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HALO STRUCTURE SHOWN BY RR LYRAE STARS IN THE ANTICENTER DIRECTION

T. D. KINMAN AND A. SAHA
NOAO,[1] P.O. Box 26732, Tucson, AZ 85726; tkinman@noao.edu, asaha@noao.edu
AND
J. R. PIER
US Naval Observatory, Flagstaff Station, P.O. Box 1149, Flagstaff, AZ 86002-1129; jrp@nofs.navy.mil
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ABSTRACT

Newberg et al., Yanny et al., Ibata et al., Rocha-Pinto et al., and Martin et al. have reported overdensities of stars that form a ring with a galactocentric distance ($R_{\rm gal}$) of $\lesssim$18 kpc. Martin et al. and Frinchaboy et al. have found star clusters associated with these overdensities; Martin et al. found what seems to be the central overdensity in Canis Major, so we shall refer to it as the CMa ring. The stars in the CMa ring have a small velocity dispersion and [Fe/H] of about -0.4 and -1.6, respectively. Zinn et al. found a small RR Lyrae overdensity in the more populous southern arc of the CMa ring. We do not find any overdensity of RR Lyrae stars in a 65 deg^2 field that covers a more tenuous part of the ring in the anticenter. Existing evidence suggests that the halo component of the CMa ring has a horizontal-branch (HB) morphology that does not favor RR Lyrae stars; the evidence from the associated clusters suggests that it may be richer in blue HB stars. Our RR Lyrae sample in the anticenter contains three groups (each containing three stars that have a high probability of physical association). These groups account for half of the RR Lyrae stars with 17 kpc $\leq R_{\rm gal} \leq$ 28 kpc in this field; all of these RR Lyrae stars are of Oosterhoff I type. It is suggested that they may be globular cluster remnants.

Subject headings: Galaxy: halo — Galaxy: structure

1. INTRODUCTION

Newberg et al. (2002) and Yanny et al. (2003) have reported that there is a significant overdensity of turnoff (TO) stars in the Sloan Digital Sky Survey in the direction of the Galactic anticenter. This feature is a ringlike structure that has a fairly constant galactocentric distance ($R_{\rm gal}$) of 18 ± 2 kpc between galactic longitudes (l) 180° and 225°. Yanny et al. (2003) find velocity dispersions of 23, 30, and 30 km s^{-1} for the stars in fields with l, b of (225°, +28°), (182°, +27°), and (188°, +24°), respectively. These TO stars have the color of a spheroid population with an [Fe/H] of -1.6 ± 0.3. Ibata et al. (2003), using data from the Isaac Newton Telescope Wide Field Camera, have shown that this structure extends over ~100° in the sky. The feature has also been found in Two Micron All Sky Survey M giants (Rocha-Pinto et al. 2003; Majewski et al. 2003; Martin et al. 2004) at $R_{\rm gal} = 18 \pm 2$ kpc and $+12° \leq b \leq +36°$, $100° \leq l \leq 270°$. These M giants have an [Fe/H] of -0.4 ± 0.3 and a velocity dispersion of 20 ± 4 km s^{-1} (Crane et al. 2003). Frinchaboy et al. (2004) have found a variety of both open and globular clusters that are associated with these overdensities. Martin et al. (2004) have also discovered the association of some of the same globular clusters with the large overdensity that they found in Canis Major. Bellazzini et al. (2003) found evidence of this CMa galaxy in the color-magnitude diagrams of open clusters in its direction and derived a distance modulus $(m-M)_0$ for the CMa galaxy of 14.6 ± 0.3; the corresponding $R_{\rm gal}$ is 14.1 ± 1.1 kpc, which is somewhat less than the earlier estimates quoted above. The metallicity of the predominant population of the CMa galaxy is $-0.7 \leq$ [M/H] ≤ 0.0, and its age is in the range ~ 2–7 Gyr. This later work supports the idea that the CMa ring has been produced by the tidal disruption of a dwarf satellite (Newberg et al. 2002; Yanny et al. 2003; Rocha-Pinto et al. 2003; Martin et al. 2004) rather than by a distortion of the galactic disk (Newberg et al. 2002; Ibata et al. 2003; Sikivie 2003). A more general discussion of the origin of the ring has been given by Helmi et al. (2003). Presumably, the halo or spheroidal population identified by Yanny et al. (2003) can be seen with other halo tracers such as RR Lyrae stars. Here we describe an attempt to find such stars in the anticenter part of the ring. While this work was in progress, Zinn et al. (2003) announced the discovery of an overdensity of RR Lyrae stars in the more populous southern arc of the ring. The resulting limits on the RR Lyrae density in the CMa ring put new constraints on its halo component.

