Post-AGB Stars as Standard Extragalactic Candles

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Stars evolving off the asymptotic giant branch and passing through spectral types F and A are excellent candidates for a new extragalactic standard candle. These post-AGB (PAGB) stars are the visually brightest members of Population II systems. They should have a narrow luminosity function, bounded from above by the shorter transition times of more massive and more luminous remnants, and from below by the core mass corresponding to the lowest-mass stars that are leaving the main sequence.

Moreover, PAGB A-F supergiants are easily recognized because of their enormous Balmer jumps, and should lie both in ellipticals and the halos of spirals. I describe a photometric system that combines the Gunn $u$ filter (lying below the Balmer jump) with the standard Johnson-Kron-Cousins $BVI$ bandpasses, and report a successful search for PAGB stars in the halo of M31 using this $uBVI$ system.

The zero-point calibration will come from PAGB A and F stars in Galactic globular clusters. Four are presently known, and have a mean $M_V = -3.4$ with a scatter of only 0.2 mag. Two are in the same cluster, NGC 5986, and their $V$ magnitudes differ by only 0.09 mag, strongly suggesting a narrow luminosity function. Adopting this $M_V$ and calculating the M31 distance from its halo PAGB stars, we exactly reproduce the accepted value.

Future plans include a $uBVI$ survey of all Milky Way globular clusters for PAGB stars in order to strengthen the zero-point calibration, and a survey of Local Group galaxies to check the calibration. Ultimately we believe we can reach the Virgo Cluster through a distance ladder with only three rungs: subdwarf parallaxes, Milky Way globular clusters, and then directly to Virgo (with HST).

1. Introduction

As is well known, the zero point of the extragalactic distance scale depends heavily on just one method—Cepheid variable stars. With the continuing conflict between stellar ages and the age of the Universe implied by the Hubble Constant, it is worth checking the zero point with as many independent methods as possible.

I will argue in this paper that a class of “Population II” stars, evolving off the asymptotic giant branch (AGB), may constitute a superb new class of standard stellar candles. I will explain why these “post-AGB” (PAGB) stars are expected to have a narrow luminosity function as they evolve through spectral types F and A, point out that they should lie in systems that do not possess Cepheids or complicated interstellar extinction (elliptical galaxies, and halos of spirals), and show how they can be calibrated within the Milky Way. Thus these PAGB stars should become an important new primary distance indicator, which, I will argue, may prove to be of comparable utility to the Population I Cepheids.

My collaborators in this work are Laura K. Fullton, Abhijit Saha, and Karen Schaefer (all at STScI), and Rex Saffer (Villanova University).

2. “Population II” Standard Candles

Here we use the term “Population II candles” to refer to distance indicators that arise from old stellar populations. Among the best-known Population II candles are
the RR Lyrae variables. Their zero points can be calibrated in the Galaxy through various means (e.g., statistical parallaxes, the Baade-Wesselink method, and globular clusters), and thus they can be considered to be primary distance indicators. They are useful for measuring distances within the Local Group (see the reviews by Jacoby et al. 1992 and van den Bergh 1992, and a remarkable series of papers by Saha, Hoessel, and collaborators—Saha et al. 1992 and references therein). However, at \( M_V \approx +0.6 \), RR Lyrae stars are too faint for ground-based detection outside the Local Group. Even \( HST \) can go only a small distance beyond the Local Group at this brightness level.

There are other, brighter Population II stellar distance indicators. These include (1) long-period variables (cf. Feast 1996 and references therein); (2) non-variable AGB stars (e.g., the carbon-star luminosity function—see Pritchet et al. 1987; Brewer, Richer, & Crabtree 1995); and (3) the luminosity of the red-giant tip (Lee, Freedman, & Madore 1993; Madore & Freedman 1995; Madore, this workshop), which is now being used to find distances well outside the Local Group (e.g., \( HST \) has detected the red-giant tip in NGC 5128—Soria et al. 1996). The method of surface-brightness fluctuations (SBFs; see Tonry & Schneider 1988; Jacoby et al. 1992; Tonry, this workshop) is also based on the luminosities of red giants in old populations. The planetary-nebula luminosity function (PNLF; Jacoby et al. 1992; Jacoby, this workshop) technique is based on the descendants of AGB stars of low to intermediate mass.

