DISTANCE TO M31 WITH THE HUBBLE SPACE TELESCOPE AND HIPPARCOS RED CLUMP STARS

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ABSTRACT

Following the approach by Paczyński & Stanek, we compare the red clump stars with parallaxes known to better than 10% in the Hipparcos catalog with the red clump stars observed in three fields in M31 using the Hubble Space Telescope. There are ~600 and ~6300 such stars in the two data sets, respectively. The local red clump luminosity function is well represented by a Gaussian with the peak at $M_{I,m} = -0.23$ and the dispersion $σ_{bc} ≈ 0.2$ mag. This allows a single-step determination of the distance modulus to M31, $μ_{0,M31} = 24.471 ± 0.035 ± 0.045$ mag (statistical plus systematic error), and the corresponding distance, $R_{M31} = 784 ± 13 ± 17$ kpc. The number of red clump stars is large enough that the formal statistical error in the distance is only $≤ 2%$. We also correct the treatment of the local interstellar extinction by Paczyński & Stanek, and we obtain the Galactocentric distance modulus, $μ_{0,GC} = 14.57 ± 0.04 ± 0.04$ mag (statistical plus systematic error), and the corresponding Galactocentric distance, $R_0 = 8.2 ± 0.15 ± 0.15$ kpc.

Subject headings: galaxies: distances and redshifts — galaxies: individual (M31) — Galaxy: center — solar system: general — stars: horizontal-branch

1. INTRODUCTION

The distance modulus to the M31 galaxy is $μ_{0,M31} ≈ 24.4 ± 0.15$ mag (for discussion, see, e.g., Huterer, Sasselov, & Schechter 1995 and Holland 1998). In this Letter, we follow the approach of Paczyński & Stanek (1998, hereafter P&S) and present an estimate of the distance to M31 based on the comparison between the red clump giants observed locally by the Hipparcos (Perryman et al. 1997) satellite and those observed in M31 with the Hubble Space Telescope (HST) (Holland, Fahman, & Richer 1996; Rich et al. 1996). These stars are the metal-rich equivalent of the better known horizontal-branch stars, and theoretical models predict that their absolute luminosity depends only weakly on their age and chemical composition (Seidel, Demarque, & Weinberg 1987; Castellani, Chieffi, & Straniero 1992; Jimenez, Flynn, & Kotoneva 1998).

Indeed, the absolute magnitude–color diagram of Hipparcos (Perryman et al. 1997, their Fig. 3) clearly shows how compact the red clump is. In this Letter, we determine the variance in the $I$-band magnitude to be only $≤ 0.15$ mag.

As discussed by P&S, any method of the distance determination that is based on stars suffers from at least four problems:

1. The accuracy depends on the absolute magnitude determination for the nearby stars.
2. Interstellar extinction has to be determined for the stars in the target source as well as for those near the Sun.
3. The masses, ages, and chemical composition may be different for the stars in the source and for their counterparts near the Sun.
4. The statistical error is large if the number of stars is small.

The red clump giants are the only type of stars that do not suffer from the fourth problem. In spite of their large number and our sound theoretical understanding of them, these stars have seldom been used as the distance indicators. Recently, however, Stanek (1995) and Stanek et al. (1994, 1997) used these stars to map the Galactic bar. P&S used the red clump stars observed by the Optical Gravitational Lensing Experiment (OGLE) (Udalski et al. 1993) to obtain an estimate of the distance to the Galactic center. In this Letter, we follow the approach of P&S and compare the absolute magnitudes of ~600 nearby red clump stars with accurate (better than 10%) trigonometric parallaxes measured by Hipparcos with the apparent magnitudes of ~6300 red clump stars observed by the HST in the halo of M31 (Holland et al. 1996) and in the M31 globular cluster G1 (Rich et al. 1996). This comparison gives the distance to M31 in a single step.

