A COMBINED PHOTOMETRIC/SPECTROSCOPIC STUDY OF RR LYRAE STARS IN THE GLOBULAR CLUSTER OMEGA CENTAURI

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1. INTRODUCTION

Most CM diagrams of well observed galactic globular clusters have giant branch widths which are understandable in terms of realistic estimates of random (and systematic) error associated with data acquisition and reduction. Not Omega Centauri. The scatter in (B-V) color among Omega Centauri giant branch stars is considerably greater than that allowed by observational error, differential reddening, or star-to-star mass and/or helium abundance variation (Demarque and Geisler 1963; Woolley 1966; Dickens and Woolley 1967; Rood 1973; Cannon and Stobie 1973; Cannon and Kontizas 1974; Iben 1974; Norris and Bessell 1975; Hesser et al. 1976; 1977). This problem is an old one, but one which has recently received a flurry of attention. Indeed, our next speakers have investigated possible causal relationships between interior mixing and Omega Centauri giant (or subgiant) color. I see from the program that they intend to discuss such things today, so we shall try to avoid those topics as much as possible.

Instead, we wish to concentrate on an analysis of spectroscopic and photometric data for the cluster's RR Lyrae stars. Working within the formalism defined by some of the latest stellar atmosphere, stellar evolution, and pulsation calculations, we find that we are able to make several interesting deductions and

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inferences concerning (1) the chemical composition dependence of RR Lyrae absolute magnitudes, and (2) the chemical composition dependence of total mass loss during earlier evolutionary states. Almost all the material we shall report and discuss today is new, in the sense that it is drawn from papers (either in press, or in preparation) by various permutations of Butler, Bell, Dickens and Epps.

1.1 Rationale and Spectroscopic Method

In Fig. 1 we superimpose a series of giant branch loci for the well observed globular clusters M92 (Sandage and Walker 1966), M5 (Arp 1962), and 47 Tuc (Hartwick and Hesser 1974) with a schematic representation of the Dickens and Woolley (1967) Omega Centauri CM diagram. One major parameter which is unquestionably different for each of the first three clusters is [Fe/H] = log (Fe/H)* - log (Fe/H)$_\odot$. According to Hesser et al. (1977), [Fe/H] = -2.2, -1.0 and -0.4, respectively, for M92, M5 and 47 Tuc. If we suppose that either [Fe/H] or something predictable from it dominates giant-branch color, then we can deduce there might well exist a large range (-0.8 $\gtrsim$ [Fe/H] $\gtrsim$ -1.7) in chemical composition among members of Omega Centauri, including the RR Lyraes.

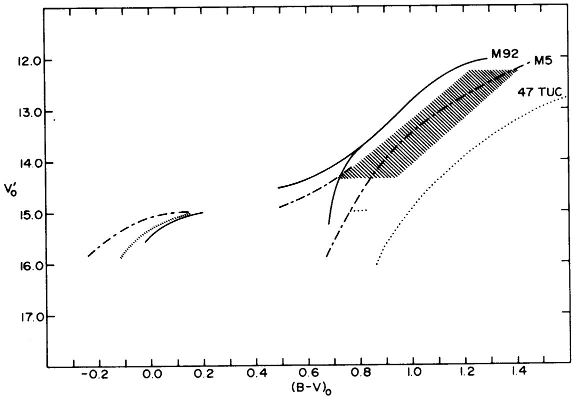

Fig. 1. Superposition of mean giant-branch loci for the well observed globular clusters M92 ([Fe/H] = -2.2), M5 ([Fe/H] = -1.0) and 47 Tuc ([Fe/H] = -0.4) with a schematic representation of the Omega Cenaturi giant branch. Intrinsic giant-branch width was obtained from a quadratic combination of observed width (0.24) and an estimate of observational scatter of ± $0\overset{m}{.}07$ in (B-V). It is important to warn the reader that different investigators find quite different values of giant-branch width. For example, Cannon and Stobie (1973) give a lower limit of 0.3, while Bessell and Norris (1976) prefer 0.4.

Although Omega Centauri is not very rich in RR Lyrae stars when things are normalized in terms of the number of red-giant progenitors, or in terms of total cluster luminosity, it nevertheless contains nearly 150 of them (with the cluster's great mass partly responsible for such a large absolute number).

