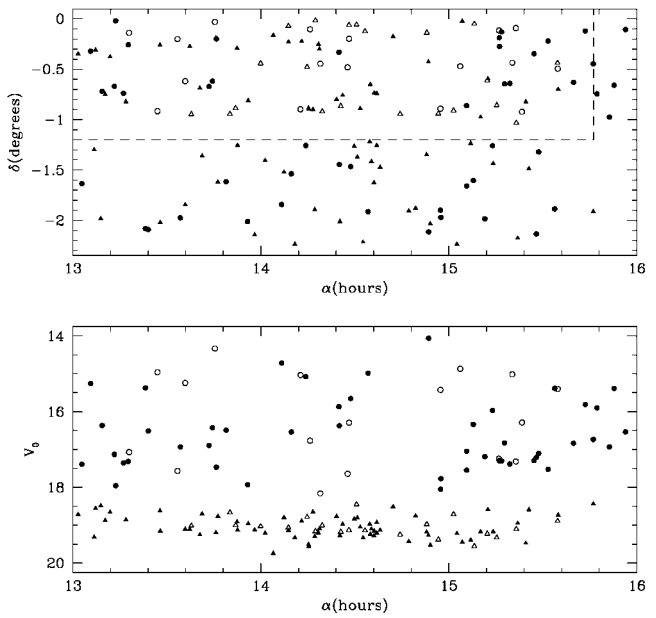

FIG. 2.—*Top:* Distribution of the RR Lyrae stars in the sky. The dashed line encloses the region of overlap with SDSS. *Bottom:* Distribution of the V_0 (extinction-corrected) magnitudes of the stars as a function of right ascension. In both panels, open symbols are stars discovered first by SDSS and recovered by our survey. Triangles are the stars in the clump ($V_0 \geq 18.4$).

The limiting magnitude of the survey is ~19.7 in V (signal-to-noise ratio = 10), which was set by the drift time of a star across a chip (140 s at $\delta = 0$) and the seeing, which varied from 1.″9 to 3.″2. Saturation of the CCDs occurred at $V = 13.5$. We obtained between 20 and 30 scans of the region $\alpha = 13^h$ to 16^h, $\delta = -2°20'$ to $+0°02'$ (100 deg^2) during 1999 February to 2000 April. Because of the defects of the CCDs or high levels of cloudiness, a small fraction of the stars could not be measured more than 12 times.

The standard QUEST software performed bias subtraction, flat-fielding, and aperture photometry in each of the four filter bands in which an object was observed. The instrumental magnitudes were normalized to a reference scan in order to remove variable atmospheric extinction due to differences in air mass and transparency. This normalization to reference magnitudes was made in bins of 0.°25 of right ascension (~1 minute of time in drift-scan mode). Each bin contains typically 1000 stars, which produces a robust estimate of the zero-point difference between the scan and the reference scan. The random errors of the differential magnitudes amount to 0.02 for $V \leq 17$ but climb to 0.12 at $V = 19.7$ as photon statistics dominate the noise. Roughly 40 secondary standard stars were set up with the 1 m Yale-AURA-Lisbon-Ohio telescope at Cerro Tololo Inter-American Observatory. The zero-point error in V is ~0.03 mag.

To find the variable stars, we used a χ^2 test (e.g., Saha & Hoessel 1990) on the normalized instrumental magnitudes. If the probability that the observed variation of a star is caused by errors alone is very small (<0.01), then the star is labeled as variable. The RRs were identified by first reducing the list of variable stars to those with amplitudes between 0.25 and 1.5 mag in V and with $V-R$ colors less than 0.55. We then isolated stars with periods in the range 0.2–1.0 days. The phased light curves were examined by eye, and RRs of type ab were easily recognized by the light-curve shapes. Although this method also detected several type c RRs, which have lower amplitudes and more sinusoidal light curves than the type ab, it is not optimum for finding them. We will search our data later for type c, which are less numerous than the type ab variables. The quality of the light curves that are produced by the data is illustrated in Figure 1.

The completeness of the survey is a complex problem because the number of observations of each star depends on position on the sky and magnitude. Using Monte Carlo simulations we estimate that the survey is ~80%–100% complete for $V < 18.5$ and ~55%–78% complete at the faint end of the survey. A more detailed description of these simulations and the techniques of the survey is given in A. K. Vivas et al. (2001, in preparation).

3. RESULTS

The survey found a total of 135 RRs of type ab and 13 of type c. The distributions of these stars on the sky and in magnitude as a function of right ascension are shown in Figure 2. This figure also illustrates the region of overlap with the SDSS. The magnitudes were corrected for interstellar extinction using the maps of Schlegel, Finkbeiner, & Davis (1998).

