THE ASTROPHYSICAL JOURNAL, 201:L71–L74, 1975 October 15

THE CHEMICAL INHOMOGENEITY OF OMEGA CENTAURI

K. C. FREEMAN AND A. W. RODGERS
Mount Stromlo and Siding Spring Observatory, Research School of Physical Sciences, Australian National University
Received 1975 June 2; revised 1975 July 14

ABSTRACT

Observations of 25 RR Lyrae stars in ω Cen have revealed a diversity in the composition of these stars. The composition spread explains the ill-defined giant branch and the existence of M stars in the cluster. The diversity may be due either to variable amounts of giant-branch mixing or to metal enrichment of protostellar gas during the cluster collapse. Among other considerations, the uniqueness of ω Cen leads us to prefer the latter hypothesis.

Subject headings: globular clusters — star formation — stellar evolution

I. INTRODUCTION

Although many properties of globular clusters are now reasonably well understood, some features are not yet explained. These include: (i) The different radial distribution of bright giants and RR Lyrae stars in some clusters (e.g., ω Cen, M3). In some cases this could just reflect dynamical relaxation after mass loss during post-giant evolution. In others, like ω Cen, the relaxation time ($\sim 3 \times 10^9$ years [Peterson and King 1975]) is much longer than the giant–RR Lyrae evolution time ($\sim 10^8$ years [Iben 1974]), so the dynamical explanation cannot be correct. (ii) For several clusters the color of the integrated light changes with radius (Gascoigne and Burr 1957; Chun and Freeman 1975). For at least some of these clusters, realistic dynamical models show that these color changes are too large to be explained by equipartition of energy over stars of different masses (Da Costa, unpublished). (iii) Some clusters with [Fe/H] $\leq$ 1.3, including ω Cen and NGC 6397, ([Fe/H] = −2.0) (Glass and Feast 1973; Hyland and Rodgers 1974), have stars with strong TiO bands. (iv) The color-magnitude diagram for the massive cluster ω Cen shows an unusually broad giant branch (Geyer 1967; Cannon and Stobie 1973).

These four features suggest to us that some globular clusters may be chemically inhomogeneous. In particular, (i) and (ii) may point to a *radial* variation of the mean heavy-element abundance Z within these clusters.

This is a familiar concept for the elliptical galaxies, which share some dynamical properties with the globular clusters. It seems likely that the present chemical abundances (and therefore any abundance gradients) in galaxies were established mainly during their collapse phase (Eggen *et al.* 1962). For galaxies this collapse phase lasts about 10^8 years, which is much longer than the evolution time for the most massive stars (10^5–10^6 years) through which the heavy-element enrichment probably took place. There is strong evidence that globular clusters also collapsed rapidly during their formation (see Freeman 1974). Their collapse time is only about 10^6 years, but this is still long enough for a few generations of star formation to occur and possibly to establish an abundance gradient, as in the ellipticals.

If globular clusters are indeed chemically inhomogeneous, then this could suggest that a significant fraction of their heavy elements is produced by the clusters themselves. This would have important implications for understanding the morphology of cluster color-magnitude diagrams, and for the question of why there are no clusters with [Fe/H] < -2 (cf. Silk and Siluk 1972; Rodgers 1974).

In this *Letter* we describe Ca II K-line measurements for several RR Lyrae stars in the cluster ω Cen. RR Lyrae stars have probably not experienced any significant internal mixing (for an alternative view see Rood 1970), so the K-line strengths give a measure of the [Ca/H] value at the time of their formation. We can then use these [Ca/H] values to give a rather direct estimate of the cluster's chemical inhomogeneity.

II. OBSERVATIONS

The cluster variables selected for observation were taken from Martin's (1938) discussion of the photometry of variable stars in ω Cen. Type *a*, *b* variables were preferred over type *c* because of their generally lower temperatures and hence stronger K line, thus minimizing the influence of a variable interstellar K component. The stars observed were also chosen not to have nearby cluster giants which would contaminate line strengths observed in the RR Lyrae stars.