In the visual region, low dispersion spectra of RR Lyrae stars are dominated by strong absorption lines of hydrogen (Balmer series) and the H and K-lines of singly ionized calcium. In the temperature domain occupied by RR Lyrae stars, hydrogen-line strength is extremely (and almost entirely) temperature dependent whereas K-line strength is sensitive to both temperature and calcium abundance. One can use measurements of hydrogen-line strength to allow for the K-line's temperature dependence, thus clearing the way for an abundance determination. This is the essence of the Preston ΔS method (Preston 1959; Butler 1975). In practice, one assigns to each RR Lyrae star a spectral classification based on hydrogen-line strength Sp(H), and one based on K-line strength Sp(K). ΔS is simply the difference in tenths of a spectral class, between Sp(H) and Sp(K). It is a parameter having values ranging from ~ 0 to 10, and internally calibrated through high dispersion (8-16 Å/mm) curve-of-growth abundance analyses of ~ 40 spectra of 13 bright, field RR Lyrae stars. The fundamental calibration is reproduced in Fig. 2. The great power, and hence great appeal of the technique, is obvious from the figure (see caption).

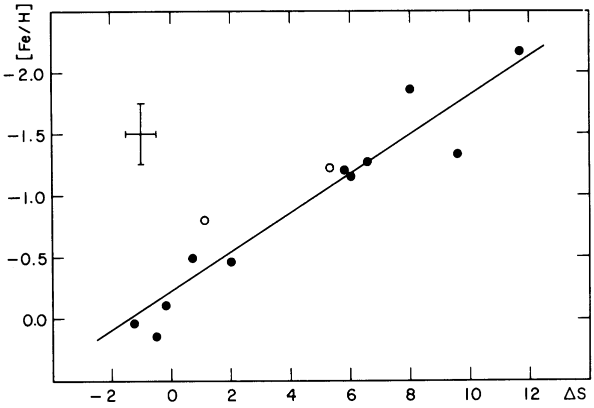

Fig. 2. A single ΔS measurement of precision ±1 leads to an [Fe/H] value of precision comparable to that obtainable from a high dispersion curve-of-growth analysis. Filled circles, ab-type RR Lyraes; open circles, c-types.

2. DATA AND DISCUSSION

Several years ago, we began a major observing program in which (1) ΔS measurements (and hence [Fe/H] determinations) would be made for a large number of RR Lyrae stars in Omega Centauri, and (2) new photographic photometry would be obtained for the purpose of analyzing pulsation characteristics. Today, leaving all details regarding observing technique, data reduction procedure, etc., to the publications already mentioned, we report on what has come of it.

Our spectroscopic data are displayed in Fig. 3. Many data points represent mean values from 3 or 4 observations, with individual observations having a maximum weight W=5. The two underlined symbols represent variables which can be called "BL Her stars", i.e., variables having P ~ 1-3 days, and magnitudes ~ 1 mag brighter than the RR Lyraes. A striking characteristic of the figure is that the scatter in [Fe/H] is considerably greater than that allowed by error estimates. Also, the c-types as a group are systematically more metal deficient than the ab-types. Freeman and Rodgers (1975) have used a slight variation of the ΔS method in determining calcium abundances for 25 Omega Centauri RR Lyrae stars, and in Fig. 4, we present their data, re-reduced to be more or less on the ΔS system, and combined with ours. Data in Fig. 4 constitute the fundamental spectroscopic material used in the remainder of the present report.

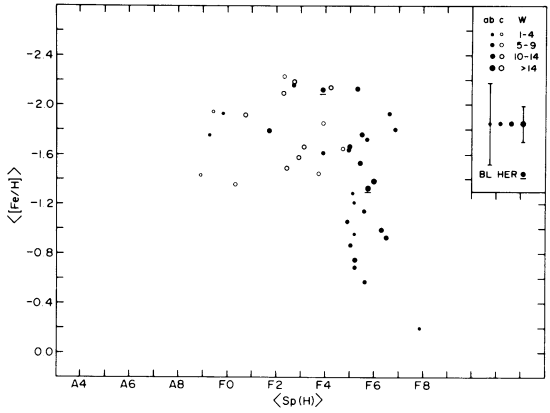

Fig. 3. Spectroscopic data for individual variable stars in Omega Centauri: filled circles, ab-type RR Lyraes; open circles, c-types; underlined circles, BL Her stars.