2. THE RR LYRAE STARS AND THE CMa RING

Figure 1 shows where the CMa ring has been discovered in some of the surveys in the anticenter. This l, b plot also shows the RR Lyrae stars in this region (as open circles) that are given in the General Catalogue of Variable Stars;[2] these were originally discovered in the surveys by Kinman, Mahaffey, & Wirtanen (1982) and Saha (1984). The radial velocities and abundances for many of these stars have recently been discussed by Pier, Saha, & Kinman (2003), who include both new data and a rediscussion of earlier work (Butler et al. 1982; Saha & Oke 1984; Suntzeff, Kinman, & Kraft 1991; Kinman, Pier, & Suntzeff 1996). Also shown (as crosses) in Figure 1 are stars known to be RR Lyrae stars from unpublished photometry but for which no other data are yet available. These unpublished RR Lyrae stars are probably subsampled; we assumed an M_v of +0.55 for them when calculating the space densities. In the case of the published RR Lyrae stars, we used an M_v derived from their [Fe/H] or period (if [Fe/H] was not available) using the expressions given by Kinman (2002); the galactic extinctions were taken from Schlegel, Finkbeiner, & Davis (1998). The space densities are only based on the RR Lyrae variable stars that lie in the 65 ± 10 deg^2 area (22°.2 $\leq b \leq$ 32°.2 and 176°.2 $\leq l \leq$ 183°.5) that is close to the fields studied by Yanny et al. (2003)

[1] The NOAO is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

[2] See http://www.sai.msu.su/groups/cluster/gcvs/gcvs.

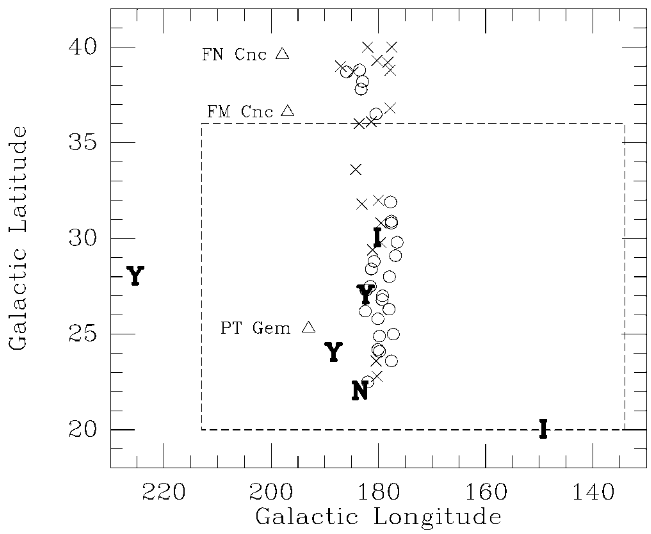

FIG. 1.—Anticenter field showing disposition of RR Lyrae stars (published as open circles and unpublished as crosses). The three RR Lyrae stars discovered by Wetterer & McGraw (1996) are shown as triangles. Fields studied by Newberg et al. (2002), Ibata et al. (2003), and Yanny et al. (2003) are labeled N, I, and Y, respectively. The field studied by Rocha-Pinto et al. (2003) is shown as a dashed rectangle.