2. THE DATA AND PRELIMINARY RESULTS

Inspection of the color-magnitude diagrams (CMDs) based on Hipparcos and OGLE data revealed a strong dependence of the $V$-band magnitude of red clump giants on their color, while their $I$-band magnitudes revealed no significant color dependence (P&S, their Figs. 1 and 2). Thus, on purely observational grounds, the $I$ band seems to be the best in the applications in which the red clump stars are used as standard candles. It is possible that bolometric corrections to the $I$ band are very small for these moderately cool stars, and theoretical models show only a weak dependence of $M_{bol}$ on either age or chemical composition (Seidel et al. 1989; Castellani et al. 1992; Jimenez et al. 1998).

The Hipparcos-based absolute magnitude–color diagram is shown in the upper left panel of Figure 1, for the stars with parallaxes measured to better than 10%. There are 664 such stars within the dashed rectangle $[0.8 < (V - I) < 1.25]$ in the upper left panel of Figure 1. P&S derived the absolute magnitude of the nearby red clump stars to be $M_{I,m} = -0.185 ± 0.016$. We will discuss this number later in the Letter.

Deep CMDs were obtained for several lines of sight toward M31, mostly to study the M31 globular clusters (Ajhar et al. 1996; Fusi Pecci et al. 1996; Holland et al. 1996; Holland, Fahman, & Richer 1997; Rich et al. 1996). We selected the $V, V - I$ CMDs obtained by Rich et al. (1996) for the M31 globular cluster G1 and by Holland et al. (1996) for two fields
(adjacent to the M31 globular clusters G302 and G312) in the M31 halo. These fields are located ≈30', 50', and 150' from the center of M31, respectively. The G302 and G312 CMDs were corrected for the reddening and extinction by using a value of $E(B-V) = 0.08$ (Burstein & Heiles 1982). For G1, we used a value of $E(B-V) = 0.058$ taken from Schlegel, Finkbeiner, & Davis (1998). The red clump–dominated parts of the G302, G312, and G1 CMDs are shown in the upper right, lower left, and lower right panels of Figure 1, respectively. As discussed by Holland et al. (1996), the CMDs for G302 and G312 indicate multiple stellar populations, consistent with a mix of 50%–75% metal-rich stars and 25%–50% metal-poor stars. This is reflected by the presence of horizontal-branch stars in M31 that are bluer [(V − I) < 0.8] than the red clump stars in the solar neighborhood. Rich et al. (1996) concluded that the properties of the G1 CMD are most consistent with those of an old globular cluster with the metallicity of 47 Tuc. Given the fact that the average luminosity of the red clump stars appears to be independent of their color, and hence metallicity, in Baade’s window (P&S, their Fig. 1) and in the solar neighborhood (Fig. 1, upper left panel), it seems safe to determine the distance to M31 by comparing these two populations, especially using the overlapping region in color.

Following P&S, we selected the red clump stars in the color range 0.8 < (V − I)$_0$ < 1.25 in the G302 field (4357 stars), in the G312 field (980 stars), and in the G1 globular cluster (937 stars). The color range was selected to correspond to the color range of the red clump stars observed locally by Hipparcos (Fig. 1, upper left panel). We fitted all three distributions with a function

$$n(I_0) = a + b(I_0 - I_{0,w}) + c(I_0 - I_{0,w})^2$$

$$+ \frac{N_{BC}}{\sigma_{BC}\sqrt{2\pi}} \exp \left[ -\frac{(I_0 - I_{0,w})^2}{2\sigma_{BC}^2} \right]$$

(please note the typographical error in P&S’s eq. [1], where the factor of 2 in the denominator of the exponent was incor-

rectly squared). The first three terms describe a fit to the “background” distribution of the red giant stars, and the Gaussian term represents a fit to the red clump itself. $I_{0,w}$ corresponds to the peak magnitude of the red clump population. We obtained the values of $I_{0,w} = 24.245 \pm 0.006$ for the G302 field, $I_{0,w} = 24.222 \pm 0.014$ for the G312 field, and $I_{0,w} = 24.209 \pm 0.013$ for the G1 cluster. This, in combination with the value of $M_{I,BC} = -0.185 \pm 0.016$ for the local red clump stars, gives the preliminary distance moduli of $(m-M)_{G302} = 24.43 \pm 0.02$, $(m-M)_{G312} = 24.41 \pm 0.02$, and $(m-M)_{G1} = 24.39 \pm 0.02$.