Many authors, including several at this workshop, have listed the requirements for a standard candle. A good outline is given by Aaronson & Mould (1986), who list the following criteria (to which I have added parenthetical remarks that apply specifically to stellar candles):

- Small scatter (e.g., a small range in \( M_V \))
- Available over wide distance range (i.e., high luminosity)
- Minimal corrections (e.g., reddening unimportant; weak metallicity dependence)
- Objective measurables (e.g., stellar magnitudes)
- Physical basis (e.g., a basis in theoretical evolutionary tracks)

To which one can add as additional desiderata:

- Easily recognizable objects (i.e., requiring a minimum of scarce telescope time)
- Calibratable within our Galaxy (i.e., primary distance indicators)

Although the various Population II candles mentioned above have proven extremely useful, they nevertheless do not necessarily satisfy all of the Aaronson-Mould criteria. For example, RR Lyrae stars, as noted, are not of high luminosity, and they (as well as LPVs) require a long time-series of telescope time for their detection. The absolute magnitudes of red giants, AGB stars, and planetary nebulae cover a wide range, so one must go deep enough, and detect enough objects, to recognize changes in their luminosity functions (i.e., the red-giant or AGB tips, or the turnover near the bright end of the PNLF). The PNLF does not have a primary zero point established within the Milky Way (due to our very poor knowledge of the distances of individual Galactic PNe), and the SBF method was likewise not initially based on a Galactic calibration (although Ajhar & Tonry 1994 have recently tested the method with observations of Galactic globular clusters).

By contrast, I will argue that PAGB stars, as they pass through spectral types F and A, satisfy all of the standard-candle criteria itemized above. They are thus a particularly “clean” candle, which will allow us to step out to the Virgo Cluster (with \( HST \)) on the basis of a remarkably small number of “rungs” in the distance ladder.
3. PAGB A- and F-Type Supergiants as Standard Candles

As a low- to intermediate-mass star nears the tip of the AGB, the mass of its hydrogen-rich envelope decreases due to nuclear burning from below and stellar-wind mass loss from above. When the envelope mass reaches \( \sim 10^{-2} M_\odot \), the star leaves the AGB and evolves rapidly across the HR diagram toward higher effective temperatures. On a time scale of a few times \( \sim 10^4 \) yr or less, \( T_{\text{eff}} \) reaches \( \sim 30,000 \) K and the surrounding AGB wind is ionized by stellar UV radiation, producing a planetary nebula (PN).

Our proposed new extragalactic candles are the transition objects of spectral types A and F, located between the AGB and the realm of PN nuclei. They lie in the approximate temperature range \( 5,000 \) K < \( T_{\text{eff}} \) < 10,000 K.

The top panel of Fig. 1 shows typical theoretical PAGB evolutionary tracks in the HR diagram, for several remnant masses. (The plotted tracks are taken from interpolations by L. Stanghellini between the well-known Schönberner and Paczynski PAGB tracks—see Stanghellini & Renzini 1993.) The PAGB stars evolve across the HR diagram at constant luminosity, with higher \( \log L/L_\odot \) corresponding to higher remnant mass. (The transition of the PAGB star across the HR diagram is so rapid that there is essentially no evolution in the luminosity of its core; as first discovered by Paczynski 1971, the luminosity is simply a function of the core mass.) Also shown schematically is the Cepheid instability strip. The dashed rectangle shows the approximate location of the A- and F-type PAGB stars with which we are concerned here; they are blueward of the instability strip. The vertical dashed line is located at 30,000 K and marks the transition from PAGB star to planetary-nebula nucleus (PNN).

The bottom panel of Fig. 1 plots the bolometric correction (from Kurucz model atmospheres) against effective temperature. Since the PAGB tracks are horizontal in \( \log L/L_\odot \), this plot shows the shape of the tracks in the \( V \) magnitude. Because the bolometric correction is smallest for PAGB stars of types late F and early A, they are the visually brightest members of Population II. The hotter PAGB stars fade rapidly as \( T_{\text{eff}} \) increases above \( \sim 10,000 \) K. (Hot PAGB stars have been discovered in several globular clusters—see de Boer 1987 for a summary of ground-based searches, and Dixon et al. 1994 and references therein for space-based work. However, the strong dependence of the B.C. upon \( T_{\text{eff}} \), combined with the weak temperature dependence of \( B - V \), makes it unlikely that the PAGB stars above 10,000 K will be useful candles.)