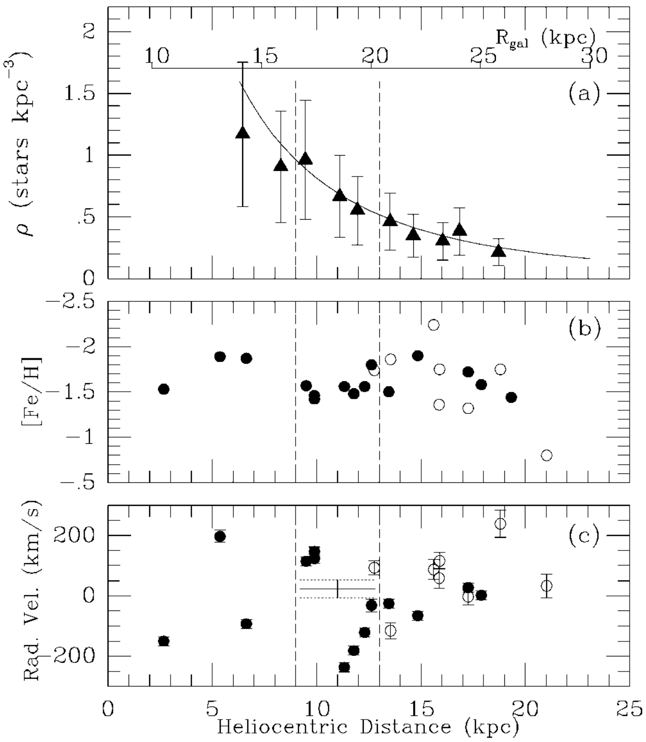

FIG. 2.—(*a*) Space density, (*b*) metallicity [Fe/H], and (*c*) heliocentric radial velocity of the RR Lyrae stars as a function of heliocentric distance. The solid curve in (*a*) shows an R_{gal}^{-3} density law. The vertical dashed lines show the expected location of the CMa ring, and the horizontal lines in (*c*) are its expected 1 σ limits in velocity. The open circles are data from Saha (1984).

and Ibata et al. (2003). These densities were derived by taking the variable stars in groups of four (cf. Kinman, Wirtanen, & Janes 1965) and refer to both type *ab* and type *c* stars; they are not corrected for completeness;[3] they are shown as a function of both heliocentric and galactocentric distance in Figure 2*a* (assuming a solar R_{gal} of 8.0 kpc). Figures 2*b* and 2*c* show the [Fe/H] and radial velocities, respectively, as a function of heliocentric distance. Ivezić et al. (2003) have shown from a large sample of RR Lyrae stars outside the Sgr dwarf tidal stream (5 kpc $\leq R_{gal} \leq$ 60 kpc) that the halo density falls off as R_{gal}^{-3}. Such an inverse cube law, normalized to the present data, is shown by the solid curve in Figure 2*a* and gives a satisfactory fit to our data. Thus, in this part of the sky, the RR Lyrae stars show no overdensity at heliocentric distances between 9 and 13 kpc where the ring structure was found by Yanny et al. (2003), nor, for that matter, at other distances covered by these observations. Also, there are no RR Lyrae stars at this location that have radial velocities within 2 σ of that expected for the ring.[4] Thus, our anticenter sample of RR Lyrae stars gives no indication that the CMa ring has a halo component.[5]

There are eight RR Lyrae stars in our sample ($\langle l \rangle, \langle b \rangle$ = 180°, +27°) that have the heliocentric distance of the ring between 9 and 13 kpc and a mean height (Z) above the plane of 5.11 kpc. At this Z, the CMa ring contains ~290 TO stars in each 12.5 deg^2 field according to Figure 12 of Yanny et al. (2003). There should therefore be ~1508 TO stars in our 65 deg^2 field. Yanny et al. (2003) assume that the composition is like that of the globular cluster Pal 5, which has a cluster mass of 50 $M_\odot$ for each TO star (Odenkirchen et al. 2001). This gives a mass for the part of the ring in our field of 7.54×10^4 $M_\odot$. Pal 5 has a mass of between 4.5 and 6.5×10^3 $M_\odot$ (Odenkirchen et al. 2002) and contains five RR Lyrae stars (Suntzeff et al. 1991), so if we can scale the number of RR Lyrae stars by cluster mass, there should be ~69 RR Lyrae stars in our field. The number of RR Lyrae stars in a cluster depends on the distribution of stars along its horizontal branch (HB). Suntzeff et al. (1991) normalize this number (N_{RR}) to that which a cluster would have at a fixed M_v of −7.5 (essentially implying a fixed mass-to-light ratio). In their compilation, clusters that have an evenly populated HB (Pal 5, M3) have the most RR Lyrae stars ($N_{RR} \sim 50$),[6] while those with very red, very blue, or bimodal distributions have the least RR Lyrae stars ($N_{RR} \sim 0$). Suntzeff et al. (1991) give mean values of N_{RR} of 9.9 and 17.8 for the globular clusters of the inner and outer halo, respectively. Thus, even if the halo component of the CMa ring is made up from stars like those in the inner halo globular clusters, the predicted number of RR Lyrae stars is greater than we observe. Frinchaboy et al. (2004) have shown that the globular clusters most likely to be associated with the ring are NGC 2298, NGC 2808, and NGC 5286. Suntzeff et al. (1991) give N_{RR} of 8.3 and 6.9, respectively, for NGC 2298 and 5286, while a new survey of NGC 2808 by Corwin et al. (2003)