In the region of overlap, the SDSS identified 59 stars as RRs. Our survey recovered 50 of these stars, or 85%. The remaining nine stars were either so faint that we had too few observations to calculate periods or were missed by our software because they lie on bad columns in the reference scan. Of the 50 stars for which we had adequate observations, 34 were confirmed to be RRs of type ab and four were confirmed as type c. We suspect that the remaining 12 stars are not RRs or ones whose light curves are strongly affected by the Blazhko effect. However, we found in addition many more RRs. We found a total of 90 RRs in this region, of which only 42% were identified by the two-epoch SDSS survey. This is consistent with the completeness estimate made by Ivezic et al. (2000).

The plot of the mean magnitudes against right ascension in

the lower panel of Figure 2 shows a very conspicuous clustering in $\langle V_0 \rangle$ between ~19.0 and 19.5. This is the clump of stars that the SDSS (Ivezic et al. 2000; Yanny et al. 2000) discovered earlier. Our survey confirms the existence of this feature of the Galactic halo, which is conclusive evidence that the density contours of the halo are not smooth (see also Fig. 4), and provides a detailed description of its properties.

The overdensity of the clump with respect to the background of halo stars appears to be about a factor of 10 (see below). Consequently, little error is probably introduced if we consider all of the 84 stars with $\langle V_0 \rangle \geq 18.4$ to be clump members when estimating its dimensions. The clump extends from the western limit of our survey at 13^h to at least $15^h.5$, a span of $37^\circ.5$ (see Fig. 2). Between 13^h and $\sim 14^h.2$, the faint limit of the clump appears to be significantly brighter than the limit of our survey. This is less clear from $14^h.2$ to $15^h.5$, and the apparent disappearance of the clump between $\sim 15^h.5$ and 16^h may be caused by it moving fainter than our limit. Our data from 13^h to 14^h indicate that the standard deviation in $\langle V_0 \rangle$ is only 0.26 mag, which we show below is evidence for a relatively small depth along the line of sight. This is consistent with the SDSS, which did not find any RRs at $r' > 20$. From 13^h to $15^h.5$, clump stars are found at all δ in our survey. If we consider the additional area surveyed by the SDSS, the clump extends at least $3^\circ.5$ in δ. The highest concentration of stars occurs at $\alpha = 14^h.6$, where there are as many as two RRs per deg^2. There is no obvious concentration in δ, although there is a slight decrease in RRs from north to south.

To calculate the distances to the RRs, we have assumed that they have an absolute visual magnitude (M_V) of +0.56. This value is appropriate for a stellar population with [Fe/H] = −1.6, which is typical of the halo, and a horizontal branch (HB) morphology that produces a large population of RRs (Demarque et al. 2000). It is near the middle of the range given for this [Fe/H] by several observational studies (see A. K. Vivas et al. 2001, in preparation, for more discussion). With this value of M_V, the distance to the clump is approximately 50 kpc, and its minimum dimensions of $37^\circ.5$ and $3^\circ.5$ in α and δ, respectively, translate into ≥30 by ≥3 kpc. The dispersion in $\langle V_0 \rangle$ (0.26 mag, see above) is due to the observational errors in $\langle V \rangle$ (~0.08 mag), the errors in the correction for interstellar extinction (~0.06), the dispersion in the distance modulus, and two effects related to the properties of HB stars, the dispersion in RR absolute magnitude caused by evolution (~0.08 mag from the color-magnitude diagrams of globular clusters, e.g., Table 13 in Sandage 1990) and by the dispersion in [Fe/H] in the stellar population. Taking σ[Fe/H] = 0.5 as a value typical of dwarf galaxies (including Sgr; Mateo 1998) and the Demarque et al. (2000) M_V-[Fe/H] relation, we estimate a dispersion of ~0.1 from this source. Subtracting in quadrature the observational errors and these other estimates from the observed dispersion in $\langle V_0 \rangle$, we find a dispersion of 0.2 mag in the distance modulus. This suggests that the depth along the line of sight has a dispersion of ~5 kpc. The clump is long, ≥30 kpc, and thin, ~5 kpc; however, until more is known about its extent in δ, we do not know whether it resembles a sheet or a ribbon.