In Fig. 5, we present a montage of spectra showing the extreme star-to-star variation in K-line strength. All stars were observed at a phase near minimum light, so they all have roughly similar temperatures, as is obvious from the hydrogen-line strengths. These spectra were obtained just a few months ago, and have not been included in Figs. 3 or 4. Significantly, when the spectra are ordered by K-line strength, they are also ordered by [Fe/H] from previously obtained data. From data presented in Figs. 3, 4 and 5, and from the lack of scatter in Fig. 2, we are confident that there exists a large range in [Fe/H] among individual RR Lyrae stars in

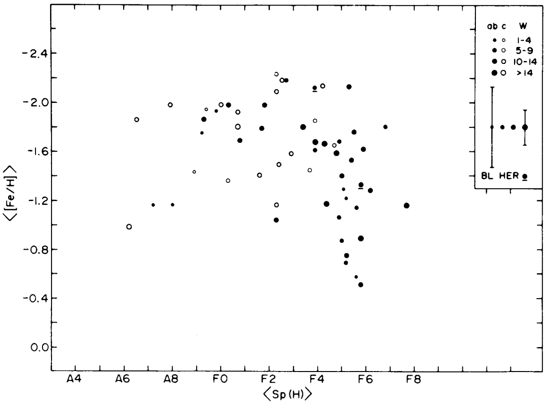

Fig. 4. Freeman and Rodgers' (1975) spectroscopic data combined with ours.

Omega Centauri. If the giants share the same range in [Fe/H] as the RR Lyraes, namedly Δ [Fe/H] ~ 1, then much, if not all, of the great giant branch width is explained quite naturally.

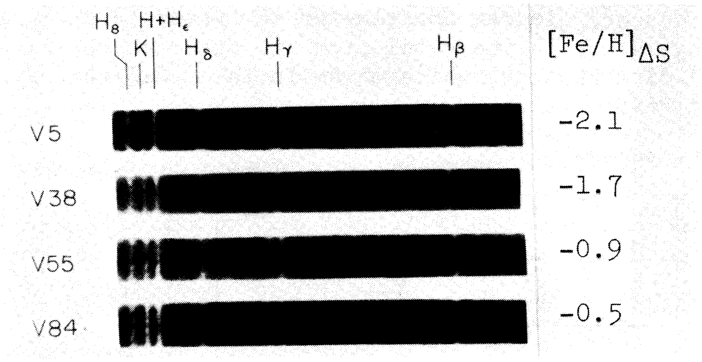

Fig. 5. Reproduction of spectra of 4 Omega Centauri RR Lyrae stars showing an enormous range in K-line strength. The spectra are widened to ~ twice the value typical for an observation of weight 5.

2.1 Oosterhoff Characteristics

There exists yet another line of evidence (although less direct than the spectroscopy) supporting a large abundance range. If we sort data in Fig. 4 into two bins: one for stars having [Fe/H] > -1, and the other, for [Fe/H] < -1 (hereafter, "metal-rich", and "metal-poor" bins, respectively), then we can compare Oosterhoff characteristics of stars in each bin with those of stars in other globular clusters. We made the comparison in Table I, in which a summary of Oosterhoff characteristics for other globular clusters has been taken from van Albada and Baker (1972). Note that stars in the metal-rich bin appear to have Oosterhoff group I characteristics, while those in the metal-poor bin, group II.

TABLE I

OMEGA CENTAURI CHARACTERISTICS

Bin:	Metal-Rich	Metal-Poor
n	7	49
<P(ab)>	0.57	0.49
<P(c)>	0.31	0.37
n(c/ab)	0.17	0.63

GLOBULAR CLUSTER CHARACTERISTICS

Group:	I	II
<P(ab)>	0.55	0.65
<P(c)>	0.32	0.37
n(c/ab)	0.2	0.8
metals	weak	very weak

The period-frequency diagram for cluster RR Lyraes (Fig. 6) shows the same thing; stars in the metal-rich bin favor an M5-like ([Fe/H] = -1) distribution, while those in the metal-poor group M15, or M92 ([Fe/H]= -2).

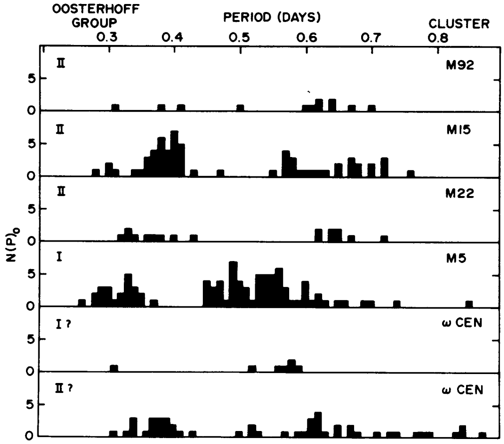

Fig. 6. Period-frequency distributions for Omega Centauri RR Lyrae stars belonging to the metal-rich (I?), and metal-poor (II?) bins, compared with distributions for other clusters.