[3] We estimate that the published variable stars are >95% complete for the type *ab* variable stars with *B* amplitudes greater than 0.75 mag at the distance of the ring; the lower amplitude published variable stars are less complete, but this is partly compensated for by the unpublished variable stars that were discovered as variable blue horizontal-branch stars and are mostly of low amplitude.

[4] After this Letter was first submitted, Yanny et al. (2003) revised their radial velocities slightly. AC Lyn and XZ Lyn, at distances of 13.5 and 12.6 kpc, respectively, have radial velocities that now lie 1.6 σ and 1.8 σ, respectively, from the mean velocity of the structure.

[5] Our referee has pointed out that there is a small overdensity at about the 1 σ level in the space density vs. R_{gal} plot given by Wetterer & McGraw (1996) in Fig. 5 of their paper. These authors do not mention this overdensity, but we note that it is produced by three stars (PT Gem, FM Cnc, and FN Cnc) that lie close to the anticenter part of the ring structure (Fig. 1); it would be valuable to get their radial velocities. Our space densities agree well with those of Wetterer & McGraw (1996), about 0.6 stars per kpc^3 at an R_{gal} of 20 kpc. The space densities of Ivezić et al. (2003) are about half this because of the lower efficiency of their survey.

[6] Mackey & Gilmore (2003) have found globular clusters with $N_{RR} > 100$ in the Fornax dwarf galaxy, although the galaxy itself has $N_{RR} \sim 3$.

TABLE 1
PREDICTED AND OBSERVED NUMBERS OF RR LYRAE STARS IN ANTICENTER AND QUEST FIELDS

FIELD l, b	AREA[a] (deg^2)	N[b]	n[c]	NUMBER OF RR LYRAE STARS 1[d]	2[e]	3[f]	4[g]	5[h]	6[i]	Observations[j]	SOURCE OF OBSERVATIONS
180°, +28°	65	290	1504	69	24	13	11	9	4	0	This Letter
199°, −27°	18	1300	1870	85	30	17	14	12	5	6	Zinn et al. (2003)

[a] Area searched for variable stars.
[b] Number of TO stars in 12.5 deg^2 field from Yanny et al. (2003).
[c] Number of TO stars in searched field.
[d] This prediction assumes a population like that of Pal 5 (Yanny et al. 2003; Odenkirchen et al. 2002; Suntzeff et al. 1991).
[e] This prediction assumes a population like that of outer halo globulars (Suntzeff et al. 1991).
[f] This prediction assumes a population like that of inner halo globulars (Suntzeff et al. 1991).
[g] This prediction assumes a population like that of NGC 2298 (Suntzeff et al. 1991).
[h] This prediction assumes a population like that of NGC 5286 (Suntzeff et al. 1991).
[i] This prediction assumes a population like that of NGC 2808 (Wetterer & McGraw 1996).
[j] Number of RR Lyrae stars discovered in QUEST survey.

gives 3.2 for this cluster.[7] The numbers of RR Lyrae stars predicted for a ring halo made of such clusters is compared with the observed numbers in Table 1.

Zinn et al. (2003) report an overdensity of RR Lyrae stars in their QUEST (QUasar Equatorial Survey Team) survey in the southern arc of the ring. This overdensity (in their Fig. 5) is seen as approximately six RR Lyrae stars with $V_0 \sim 15.5$ in a range of R.A. of ∼7°.5. This corresponds to a field of ∼18 deg^2 at l = 199° and $b = -27°$. Although this part of the ring is much more populous than that in the anticenter, their search field is smaller than our anticenter field, and so the predicted numbers of RR Lyrae stars in the two fields are rather comparable. It is seen that the number of RR Lyrae stars observed by Zinn et al. (2003) is close to that expected from a ring halo made from clusters like NGC 2298, 2808, and 5286 (Table 1). The modulus $(m - M)_0$ of the QUEST RR Lyrae overdensity is ∼14.95, which corresponds to a $R_{\rm gal}$ of 17.1 kpc; this is somewhat greater than the $R_{\rm gal}$ of 14.1 ± 1.1 kpc that corresponds to the distance of the CMa galaxy at $(l, b) \sim (240°, -7°)$ that was found by Bellazzini et al. (2003).