The distribution of the local and the M31/G302 red clump stars as a function of their absolute I-band magnitude is shown in Figure 2 with two histograms, as well as with two analytical fits of the type described by equation (1); all distributions are normalized. The Gaussian fitted to the G302 field red clump distribution has a small $\sigma_{BC}$ of 0.15 mag, and the Gaussian fitted to the Hipparcos distribution has $\sigma_{BC} = 0.24$ mag. This difference could be due to the Hipparcos stars having ≤10% parallax errors, broadening the derived distribution. By the same argument, the narrowness of the red clumps in M31 indicates that the HST I-band photometry is still very accurate at I ~ 24.5 mag.

As we discussed above, P&S found no significant color dependence in the I-band magnitudes of the red clump stars in both the Hipparcos and OGLE data. However, a visual examination of the M31 data in Figure 1 suggests that the blue edge of the red clump is ~0.2 mag fainter than the red edge. To investigate this effect, we divided the red clump region of the most star-rich G302 field into nine color bins (there were between 250 and 1050 stars in each bin), and for each bin we performed the fit described above. The result appears in Figure 3, where we show $I_{0,w}$ for each bin. The red clump exhibits a relatively sharp downturn for (V − I)$_0$ > 0.8 mag, but there is basically no color dependence for (V − I)$_0$ < 0.8 mag, consis-
Fig. 3.—The dependence of the peak brightness of the red clump \( I_{\text{om}} \) on the \((V - I)_{0}\) color for the most star-rich M31/G302 field. The red clump exhibits a relatively sharp downturn for \((V - I)_0 < 0.8\) mag, but there is no color dependence for \((V - I)_0 > 0.8\) mag. In the color range \(0.8 < (V - I)_0 < 1.25\), used for the comparison with the \textit{Hipparcos} red clump, \(I_{\text{om}}\) varies only from 24.22 to 24.268 and in a random fashion.

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3. CORRECTING SOME ERRORS

The very small formal statistical error for our distance to M31 follows from the very large number of red clump stars measured by \textit{Hipparcos} and observed in M31. The number of these stars is several orders of magnitude larger than the number of either RR Lyrae or Mira variables, and the observed dispersion in their magnitudes is as small as \(\sigma_{\text{rc}} \approx 0.15\) mag in the \textit{HST} data for the M31 fields. However, in addition to small statistical errors, there are possibly larger systematic errors discussed by P&S, some of which we try to estimate and correct for.

P&S checked whether the 10% error limit adopted was not too generous, and they repeated the analysis with a more stringent 5% upper limit to the parallax errors. This reduced the number of stars within the rectangle shown in Figure 1 from 664 to 240 and gave \(M_{\text{pm}} = -0.173 \pm 0.027\), within statistical errors of \(M_{\text{pm}} = -0.185 \pm 0.016\) obtained for the 10% sample.