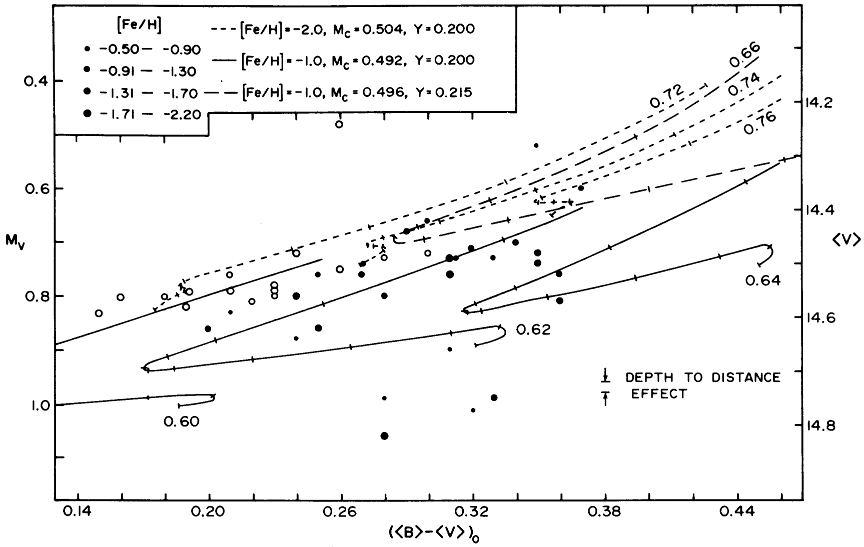

Fig. 7. Evolutionary tracks for model horizontal-branch stars superimposed on the CM diagram of Omega Centauri RR Lyrae stars. Filled circles, ab-types; open circles, c-types. Tick marks delineate intervals of 10^7 years. Track labels give values of total mass. See text for discussion.

2.2 CM Diagram for the RR Lyrae Stars

In Fig. 7 we give our new CM diagram for Omega Centauri RR Lyrae stars. Mean apparent visual magnitude <V> is plotted against <B> - <V>, corrected for an adopted color excess of E(B-V) = 0.11. Evolutionary tracks result from interpolation in the grids of Sweigart and Gross (1976; 1977); theoretical quantities were related to observational ones via a new grid of color-temperature-chemical composition relations appropriate for RR Lyrae stars.

Under the assumptions (1) that $\Delta\log Z = \Delta[Fe/H]$ and (2) a star with log Z = -3 has [Fe/H] = -1.4, we began by considering the main-sequence to helium-flash evolution of two stars having [Fe/H] values (-1 and -2) characteristic of the observed range for RR Lyrae stars in Omega Centauri; the stars are otherwise identical, having $M/M_\odot = 0.9$. The metal-rich star takes 1.6 x 10^9 years longer to get from main-sequence to helium flash. In order for both stars to reach helium-flash at the same time, the metal-rich one must have evolved from a slightly more massive (~0.02 $M_\odot$) main-sequence progenitor. At the time of helium flash, the core masses are significantly different, with the metal-rich star having $M_c = 0.492\ M_\odot$, and the metal-poor one, 0.504 $M_\odot$. For the horizontal-branch phase of evolution, we retrieved several sets of sequences: one for a star with [Fe/H] = -1, $M_c = 0.492\ M_\odot$, and $M/M_\odot = 0.72$, 0.74, and 0.76, and another for [Fe/H] = -2, $M_c = 0.504\ M_\odot$, and $M/M_\odot = 0.60$, 0.62, and 0.64. Both sets are for Y = 0.20. An additional track was found for a model with [Fe/H] = -1, M_c = 0.496 $M_\odot$, $M/M_\odot$ = 0.66, and Y = 0.215. It is apparent from Fig. 7 that if Δ[Fe/H] = Δlog Z, then the metal-rich RR Lyraes in Omega Centauri are $\sim$ 0.1 $M_\odot$ less massive than the metal-poor ones.