Can these results be reconciled? The completeness for the lower amplitude variable stars (type *c* and the type *ab* of the longest period) in these surveys is difficult to estimate precisely. Eight RR Lyrae stars were found with heliocentric distances between 9 and 13 kpc; the uncertainty of the space density is therefore about 30%. The RR Lyrae survey by Wetterer & McGraw (1996) suggests an overdensity at the 1 σ level. From this and from the various uncertainties previously discussed, we suggest *possible upper limits* of 2 and 10 RR Lyrae stars for the anticenter and southern arc fields, respectively; we emphasize that, of necessity, these are quite rough estimates. The number of RR Lyrae stars in the two fields should scale with the TO star counts. The estimate of the TO counts in the anticenter is much less certain because of the large variation from field to field and because these TO counts are only a fraction of the background. There is also the possibility that the number of halo TO stars has been overestimated because of the presence of TO stars of another population (such as that implied by the higher metallicity stars found by Rocha-Pinto et al. 2003, Crane et al. 2003, and Bellazzini et al. 2003). There is also a significant range in HB morphology among the clusters associated with the CMa ring, so its halo component may not be homogeneous. Bearing these uncertainties in mind, there probably is no serious disagreement between our result and that of Zinn et al. (2003). Overall, the present evidence suggests that the CMa ring has a halo population that is relatively poor in RR Lyrae stars. This is what we would expect from the HB properties of the globular clusters that Frinchaboy et al. (2004) and Martin et al. (2004) have found associated with the CMa ring. Several of these clusters have a strong blue HB morphology (NGC 2808 is bimodal), and this suggests that the ring halo may have a detectable blue HB star component.

[7] In addition to NGC 2298 and 2808, Martin et al. (2004) also associate NGC 1851 and 1904 with the ring; these clusters have $N_{\rm RR}$ of 10.5 and 5.4, respectively.

TABLE 2
RR LYRAE STARS IN GROUPS

Star	Type	Period (days)	[Fe/H]	Radial Velocity (km s^{-1})	Distance (kpc)
		Group I			
VY Lyn	RR*c*	0.3539	−1.57	+114.5 ± 15	9.49
ZZ Lyn	RR*ab*	0.4861	−1.42	+147.5 ± 15	9.90
AD Lyn	RR*c*	0.3550	−1.46	+123.6 ± 15	9.90
		Group II			
AZ Lyn	RR*ab*	0.4745	−2.24[a]	+87 ± 33	15.60
BB Lyn	RR*ab*	0.5585	−1.36[a]	+56 ± 33	15.87
V386 Aur	RR*c*	0.3049	−1.75[a]	+116 ± 26	15.90
		Group III			
V387 Aur	RR*ab*	0.4923	−1.32[a]	−003 ± 27	17.25
WX Lyn	RR*ab*	0.5529	−1.72	+026.3 ± 15	17.27
VX Lyn	RR*ab*	0.5533	−1.58	+001.3 ± 15	17.89

[a] [Fe/H] derived from data in Saha (1984).

3. SUBSTRUCTURE IN THE DISTRIBUTION OF THE FIELD RR LYRAE STARS

Although the field RR Lyrae stars in the anticenter do not show the large structure of the CMa ring, they do show structure on a much smaller scale. The plot of our RR Lyrae star sample in Figure 2*c* shows three groups (I, II, and III) at heliocentric distances of 9.8, 15.8, and 17.5 kpc. Each of these groups contains three stars; the properties of these stars are given in Table 2. The properties of the groups are given in Table 3. We note that an error of ±0.05 in the V magnitude of a star would give errors in its distance of 0.23, 0.37, and 0.42 kpc for groups I, II, and III, respectively. Thus, the scatter in both the distances and the velocities in each group is comparable to the scatter in their likely measurement errors. These errors are somewhat higher for group II, for which the data come from Saha (1984) alone. The volumes that enclose each of these groups are given in Table 3. The density (ρ in stars kpc^{-3}) of groups I and III is significantly greater than the smoothed local density (D) given by the curve in Figure 1. The velocities, however, provide more compelling evidence of a physical association. We assume