Moreover, we expect the luminosity function (LF) for PAGB A and F stars to be quite narrow, for the following reasons. (1) A very sharp lower cutoff should exist, corresponding to the lowest-mass stars in the stellar population which are currently leaving the main sequence. For an old population, such as in the halo of a spiral galaxy, this lower cutoff will correspond to PAGB stars of approximately 0.55\( M_\odot \), which are the descendants of main-sequence stars of \( \sim 0.8 \)\( M_\odot \). (2) The upper cutoff of the PAGB LF is set by the shorter transition times for more massive remnants. Much more rapid evolution at higher masses and luminosities was a general property of the earlier calculations of PAGB evolution (e.g., Paczynski 1971; Schönberner 1983). Actually, however, the transition times are extremely dependent upon the adopted mass-loss laws and are thus rather uncertain; see the detailed discussions by Blöcker & Schönberner (1990), Vassiliadis & Wood (1994), and Blöcker (1995). Nevertheless, in the Vassiliadis & Wood (1994) calculations, evolutionary timescales at \( T_{\text{eff}} \approx 10,000 \) K range from 10,000 yr at 0.569\( M_\odot \) down to 100 yr at 0.754\( M_\odot \) (these are the times taken to go from \( \log T_{\text{eff}} = 4.0 \) to 4.5). Blöcker’s recent isochrones (1995, Fig. 12) also indicate more rapid evolution at higher luminosities. (3) Quite apart from considerations of transition times across the HR diagram, the more massive and brighter remnants will be rarer in a population with a range of stellar...
Figure 1. (Top). Schematic HR diagram showing PAGB tracks for three remnant masses, the pulsational instability strip, the location where ionization of the circumstellar wind creates a planetary nebula (vertical dashed line), and the location of the A- and F-type PAGB supergiants discussed here (dashed rectangle). (Bottom). The bolometric correction, plotted to the same scale as the top figure, but in magnitude units. This curve shows the shape the PAGB tracks will have in a plot of \( V \) magnitude vs. \( T_{\text{eff}} \). PAGB stars are at their greatest visual brightness as they pass through spectral types F and A, and are fainter both near the AGB and when they reach high temperatures. *PAGB A and F stars are the visually brightest members of Population II.*

Theoretical tracks tell us that the PAGB LF should shrink almost to a delta function. If true, this would mean that we would only have to detect the PAGB stars; it would not be necessary to go much deeper than the detection, as is necessary in methods such as the red-giant tip or PNLF.

### 4. Field PAGB A and F Type Supergiants

Significant numbers of field PAGB A and F stars are now known in the solar neighborhood, e.g., from objective-prism surveys for high-latitude supergiants, or from optical identifications of IRAS sources. Examples of those with \( T_{\text{eff}} \) and \( \log g \) determined from high-resolution model-atmosphere analyses are listed in Table 1. Also included is the bright A-type supergiant, ROA 24 = HD 116745, in the globular cluster \( \omega \) Cen. As the
Table 1. Field PAGB A-F Supergiants with Atmospheric Analyses

| Star            | $T_\text{eff}$ | log $g$ | Reference                      |
|-----------------|----------------|---------|--------------------------------|
| HD 187885       | 8000           | 1.0     | Van Winckel et al. 1996a       |
| HD 133656       | 8000           | 1.25    | Van Winckel et al. 1996b       |
| HD 44179        | 7500           | 0.8     | Waelkens et al. 1992           |
| BD +39°4926     | 7500           | 1.0     | Kodaira et al. 1970            |
| HR 4049         | 7500           | 1.0     | Lambert et al. 1988            |
| HR 6144         | 7200           | 0.5     | Luck, Bond & Lambert 1990      |
| IRAS 07134+1005 | 7000           | 0.1     | Klochkova 1995                 |
| ω Cen 24        | 6950           | 1.2     | Gonzalez & Wallerstein 1992    |
| HD 161796       | 6600           | 0.0     | Luck, Bond & Lambert 1990      |
| IRAS 18095+2704 | 6600           | 1.0     | Klochkova 1995                 |
| HR 7671         | 6600           | 1.4     | Luck, Bond & Lambert 1990      |
| 89 Her          | 6550           | 0.6     | Luck, Bond & Lambert 1990      |
| HD 56126        | 6500           | 0.5     | Parthasarathy et al. 1992      |
| HD 46703        | 6000           | 0.4     | Luck & Bond 1984               |
| HD 52961        | 6000           | 0.5     | Waelkens et al. 1991           |
| HR 4912         | 6000           | 0.6     | Luck, Lambert & Bond 1983      |
| RU Cen          | 6000           | 1.1     | Luck & Bond 1989               |
| IRAS 22272+5435 | 5600           | 0.5     | Zacs, Klochkova & Panchuk 1995 |

Figure 2. Positions of the field PAGB stars from Table 1 in the gravity-temperature plane. Also shown are the evolutionary tracks from the top panel of Fig. 1, transformed to the log $g$, $T_\text{eff}$ plane. The positions of the field stars are consistent with them lying on PAGB tracks.

The table shows, the ω Cen star’s parameters are indistinguishable from those of the field PAGB candidates.

Fig. 2 shows the positions of these stars in the log $g$ vs. $T_\text{eff}$ diagram, along with the PAGB evolutionary tracks transformed to these coordinates. This comparison shows that the atmospheric parameters of the field stars (and the ω Cen star) are fully consistent with their lying on standard PAGB tracks.