2.3 Chemical Composition Dependence of RR Lyrae Luminosity

We note with considerable interest that stars in the metal-rich group have very nearly the same mean magnitude as those in the metal-poor group: <V> = $14\overset{m}{.}62 \pm 0\overset{m}{.}07$ (m.e.) for the metal-rich variables, and $14\overset{m}{.}53 \pm 0\overset{m}{.}02$ for the metal-poor ones. This is not expected from the tracks of Fig. 7, and that is because we have left out one important effect. Red giant models of Sweigart and Gross (1977) indicate differential, Z-dependent envelope helium enrichment through convective mixing as the star is ascending the giant-branch for the first time. It turns out that Δlog Z = 1 leads to ΔY_e = 0.005, with the higher Z model having the greater enrichment. The extra envelope helium abundance makes up for much of the luminosity difference which arises from a large star-to-star range in Z. We should not be surprised, then, that magnitudes of Omega Centauri RR Lyrae stars have such a slight Z-dependence.

It is of interest to compare (in Table II) our results with those from statistical (Hemenway 1975) and photometric (McDonald 1977) parallaxes for field RR Lyrae stars, even though conclusions drawn from such a comparison are fraught with numerous implicit assumptions regarding the stars' backgrounds and evolutionary histories.

TABLE II

RR LYRAE ABSOLUTE MAGNITUDES

$[Fe/H]_{\Delta S}$	$\langle M_V \rangle^{stat}_{H}$	$\langle M_V \rangle^{phot}_{Mc}$	$\langle M_V \rangle^{evol}_{\omega\ Cen}$
>-0.7	$+0\overset{m}{.}21 \pm 0.54$	$+0\overset{m}{.}82 \pm 0.20$	----
-0.7 to -1.2	$+0.44 \pm 0.43$	$+0.58 \pm 0.20$	$\langle M_V \rangle \pm 0\overset{m}{.}07$
<-1.2	$+0.44 \pm 0.46$	$+0.55 \pm 0.20$	$\langle M_V \rangle - 0\overset{m}{.}09 \pm 0\overset{m}{.}02$

If we adopt McDonald's (1977) value of $\langle M_V \rangle$ = $+0\overset{m}{.}55$, then we find Y = 0.23, and $M/M_\odot$ = 0.68 and 0.77 for our metal-rich, and metal-poor groups, respectively. On the other hand, if we compare the Omega Centauri RR Lyrae gap width with widths from calculations of Deupree (1977), we find).23 $\lesssim$ Y $\lesssim$ 0.28, with a "best" value which must await the completion of a formal analysis of scatter in <B> - <V>. No matter what value of Y we finally settle on, the 0.1 $M_\odot$ mass difference between the metal-rich and metal-poor stars remains, as does the very small luminosity difference. Our mass result is strongly coupled to the theoretical formalism employed, but the luminosity result is *purely empirical*.

3. CONCLUDING REMARKS AND PROSPECTS FOR FUTURE WORK

I. Under the assumption that we understand the basic features of stellar evolution for low-mass stars, we conclude that a large-scale spatial chemical composition inhomogeneity existed in the proto-cluster cosmic cloud which was to become Omega Centauri. Several hundred solar masses of heavy elements must have been deposited in various regions of the cloud prior to, or during collapse. New high-dispersion spectroscopic equipment expected to be operational soon at CTIO raises the truly fascinating possibility of studying explosive nucleosynthesis elemental yield for a system which has been isolated from the galactic chemical genetic pool for nearly 15 billion years.

II. Considering the large range ($0\overset{\mathrm{m}}{.}24$ - $0\overset{\mathrm{m}}{.}40$) in Omega Centauri giant-branch width adopted by different investigators, it is clear that great need exists for a new Omega Centauri CM diagram -- a diagram obtained *not* for the purpose of simply locating major sequences, but one obtained for the purpose of determining *precise* values of cosmic scatter in the various sequences.

III. Finally, we note the intriguing possibilities of (1) checking the stellar evolution theory results concerning mass differences between metal-rich and metal-poor Omega Centauri RR Lyrae stars, and (2) checking the possibility that the supernovae which contaminated the proto-cluster cloud might have built up "primordial" overabundances of one or more of the CNO group elements. One can use results from linear, nonadiabatic pulsation calculations (van Albada and Baker 1971; Iben 1971) to determine mass values for individual stars. In the [Fe/H] - $M/M_\odot$ diagram, our Fig. 7 predicts a slope of -9.5 for the case in which $\Delta\log Z = \Delta$[Fe/H].