To calculate the number density of RRs, we divided the survey into eight equal strips in α and followed the procedure of Saha (1985) in each strip. After obtaining the densities along the lines of sight, we transformed from heliocentric to Galactocentric coordinates and averaged the densities in bins of equal size in log Galactocentric distance (R). These densities are plotted against log R in the top panel of Figure 3, where the line was fitted to the nine points that define a lower envelope

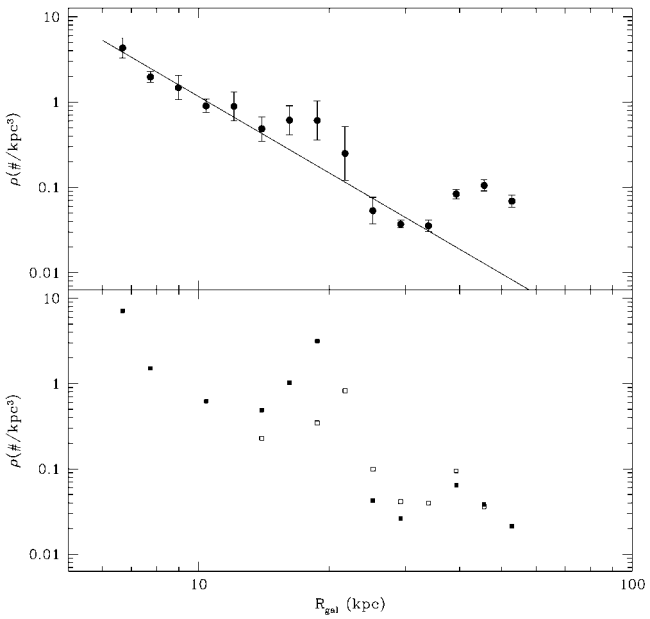

FIG. 3.—*Top:* Radial density profile of the RR Lyrae stars found in the survey. *Bottom:* Radial density profiles in the subregion $\alpha = 13^h.0$–$13^h.375$ (*open squares*) and $\alpha = 15^h.250$–$15^h.625$ (*filled squares*), which coincides with Pal 5.

to the densities. The slope of this line (-3.0 ± 0.2) is consistent with previous determinations (Wetterer & McGraw 1996; Ivezic et al. 2000) of the density falloff in the halo.[7] The clump of RRs produces the overdensity at $R > 40$ kpc, where it is roughly 10 times the density predicted by the line.

In this figure there is evidence for another overdensity of RRs from $R \sim 16$ to 23 kpc. Unlike the distant clump, which is seen in all but the last one of the strips in α, these overdensities are visible in only two strips and appear to be two separate clusterings. The lower panel in Figure 3 shows separately the density gradients in the two strips. The most prominent one, which occurs at $R \sim 17$ kpc, is probably related to the globular cluster Pal 5, which lies within the area we surveyed on the sky. Although our software is not designed to work in crowded regions, we recovered two of the five known RR Lyrae variables in Pal 5 (all type c; Sawyer Hogg 1973). These stars were excluded before computing the densities that are plotted in Figure 3. The overdensity is produced by six other RRs, two of which lie within the tidal radius of Pal 5 and four more distant ones that are within a projected distance from the cluster of 0.6 kpc. Since other evidence suggests that Pal 5 is being disrupted by the tidal field of the Milky Way (Odenkirchen et al. 2001), we suspect that these variables had their origin in Pal 5. The other overdensity is produced by five stars that have very similar values of R and lie in the strip of α from $13^h.0$ to $13^h.375$. Four of these stars lie within 1° of each other, which is suggestive of a real clustering (see also Figs. 2 and 4). Observations will be obtained soon to see whether the radial velocities of these stars and the ones near Pal 5 are consistent with physical associations.

[7] The referee has pointed out that a fit to all the data in the top panel of Fig. 3 would yield a slope near −2, with an underdensity between 25 and 35 kpc, and that this slope is interesting because it is similar to estimates of the slope of the dark matter halo. While we too find this interesting, we are reluctant to draw conclusions from it at this time because, in directions away from the clump of RRs at $R \sim 45$ kpc, the slope definitely steepens to ~−3.

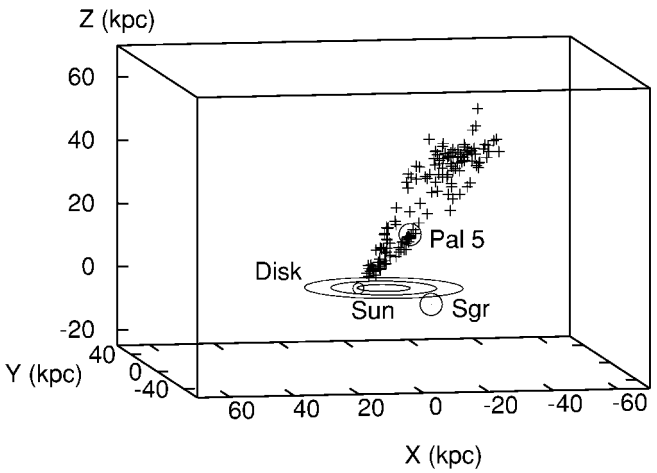

FIG. 4.—Three-dimensional view of the locations of the RRs (*plus signs*), the Sun, the Sgr dSph galaxy, and the globular cluster Pal 5. Three circles in the Galactic plane with radii of 8, 16, and 24 kpc indicate the solar radius and the approximate extents of the optical and the H I disks, respectively.