Unfortunately, the spectroscopic log $g$ values of the field PAGB stars are not accurate enough to calibrate their absolute luminosities, even if their masses were known a priori.
Therefore it is necessary to base an empirical calibration on PAGB stars in globular clusters.

### Table 2. Absolute Magnitudes of PAGB A-F Supergiants in Galactic Globular Clusters

| Cluster | NGC   | Star | $V$  | $B-V$ | Ref.$\dagger$ | $E(B-V)$ | Distance (kpc) | $M_v$ |
|---------|-------|------|------|-------|---------------|----------|----------------|-------|
| $\omega$ Cen | 5139  | ROA 24 | 10.80 | 0.36  | (1)           | 0.11     | 5.2            | $-3.1$ |
| \ldots  | 5986  | Bond 1 | 12.48 | 0.72  | (2)           | 0.25     | 10.5           | $-3.4$ |
| \ldots  | Bond 2 | 12.39 | 0.51  | \ldots | \ldots       | \ldots   | \ldots         | $-3.5$ |
| M19     | 6273  | ZNG 5 | 12.89 | 0.58  | (3)           | 0.38     | 10.6           | $-3.4$ |

Mean $-3.4$

$\sigma$ 0.2

$\dagger$ Photometry references: (1) Cannon & Stobie 1973; (2) Bond unpub.; (3) Harris et al. 1976. Reddenings and distances from Webbink 1985.

### 5. Calibration of PAGB A-F Supergiants via Globular Clusters

A few PAGB A- and F-type stars are known in globular clusters, and can serve for a preliminary calibration of their absolute magnitudes. The well-known 10th-magnitude A supergiant in $\omega$ Cen, already mentioned above, is the only star in any globular cluster with its own HD number; its proper motion and radial velocity leave little doubt that it is a cluster member (e.g., Sargent 1965). Almost 20 years ago, I discovered two PAGB candidates in the little-studied globular cluster NGC 5986 in the course of a photographic slitless-spectroscopic survey (Bond 1977); they were readily recognizable because of their enormous Balmer jumps (see below), and I subsequently obtained radial velocities confirming their membership.

Harris, Nemec, & Hesser (1983) have compiled a listing of stars in 29 globular clusters that are known or suspected to lie above the horizontal branch and to the left of the red-giant branch. Their Fig. 3 presents a composite HR diagram for these stars, and provides an additional candidate for a non-variable luminous F star, ZNG 5 in M19 (NGC 6273); but to the best of my knowledge there are no proper motions or radial velocities confirming its membership.

Table 2 lists some details for these four objects, including, in the final column, the absolute visual magnitudes calculated from the cluster distances and foreground reddening tabulated by Webbink (1985).

Table 2 dramatically confirms our expectation that the PAGB stars in old populations will have a very narrow LF: the scatter in $M_V$ among the four stars is only 0.2 mag—considerably less than the range among Cepheids at a given pulsation period. Moreover, the mean $M_V$ of $-3.4$ is in remarkable agreement with the luminosity of the lowest-mass (0.546 $M_\odot$) PAGB track of Schönbömer (1983).

The case of NGC 5986 is particularly instructive. This hitherto obscure globular cluster seems destined to fill a role comparable to that of the handful of galaxies that have produced more than one Type Ia supernova. Since this cluster contains two PAGB A stars, all questions of cluster distance and reddening drop out, and the fact that their $V$ magnitudes agree to within 0.09 mag decisively argues for a very small range in absolute magnitudes. Unfortunately, the zero point for this cluster is based at present
Figure 3. Preliminary CCD CMD for the Galactic globular cluster NGC 5986 (Bond, Fullton, Marois, & O'Brien, in preparation). The large filled circles mark the two PAGB supergiants in this cluster. Their $V$ magnitudes agree within 0.09 mag.

upon the old photographic photometry of Harris et al. (1976). To remedy this situation, L. Fullton, STScI summer students S. O’Brien and C. Marois, and myself are reducing CCD frames obtained with the CTIO 0.9- and 1.5-m telescopes. A preliminary color-magnitude diagram is shown in Fig. 3, with the two PAGB stars shown as large filled circles. They lie fully 4 mag above the horizontal branch of the cluster, and are at least a magnitude brighter than the (rather ill-defined) red-giant tip. Again, we see vividly that PAGB A and F stars are the brightest members of Population II.