By selecting the stars with accurate parallaxes from the \textit{Hipparcos} catalog, we introduced a distance bias that depends on the absolute magnitude: the stars that are intrinsically brighter can be measured accurately out to a larger distance. Therefore, there are relatively more bright stars in our \textit{Hipparcos} sample than in a volume-limited sample. In order to estimate this effect, we selected a subsample of 228 \textit{Hipparcos} stars with the distance \(d < 70\) pc, and we determined the parameters of the best fit to the luminosity function described with equation (1). This sample is not, strictly speaking, volume limited, but it is closer to that than the previous sample. We found that \(M_{\text{pm}}(d < 70) = -0.227 \pm 0.023\) and \(\sigma_{\text{rc}} = 0.209\) mag for these nearby stars, with the average distance \((d_{c70}) = 50\) pc. As discussed by Hög & Flynn (1998, their Fig. 2), one expects very little reddening, \(E(B - V) < 0.02\), for such nearby stars, so we assume that our \(d < 70\) pc sample suffers no reddening. This is contrary to what was assumed by P&S but agrees with detailed models of the optical reddening in the solar neighborhood (Méndez & van Altena 1998): we live in a bubble of low interstellar extinction (Bhat, Gupta, & Rao 1998). We therefore assume that a Gaussian with \(M_{\text{pm}} = -0.23 \pm 0.03\) and dispersion \(\sigma_{\text{rc}} \approx 0.2\) mag well represents the red clump luminosity function. We believe that a 1 \(\sigma\) error of 0.03 mag represents the uncertainty of the red clump properties better than the value of 0.09 mag derived by P&S. We correct the value of the Galactic distance modulus obtained by P&S to 

\[(M - m)_{\text{GC}} = 14.57 \pm 0.04 \pm 0.04\text{ mag (statistical plus systematic error)}\]

and the corresponding distance \(R_0 = 8.2 \pm 0.15 \pm 0.15\) kpc. The systematic error combines the uncertainty of 0.025 mag in the \(I\)-band zero point of the Stanek (1996) extinction map (Gould, Popowski, & Terndrup 1998; Alcock et al. 1998) and a possible 0.03 mag error in the OGLE \(I\)-band photometric zero point (Kiraga, Paczynski, & Stanek 1997).

There are also a number of systematic errors connected with the M31 halo red clump stars. The G1 globular cluster might be at a distance that is different from the bulk of M31. Similarly, the centroid of the Gaussian distribution of red clump giants in the M31 halo corresponds to the distance that might differ from the distance to the disk of M31. However, as discussed by Holland et al. (1996), the depth of the M31 halo is very small (~0.02 mag), so the possible shift in the M31 distance is even smaller. This is confirmed by the very similar values of distance moduli that we find for the two lines of sight in the halo of M31. A larger contribution to the error comes from the zero point in the assumed interstellar extinction, which Holland et al. (1996) took to be \(E(B - V) = 0.08\) (Burstein & Heiles 1982), but Schlegel et al. (1998) advocate a lower value of \(E(B - V) = 0.062\) as an average foreground reddening for M31. However, using the Schlegel et al. (1998) reddening map directly at the positions of G302 and G312 gives \(E(B - V) = 0.084\) and \(E(B - V) = 0.082\), respectively. For G1, we obtained a value of \(E(B - V) = 0.058\) using the map of Schlegel et al. (1998), in excellent agreement with value \(E(B - V) = 0.06\) adopted by Rich et al. (1996). Based on discussions by Schlegel et al. (1998) and by Stanek (1998), we estimate the 1 \(\sigma\) systematic error in the \(E(B - V)\) reddening to be ~0.015 mag, which, using the relation \(A_i/E(B - V) = 1.95\), translates to a systematic \(I\)-band extinction error of 0.03 mag.

Another systematic error is the uncertainty in the Wide Field Planetary Camera 2 (WFPC2) photometric zero point, which is thought to be as high as 0.05 mag based on calibrations by the Distance Scale Key Project (Hill et al. 1998). Recently, Whitmore & Heger (1997) showed that the charge transfer efficiency (CTE) for the WFPC2 CCDs depended on the total number of electrons in the star image and the sky background, including the more commonly known problem with position on the detector. Corrections for the full CTE effect would reduce the zero-point uncertainty to 0.03 mag, but only the standard Holtzman et al. (1995) ramp was applied to the data presented here. Fortunately, the red clump stars are relatively bright, and the difference between the simple-ramp CTE correction and the Whitmore correction amounts to only 2%. We therefore assume that the systematic error due to the WFPC2 photometric zero point is 0.035 mag.