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DISCUSSION

COX: There is a possibility of a wind from the RR Lyrae variable which is capable of enriching the metal content of the surface convection layers. The solar wind actually has a mass loss of hydrogen much more than for the heavier elements. Only 10^{-4} or 10^{-5} of the mass needs to be lost. Instead of trying to evoke evolutionary arguments to give different mass tracks with different helium contents, could you have a small mass range as traditionally used, with fixed helium, and have all anomalies due to an RR Lyrae wind?

BUTLER: Although we have not made calculations to examine this effect, I find it hard to believe that the large local helium overabundance which would result would not lead to unusual hydrogen-line strengths. The observed H-line strengths are normal. I agree, however, that detailed calculations would be valuable.

NORRIS: Is the range in calcium abundance observed in ω Cen unique? If Dr. Cox's suggestion is correct, one would expect to see a similar phenomenon in other clusters.

BUTLER: So far, it is unique in this respect.

WEIDEMANN: You had to invoke differential mass loss, dependent on abundance differences, in order to exaplin the position of both groups of stars. How large are these mass loss differences?

BUTLER: The exact difference depends on the adopted main-sequence mass and helium abundance of the progenitor. With plausible values of these parameters, one can deduce that a "metal-rich" RR Lyrae progenitor lost $\sim 0.2\ M/M_\odot$, and a "metal-poor" one $\sim 0.1\ M/M_\odot$.

FLOWER: Böhm-Vitense at the University of Washington has computed T_{eff}: (B-V): BC scales for a variety of metal abundances. How do your scales compare with hers and how sensitive are your results to the transformation scales?

BUTLER: I am not familiar with her color temperature or BC scales for RR Lyrae stars. In any case, it is necessary to calculate them for the correct microturbulent velocity parameter, and it is unlikely that we can make a direct comparison since our relations were computed for DBV = 3.6 km/sec, the value resulting from previous curve-of-growth determinations. The [Fe/H] spread and magnitude range results do not depend on the color temperature or BC relations. The *differential* mass result is *slightly* sensitive, while an *absolute* mass would be *extremely* sensitive to the relations adopted.

ZINN: I would like to remark that your results concerning the RR Lyrae stars in ω Cen may be inconsistent with stellar pulsation theory. If I understand your results correctly, you find that metal-rich variables have the same luminosities and effective temperatures as the metal-poor variables. Then you say that metal-rich variables must be less massive. If all these things are true, then the metal-rich variables have smaller surface gravities. Well, pulsation theory would then say that these metal-rich variables must have longer periods than the metal-poor variables. This is, of course, the opposite from the Oosterhoff effect. Have I missed something?

BUTLER: The temperatures (and luminosity) are only *approximately* equal. The average temperatures for an RR Lyrae in the metal-rich group is $\sim$ 300 K hotter than the corresponding quantity for an average star in the metal-poor group. If the "metal-rich" stars are $\sim 0.1\ M/M_\odot$ less massive than the "metal-poor" ones, then linear, non-adiabatic pulsation theory predicts a luminosity difference amounting to $\Delta V \sim 0.14$, with the most metal-rich star being the faintest. Since we found $\langle V \rangle = 14^m.62 \pm 0^m.07$ (m.e.) for the metal-rich group and $\langle V \rangle = 14^m.53 \pm 0^m.02$ for the metal-poor group, the size of the discrepancy is $\sim 0^m.05 \pm \sim 0^m.1$ (estimated error). Considering all of the uncertainties involved, and the assumptions ($\Delta \log Z = \Delta$[Fe/H]) central to the analysis, I don't think the "discrepancy" is a serious one. Note that if Δ[Fe/H] $\neq \Delta \log Z$, and if, in particular, the range in Z_{CNO} is less than the range in Z, then the mass differences could be reduced or eliminated completely.

KRAFT: Neglecting, for now, the question of the enrichment of the envelope, isn't it true that you can't change Y from your metal-rich to your metal-poor groups and have the ZAHB in the same place? Doesn't that set a limit on the range of Y between the two groups?

BUTLER: Yes, but I want to make clear that by "metal-rich" I don't mean solar abundance. The metal-rich stars are only moderately metal rich.

KRAFT: You say that the magnitudes of the two groups differ by no more than $0\overset{m}{.}1$, on the average. To what change in Y does this correspond?

BUTLER: Oh, to a ΔY of about 0.02 or 0.03.