The route to the zero-point calibration for PAGB A and F stars is thus to begin with subdwarf parallaxes (which the Hipparcos data will soon be providing) in order to set the distance scale for Galactic globular clusters through main-sequence fitting. This scale will then set the absolute magnitudes for the PAGB stars. Of course, four PAGB candidates are an insufficient number for such a calibration, and it will be necessary to find more of them in globular clusters. Paradoxically, their very high brightnesses may have hindered their recognition in the past, since cluster investigators would typically regard them as foreground stars. However, as noted below, they can be recognized very readily using multicolor photometry, and they are so bright that 1-m class telescopes are more than adequate to survey all of the Galactic globular clusters. We have now begun such a survey and hope to finish it in 1997. As shown in the Appendix below, we expect to find about a dozen PAGB A and F stars in the Milky Way globular-cluster system, a number roughly comparable to the number of Galactic Cepheids known in open clusters.

6. Discovery Techniques

Aside from an expected narrow LF, PAGB stars of spectral types A and F have another advantage; they are very easily recognized. Since they are stars of low mass ($\sim 0.55M_\odot$) but of high luminosity, they have extremely low surface gravities (cf. Table 1). Around
types A and F, the Balmer discontinuity is very sensitive to log $g$, and thus the PAGB stars will have conspicuously large Balmer jumps.

This is illustrated by Fig. 4, showing spectra I obtained in the 1970's of two of the field PAGB stars listed in Table 1: BD $+39^\circ$4926 and HD 46703, whose ultra-low log $g$ values were first recognized by Kodaira et al. (1970) and Bond (1970), respectively. $F_{\lambda}$ drops by about 1.2 mag across the Balmer jump in HD 46703, and fully 1.8 mag in the hotter BD $+39^\circ$4926.

The large Balmer jumps mean that stars of this type can be recognized easily through photometric techniques, if a filter whose bandpass is below the Balmer discontinuity is included. The classical Strömgren $uvby$ system is tailored for work of this sort, since its $u$ filter lies entirely below the Balmer jump. Examples of the use of this system to detect PAGB stars are the Bond (1970) program which, as mentioned, revealed HD 46703, and Bond & Philip (1973), which revealed another field PAGB star, HD 107369. The distinguishing characteristic is a high value of the Strömgren $c_1$ index.

The Strömgren system does, however, have the drawback of low throughput due to its narrow bandpasses. In our current work, we are developing a hybrid photometric system that combines the Gunn-Thuan $u$ filter with the standard Johnson-Kron-Cousins $BVI$ bandpasses. Gunn $u$ does transmit slightly above the Balmer jump, but simulations show that it can nevertheless measure the Balmer jump in less telescope time than Strömgren $u$, due to its greater filter throughput. Gunn $u$ also has a small red leak, unlike Strömgren $u$, but this is of little consequence as long as blue stars are being measured (and can in any case be subtracted if necessary on the basis of $I$ measurements).

Fig. 5 (kindly prepared by R. Saffer, who is computing theoretical $uBVI$ colors using model atmospheres) shows the $uBVI$ bandpasses along with a theoretical energy distribution for a 9,000 K PAGB star.
7. Potential Problems

So far I have painted a rosy picture of a promising new standard candle which combines a narrow LF with very easy detectability. Several potential problems must, however, be considered:

(a) **Rarity.** PAGB stars are extremely rare objects. A crude estimate, based on the time it takes for a star on the 0.546$M_\odot$ Schönberner (1983) track to move from $T_{\text{eff}} = 5,000$ to 10,000 K, is that there should be one PAGB star for every 2,000 red giants. Here we have defined “red giant” as first-ascent stars that lie 1 mag or more above the horizontal branch, whose lifetime is about $4 \times 10^7$ yr (Sweigart & Gross 1978, 0.9 $M_\odot$ track). Fortunately, with modern CCD techniques, it is readily possible to do photometry on tens of thousands of stars in order to find the rare needles in the haystack.

(b) **Metallicity dependence.** The dependence of PAGB luminosity upon the stellar metallicity is set by details of mass loss that are still not well understood. Nevertheless, this dependence may be small. Dopita et al. (1992) give interpolation formulae based on the Vassiliadis & Wood (1994) theoretical PAGB tracks. This work predicts (with some extrapolation) that at a fixed age of 12 Gyr, going from log($Z/Z_\odot$) = $-1$ to $-2$ brightens $M_{\text{bol}}$ by 0.3 mag. At a fixed log($Z/Z_\odot$) = $-1$, reducing the age from 12 to 8 Gyr brightens the PAGB remnants by 0.1 mag. Thus the effects of metallicity (and also age, as long as the population is still reasonably old) appear to be relatively small, and may even be calibratable.