4. DISCUSSION

The long and relatively thin clump of RRs at $R \sim 50$ kpc resembles the tidal streams that have been predicted by models of the merging of small satellite galaxies with the Milky Way. After the discovery of this clump by the SDSS, Ibata et al. (2001a), Helmi & White (2001), and Martínez-Delgado et al. (2001) have shown that it may be explained as a tidal stream from the Sgr dSph galaxy. These models predict that a quite wide stream crosses the area that we observed at an angle of ~35° with respect to α. They also estimate that the RRs in this part of the stream must have a magnitude $V \sim 19.5$, consistent with our observations. Our data show that the mean period of the type ab RRs in the clump is 0.58 days, similar to the value found in the central part of the Sgr dSph galaxy (Mateo 1996). This is not strong evidence for an association, because the RRs outside the clump are only marginally different ($\langle P \rangle = 0.56$ days).

Figure 4 is a three-dimensional representation of the Milky Way in which we have plotted the RRs in our survey, Pal 5 and the Sgr dSph galaxy. This diagram illustrates the uneven distribution of the RRs and also the very large distance separating the clump of RRs and the Sgr dSph galaxy. The idea that the halo has smooth contours in density that vary systematically is clearly incompatible with this diagram. Even if the clump is unrelated to the Sgr dSph galaxy, it has the features of a merger remnant and is therefore strong evidence in favor of the hypothesis that the stars and also the globular clusters of the outer halo are the debris left over from the accretion of small galaxies.

The Llano del Hato Observatory is operated by CIDA for the Consejo Nacional de Investigaciones Científicas y Tecnológicas and the Ministerio de Ciencia y Tecnología. This research was partially supported by the National Science Foundation under grant AST 00-98428.

REFERENCES

Bland-Hawthorn, J., & Freeman, K. 2000, Science, 287, 79
Demarque, P., Zinn, R., Lee, Y., & Yi, S. 2000, AJ, 119, 1398
Eggen, O. J. 1979, ApJ, 229, 158
———. 1996, AJ, 112, 2661
Helmi, A., & White, S. D. M. 1999, MNRAS, 307, 495
———. 2001, MNRAS, 323, 529
Helmi, A., White, S. D. M., de Zeeuw, P. T., & Zhao, H. 1999, Nature, 402, 53
Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194
Ibata, R. A., Irwin, M., Lewis, G., & Stolte, A. 2001a, ApJ, in press
Ibata, R. A., Lewis, G., Irwin, M., Totten, E., & Quinn, T. 2001b, ApJ, 551, 294
Ivezic, Z., et al. 2000, AJ, 120, 963
Johnston, K. V. 1998, ApJ, 495, 297
Majewski, S. R., Munn, J. A., & Hawley, S. L. 1994, ApJ, 427, L37
Martinez-Delgado, D., Aparicio, A., Gomez-Flechoso, M. A., & Carrera, R. 2001, ApJ, 549, L199
Mateo, M. 1996, in ASP Conf. Ser. 92, Formation of the Galactic Halo…Inside and Out, ed. H. L. Morrison & A. Sarajedini (San Francisco: ASP), 434
———. 1998, ARA&A, 36, 435
Mateo, M., Mirabal, N., Udalski, A., Szymanski, M., Kaluzny, J., Kubiak, M., Krzeminski, W., & Stanek, K. Z. 1996, ApJ, 458, L13
Morrison, H. L., Mateo, M., Olszewski, E. W., Harding, P., Dohm-Palmer, R. C., Freeman, K. C., Norris, J. E., & Morita, M. 2000, AJ, 119, 2254
Odenkirchen, M., et al. 2001, ApJ, 548, L165
Saha, A. 1985, ApJ, 289, 310
Saha, A., & Hoessel, J. G. 1990, AJ, 99, 97
Sandage, A. 1990, ApJ, 350, 603
Sawyer Hogg, H. 1973, Third Catalogue of Variable Stars in Globular Clusters (Toronto: David Dunlap Obs., Univ. Toronto)
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Snyder, J. 1998, Proc. SPIE, 3355, 635
Wetterer, C. J., & McGraw, J. T. 1996, AJ, 112, 1046
Yanny, B., et al. 2000, ApJ, 540, 825