TABLE 3
Properties of Groups of RR Lyrae Stars

Group	Distance (kpc)	⟨[Fe/H]⟩[a]	⟨RV⟩[b]	Volume[c] (kpc^3)	ρ[d]	D[e]	P[f]
I	9.76	−1.48 (±0.08)	+128.9 (±17)	0.36	8.3	0.85	1 in 726
II	15.79	−1.78 (±0.44)	+87 (±29)	4.36	0.7	0.36	1 in 76
III	17.47	−1.54 (±0.20)	+8.2 (±16)	0.55	5.5	0.29	1 in 121

[a] The rms deviation of [Fe/H] is given in parentheses.
[b] RV = radial velocity; the rms deviation in kilometers per second is given in parentheses.
[c] Volume of sphere that just encloses the group.
[d] Number of stars in group divided by volume of enclosing sphere.
[e] Smoothed local density (stars kpc^{-3}) from R_{gal}^{-3} curve (Fig. 1).
[f] Probability that velocity distribution arises by chance.

that the rms velocity dispersion is 128 km s^{-1} for the parent population[8] and calculate the probability that three stars have velocities between V and $V + \Delta V$. Let q be the probability that a star has a velocity greater than V, and let p be the probability that a star has a velocity in the velocity interval between V and $V + \Delta V$. Then P, which is the probability that all three stars will lie in this interval, is $q \times p \times p$; this was calculated assuming a Gaussian distribution and is given for each group in the final column of Table 3. Now the observed range ΔV is a little larger than that expected from the errors. Consequently, the actual probability that these are chance associations is likely to be even smaller than given in Table 3. The most certain groups (I and III) show little spread in [Fe/H]; the [Fe/H] of the stars in group II come from Saha & Oke (1984) and are of lower weight; all show period shifts that are appropriate for Oosterhoff type I (Oo I) clusters;[9] only one star whose $R_{gal} \leq$ 28 kpc is Oo II (WZ Lyn at 5.4 kpc). The Oosterhoff type can put a constraint on the origin of field RR Lyrae stars (Catelan 2003). Thus, groups composed of Oo I variable stars are less likely to have come from dwarf spheroidal galaxies that predominantly contain Oosterhoff intermediate variable stars (Pritzl et al. 2002), although the RR Lyrae variable stars of the Sagittarius dwarf galaxy are considered to be in the long-period tail of an Oo I distribution (Cseresnjes 2001). It seems more likely therefore that these groups are the remnants of homogeneous structures such as globular clusters, although Baumgardt (2002) considers that no more than 10% of the halo can have originated in this way. In this regard, it will be of great interest to know the Oosterhoff type of the RR Lyrae stars found by Zinn et al. (2003) in the southern arc of the CMa ring.

There have been several previous discoveries of small groups among halo stars (Arnold & Gilmore 1992; Côté et al. 1993; Majewski, Munn, & Hawley 1994; Kinman et al. 1996; Helmi et al. 1999; Kundu et al. 2002). Helmi et al. (1999) considered that their group made up 10% of their halo sample, but Gould (2003), from a larger sample, claims that no single solar neighborhood group can contain more than 5% of the total. The models of Bullock, Kravtsov, & Weinberg (2001) predict that the visibility of these groups should increase with increasing R_{gal}, and this appears to be the case. The stars in our three groups make up half of our sample of halo stars with 17 kpc $\leq R_{gal} \leq$ 28 kpc. It is clearly desirable to determine the proper motions of these groups so that their galactic orbits can be computed, but (because of their distance) this will not be easy.

[8] The blue HB stars in this field with 4 kpc $\leq R_{gal} \leq$ 10 kpc have a radial velocity dispersion of 133 km s^{-1}.

[9] The Oosterhoff type of an individual star can be determined from its period and blue amplitude using M3 as a reference (Sandage 1981; Suntzeff et al. 1991).

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