(c) **Variability.** These stars are close to the pulsational instability strip, and indeed there are well-known classes of PAGB variable stars, including “UU Her” or “89 Her” variables (e.g., Bond, Carney, & Grauer 1984; Fernie & Seager 1995; and references therein) as well as the cooler RV Tauri pulsators. However, by staying at spectral types A and F, we should be avoiding most variable stars. Indeed, I have monitored the PAGB stars in $\omega$ Cen and NGC 5986 during observing runs covering many years, and have never detected variability of more than a few hundredths of a magnitude.
Circumstellar extinction. A significant fraction of the PAGB stars in the solar neighborhood were recognized because of their infrared excesses, e.g., in the IRAS survey. Thus they are susceptible to circumstellar extinction, which could smear out the LF to a large extent. We have, for example, obtained a spectacular HST image of HD 44179 (listed in Table 1, and often called the “Red Rectangle”), showing that the star is in fact not seen directly at all. It lies within a thick dusty disk, and is only seen through scattered light.

Fortunately, if we confine ourselves to PAGB stars well out in galactic halos, dust formation and extinction may be much less likely. This is for several reasons: (1) dust formation may be difficult in the first place at low metallicity; (2) moreover, the long transition times for low-mass remnants give plenty of time for any dust (and gas) that is formed during the AGB phase to dissipate; (3) if the AGB “superwind” depends on Mira-type pulsation as a driving mechanism (cf. Bowen & Willson 1991), the superwind may not even occur in very metal-deficient populations that do not produce Miras.

The small scatter in $M_V$ among globular-cluster PAGB stars (see above) is in agreement with the above expectation, and indeed field PAGB stars that have halo kinematics (e.g., BD +39°4926 and HD 46703) likewise show little or no evidence for surrounding dust.

In fact, it may be that globular-cluster stars also have a difficult time producing PNe. A survey of all of the Galactic globular clusters for PNe revealed only two new ones (G. Jacoby & L. Fulton, in preparation), bringing the total known to only four. Since the number of PAGB stars known in globular clusters is already larger than four (if we include the four A-F objects listed above as well as hotter ones such as those tabulated by de Boer 1987), in spite of lifetimes comparable to those of PNe, this suggests that the typical globular-cluster star does not produce a PN during its final evolution. Perhaps the few PNe that are seen in globulars derive from blue stragglers, or other binary-star interactions.

Alternative evolutionary scenarios. We have thus far discussed hydrogen-burning PAGB stars that are leaving the AGB for the first time. There are, however, other evolutionary paths that could populate this region of the HR diagram in galactic halos. A non-exhaustive list would include helium-burning PAGB stars, “born-again” stars that are returning from the top of the white-dwarf sequence, and stripped cores in binary systems. Other possibilities include runaway Population I stars (but these would not, at $M_V \approx -3.4$, have the very low log $g$’s of low-mass PAGB stars), and various low-mass stars that fail to achieve the AGB due to low envelope masses (e.g., the so-called “AGB-manqué” and “PEAGB” stars, but their evolutionary tracks do not attain the high luminosities of the genuine PAGB stars and thus may not be a source of confusion).

Poorly understood physics. Lest the reader think that the evolution of PAGB stars is well understood, I mention the extraordinary chemical abundances seen in a subset of them, including near-solar C, N, O, S, and Zn, but strongly depleted iron-group elements (see Bond 1992; Van Winckel et al. 1995; and references therein). Apparently the material now in the photosphere at some time in the past reached a sufficient distance from the star to form grains of iron-group elements, and then the depleted gas fell back onto the star. How this could happen is still a matter of speculation. A possibly related phenomenon is that many of the field PAGB stars appear to be binaries, typically with periods of about 400–700 days (cf. Van Winckel et al. 1995).

All of the above concerns emphasize that an empirical calibration of the PAGB luminosity function and extensive testing in nearby galaxies will be necessary before they can be applied to the distance-scale problem.
8. A Preliminary Test in the Halo of M31

We have applied our $uBVI$ search technique in the halo of M31, using the Kitt Peak Mayall 4-m telescope and a 2048 $\times$ 2048 CCD which yields a 16$'$ $\times$ 16$'$ field of view. We observed three fields at about 40$'$–50$'$ from the nucleus along the minor axis, in which the surface density of M31 halo red giants is about 10,000 per CCD field. Thus we expect to find about 5 PAGB stars in each field.

Fig. 6 (left side), kindly supplied by L. Fullton, shows how we select PAGB candidates. We have plotted a $c_1$-like index, $(u - B) - (B - V)$, vs. $B - V$, and the dashed box isolates the A and F stars with large Balmer jumps (i.e., having a large $(u - B) - (B - V)$ index with $0 < B - V < 0.5$). In this field we find 6 candidates, in almost perfect agreement with expectation.