We can now derive the final distance modulus to M31 based on the lines of sight discussed in this Letter. The straight average of the red clump peak apparent magnitudes \(I_{\text{om}}\) for the
three fields is \( I_{0,m} = 24.225 \pm 0.018 \), and the weighted mean is \( I_{0,m} = 24.236 \pm 0.021 \). However, as pointed out to us by the referee, if we assume that the M31 globular cluster (GC) system is dynamically similar to the Galactic GC system, then it is highly probable that G1 does not lie at the same distance as M31 but could be expected to have a distance modulus of \( \sim 0.035 \) mag greater or smaller than that of M31, due to G1’s location in its orbit about M31. This appears to be consistent with G1 having an \( I_{0,m} \) that is 0.025 mag less than the mean of horizontal-branch stars within the halo of M31 but could be expected to have a distance modulus of \( \sim 0.035 \) mag greater or smaller than that of M31, due to G1’s location in its orbit about M31. This appears to be consistent with G1 having an \( I_{0,m} \) that is 0.025 mag less than the mean.

Using only the G302 and G312 field stars, the straight average of the red clump peak apparent magnitudes \( I_{0,m} \) is \( I_{0,m} = 24.233 \pm 0.016 \), and the weighted mean is \( I_{0,m} = 24.241 \pm 0.016 \). Using this weighted mean \( I_{0,m} \) combined with the distribution of local red clump stars, we obtain the distance modulus to M31 of \( \mu_{0,31} = 24.471 \pm 0.035 \) mag or \( R_{31} = 784 \pm 13 \) kpc (statistical error only). After adding to that the systematic error of 0.03 mag due to the uncertainty in the \( E(B-V) \) determination and 0.035 mag due to the zero-point uncertainty in the \( HST \) photometry, we arrive at the final value of \( \mu_{0,31} = 24.471 \pm 0.035 \pm 0.045 \) mag (statistical plus systematic error). It is worth noticing that Freedman & Madore (1990) obtained a very close average value of \( \mu_{0,31} = 24.44 \pm 0.13 \) mag for a sample of Cepheids observed in Baade’s fields I, III, and IV (Baade & Swope 1963, 1965).

There is yet another type of systematic error possible: the age, the chemical composition, and the masses of red clump giants may be systematically different in the M31 halo and near the Sun. As discussed in the previous section, the presence of horizontal-branch stars with \((V-I)_0<0.8\) in the halo of M31, which are basically absent in the \( Hipparcos \) sample, implies that the two populations are to some extent different (see Holland et al. 1996 and Rich et al. 1996 for more detailed discussions). Recent stellar evolutionary models (Jimenez et al. 1998) indicate that in the age range of 2–12 billion yr, the effective temperature is dominated by the metallicity. As we discussed earlier, by comparing the red clump distributions selected using the same color range, we hope to minimize the impact of the population differences on the derived distance modulus of M31. Our three lines of sight probe a large range of M31 Galactocentric distances and locations (two fields along the southeast minor axis and one along the southwest major axis) and hence metallicities and possibly ages and star formation histories. The fact that the derived distance moduli for the three fields we used in this Letter vary by only \( \sim 0.035 \) mag indicates that our approach is indeed valid.

To summarize, among the various stellar distance indicators, the red clump giants might be the best for determining the distance to M31 because there are so many of them. In particular, \( Hipparcos \) provided accurate distance determinations for almost 2000 such stars, but unfortunately \( I \)-band photometry is available for only \( \sim 30\% \) of them, so it would be important to obtain \( I \)-band photometry for all \( Hipparcos \) red clump giants. One would also like to use many more lines of sight toward M31 to understand better the effects of varying stellar populations and to reduce the uncertainty in the \( HST/Hipparcos \) comparison.

Note added in manuscript.—After we completed writing this Letter, we became aware of the paper by Holland (1998), in which he determines the distance to M31 using red giant branches of globular clusters in M31. His distance modulus of \( \mu_0 = 24.47 \pm 0.07 \) mag is identical to the value of \( \mu_{0,31} = 24.471 \pm 0.035 \pm 0.045 \) mag we obtained in this Letter.

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