Fig. 6 (right side) shows the $V, B - V$ diagram for all three fields, with the PAGB candidates (those lying inside the dashed box in the left-hand plot) marked with error bars. Although the reductions are still preliminary at this writing, these candidates have a mean $V$ of about 21.1 (if we neglect the two anomalously bright stars, which are presumably foreground horizontal-branch stars in our own Galaxy’s halo). If we adopt the Galactic calibration of $M_V = -3.4$, and a foreground reddening of $E(B - V) = 0.08$, we find a true distance modulus $(m - M)_0 = 24.2$. This is in superb agreement with the M31 distance modulus of 24.3 $\pm$ 0.1 adopted in the review article by van den Bergh (1992), and gives us confidence that our method has promise. It is, however, troubling that the scatter in the $V$ magnitude is larger than we expected, but we still need to calibrate the $(u - B) - (B - V)$ index using model atmospheres. At this stage, some of the objects in the figure may be background galaxies or QSOs with large Balmer or Lyman jumps, many of which could be weeded out through a log $g$ calibration.
9. Future Plans

Much work remains to be done in order to develop these potential excellent candles:

(a) **Primary calibration.** As mentioned above, we have begun a $uBVI$ survey of all of the Galactic globular clusters for PAGB stars. Once the subdwarf calibration becomes available from *Hipparcos* parallaxes, we will have a firm calibration of the PAGB absolute magnitudes. The PAGB stars in Milky Way globulars will typically have $V = 11$–15, and we expect to find about a dozen of them (see Appendix).

(b) **Magellanic Clouds.** We have selected PAGB candidates in the Magellanic Clouds from Curtis Schmidt objective-prism material obtained at Cerro Tololo, and are now reducing $uBVI$ CCD photometry obtained at the CTIO 1.5-m telescope. These objects, expected to lie near $V \approx 15$, will further test and strengthen the $M_V$ calibration.

(c) **Local Group.** Moving further out, we will be able to survey fields in all of the Local Group galaxies, including both dwarf ellipticals (NGC 147, NGC 185, NGC 205) and galaxies with Cepheids (M31, M33, NGC 6822, etc.), allowing a direct confrontation with the Cepheid distance scale. The PAGB stars in these galaxies will typically have $V \approx 21$, as we found in M31 already.

(d) **Intermediate distances.** If the above work is successfully completed, we would be in a position to move out to intermediate-distance galaxies such as those of the Sculptor and M81 groups. At $V = 23$–25, the PAGB stars should be reachable in about one night per field with a 4-m class telescope. (Most of the observing time must be spent in the $u$ filter, due to its relatively low throughput and the low stellar flux below the Balmer jump.) We need hardly mention that, for example, the reliable detections of Cepheids in M81 required a long series of observations with *HST* (Hughes et al. 1994). By contrast, the PAGB stars require only one epoch of observation, and we can go out into the halos where crowding and internal extinction will be much less severe.

(e) **Virgo Cluster.** Our ultimate aim will be to attain the distance of the Virgo Cluster, where the PAGB stars should have $V \approx 27.5$. This may be achievable with *HST* and its Advanced Camera, though the signal-to-noise will be low in a $u$-like filter.

10. Summary

(a) Post-AGB A-F stars appear on theoretical and empirical grounds to be excellent candidates for standard candles.

(b) From a few PAGB A-F stars known to lie in Galactic globular clusters, they appear to have a small dispersion around $M_V = -3.4$, i.e., 4 mag brighter than RR Lyrae stars. **They are the visually brightest members of Population II.**

(c) They are very easily recognized via $uBVI$ photometry, due to their extraordinarily large Balmer jumps.

(d) Their absolute magnitudes can be calibrated in the Milky Way, using subdwarf parallaxes (from *Hipparcos*) to determine distances of globular clusters that contain PAGB stars, through main-sequence fitting. We have begun a $uBVI$ survey to find more PAGB stars in Galactic globulars.

(e) Among other advantages, PAGB stars can be observed in spiral halos and in ellipticals; a time series of observations is not needed; there will be few problems with crowding or internal reddening; and, due to their narrow LF, we just need to detect them, rather than doing the “edge-finding” necessary for planetary nebulae or the red-giant tip.

(f) We therefore argue that PAGB stars may be the **best available Population II candles.** It should be possible to use them to reach the Virgo Cluster in just three steps: subdwarf parallaxes, Galactic globular clusters, and then directly to Virgo with *HST*. 

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REFERENCES

Aaronson, M., & Mould, J. 1986, ApJ, 303, 1
Ajhar, E. A., & Tonry, J. L. 1994, ApJ, 429, 557
Blöcker, T. 1995, A&A, 299, 755
Blöcker, T., & Schönberner, D. 1990, A&A, 240, 11
Bond, H. E. 1970, ApJS, 22, 117
Bond, H. E. 1977, BAAS, 9, 601
Bond, H. E. 1992, Nature, 356, 474
Bond, H. E., Carney, B. W., & Grauer, A. D. 1984, PASP, 96, 176
Bond, H. E., & Philip, A. G. D. 1973, PASP, 85, 332
Bowen, G. H., & Willson, L. A. 1991, ApJ, 375, 53
Brewer, J. P., Richer, H. B., & Crabtree, D. R. 1995, AJ, 109, 2480
Cannon, R.D., & Stobie, R.S. 1973, MNRAS, 162, 207
Ciardullo, R. 1995, in I.A.U. Highlights of Astronomy # 10, ed. I. Appenzeller (Dordrecht, Kluwer), p. 507
de Boer, K. S. 1987, in IAU Colloq. No. 95, The Second Conference on Faint Blue Stars, ed. A.G.D. Philip et al. (Schenectady, L. Davis Press), p. 95
Dixon, W.V.D., Davidsen, A. F., & Ferguson, H. C. 1994, AJ, 107, 1388
Dopita, M. A., Jacoby, G. H., & Vassiliadis, E. 1992, ApJ, 389, 27
Feast, M. W. 1996, MNRAS, 278, 11
Fernie, J. D., & Seager, S. 1995, PASP, 107, 853
Gonzalez, G., & Wallerstein, G. 1992, MNRAS, 254, 343
Harris, H. C., Nemec, J. M., & Hesser, J. E. 1983, PASP, 95, 256
Harris, W.E., Racine, R., & de Roux, J. 1976, ApJS, 31, 13
Hughes, S.M.G. et al. 1994, ApJ, 428, 143
Jacoby, G. H. et al. 1992, PASP, 104, 599
Klochkova, V. G. 1995, MNRAS, 272, 710
Kodaira, K., Greenstein, J.L., & Oke, J.B. 1970, ApJ, 159, 485
Lambert, D. L., Hinkle, K. H., & Luck, R. E. 1988, ApJ, 333, 917
Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, ApJ, 417, 553
Luck, R. E., & Bond, H. E. 1984, ApJ, 279,729
Luck, R. E., & Bond, H. E. 1989, ApJ, 342, 476
Luck, R. E., Bond, H. E., & Lambert, D. L. 1990, ApJ, 357, 188
Luck, R. E., Lambert, D. L., & Bond, H. E. 1983, PASP, 95, 413
Madore, B. F., & Freedman, W. L. 1995, AJ, 109, 1645
Paczynski, B. 1971, Acta Astr., 21, 417
Parthasarathy, M., Garcia Lario, P., & Pottasch, S. R. 1992, A&A, 264, 159
Pritchet, C. J. et al. 1987, ApJ, 323, 79
Renzini, A., & Buzzoni, A. 1986, in Spectral Evolution of Galaxies, ed. G. Chiosi & A. Renzini (Dordrecht, Kluwer), p. 195
Saha, A., Freedman, W. L., Hoessel, J. G., & Mossman, A. E. 1992, AJ, 104, 1072
Appendix A. The Expected Number of PAGB Stars in the Galactic Globular-Cluster System

We may estimate how many PAGB A-F supergiants should exist in all of the Milky Way globular clusters using the “fuel-consumption” theorem. For a wide range of underlying properties, the rate at which stars leave the AGB in a population whose total luminosity is $L$ is

$$2 \times 10^{-11} (L/L_{\odot}) \text{stars yr}^{-1}$$

(see Renzini & Buzzoni 1986; Ciardullo 1995).

The total luminosity of all Galactic globular clusters (calculated from the data in Webbink 1985) is

$$2.4 \times 10^7 L_{\odot}.$$

Hence the expected number of PAGB A-F stars in all Milky Way globulars is

$$N_{\text{PAGB}} \simeq 10 \left( \frac{\tau_{\text{PAGB}}}{20,000 \text{ yr}} \right) \text{stars},$$

where $\tau_{\text{PAGB}}$ is the time the PAGB star spends evolving from $T_{\text{eff}} = 5,000$ to $10,000 \text{ K}$. For the $0.546 M_{\odot}$ PAGB track of Schönberner (1983), $\tau_{\text{PAGB}} = 20,000 \text{ yr}$.

We thus expect to find almost a dozen PAGB stars in the survey that we have initiated. The presence of two PAGB stars in the sparse cluster NGC 5986 (see above) is a somewhat encouraging, if disquieting, indication that our prediction may be an underestimate. Quite aside from their applicability to the extragalactic distance scale, these PAGB stars may provide us with surprising new information on the late stages of stellar evolution.