The observations consist of spectrograms with dispersion of 100 Å mm^{-1} obtained with the 74-inch (1.9 m) reflector at Mount Stromlo and the Anglo-Australian Telescope at Siding Spring, both having a resolution of 3 Å. In the former spectra Hγ is unmeasurable due to pollution by city lights. The AAT spectrograms were obtained during the AAT commissioning period. For the spectra of these stars near the cluster center, a moonlight eliminator with a 1".4 × 1".5 aperture was successfully employed to reduce the cluster background and the effects of its nonuniformity.

In Table 1 we present the journal of observations with Julian Date and phase of each observation computed according to the ephemerides given by Martin.

Exposure times were typically between 60 and 150 minutes. Equivalent widths of the lines Hβ λ4861,

TABLE 1

JOURNAL OF OBSERVATIONS

Star	Plate No	JD 2440000+	Phase
7	CA 947	2568.131	0.85
27	CA 938	2567.126	0.17
32	CS3791	2520.989	0.55
38	CS3792	2521.034	0.07
55	CA 945	2568.044	0.19
63	CA 941	2567.903	0.17
69	CA 943	2567.960	0.40
74	CS3793	2521.083	0.81
79	CA 946	2568.061	0.42
84	CS3738	2490.934	0.28
85	CS3735	2488.120	0.11
89	CA 937	2567.113	0.50
96	CA 935	2567.005	0.76
99	CA 964	2579.002	0.63
114	CA 934	2566.960	0.88
118	CS3362	2129.163	0.25
119	CS3363	2129.243	0.90
119	CS3790	2520.943	0.49
126	CA 942	2567.934	0.91
134	CA 940	2567.879	0.33
136	CA 963	2578.952	0.16
139	CS3379	2188.060	0.99
144	CA 962	2578.933	0.80
144	CA 933	2566.925	0.42
145	CA 936	2567.045	0.22
153	CS3391	2187.892	0.09
160	CS3361	2129.074	0.64

Hδ λ4102, and Ca II K λ3933 were measured and are listed in Table 2. The star numbers are those assigned by Martin (1938).

III. ATMOSPHERES OF THE CLUSTER VARIABLES

Oke *et al.* (1962) and Bessell (1969) have shown that the effective gravity of RR Lyrae stars can be taken to be independent of phase at $\log g = 2.5 \pm 0.3$ between phases 0.2 and 0.8. On the rising branch of the light curve of type *a*, *b* variables a transient increase in effective gravity is observed with an amplitude of $\Delta \log g = 0.5$.

TABLE 2

LINE STRENGTHS IN OMEGA CENTAURI RR LYRAE STARS

Star	Distance (arc min)	Type	W(H)* (Å)	W_o(K) (Å)	[Ca/H]
7	14.7	a	5.0	3.5	-1.2
27	3.5	b	7.1	3.3	-0.9
32	7.5	a	5.1	5.2	-1.1
38	8.3	b	7.3	1.5	-1.6
:55	16.9	a	2.6	13.6	-0.5:
63	18.3	b	4.7	2.4	-1.6
69	18.2	^{a}irr	4.6	1.6	-1.6
74	11.6	a	6.0	1.8	-1.6
79	16.6	a	5.8	3.2	-1.1
84	19.9	a	5.5	7.3	-0.4
85	17.4	a	9.7	2.1	-0.9
89	2.6	c	5.3	4.7	-0.9
96	2.0	a	3.8	5.9	-1.0
99	2.8	a	5.3	5.2	-0.8
114	1.8	a	6.1	1.3	-1.6
118	1.9	a	3.9	4.2	-1.3
119	3.0	c	9.3	3.0	-0.6
119	3.0	c	10.1	1.7	-0.9
126	18.2	c	8.2	1.2	-1.6
134	22.4	a	4.8	3.8	-1.2
136	2.7	c	6.3	1.3	-1.6
139	1.8	a	6.7	1.7	-1.5
144	0.7	b	2.8	8.8	-0.9
144	0.7	b	3.6	7.4	-0.9
145	2.6	c	7.8	1.0	-1.6
153	2.4	c	5.5	4.6	-1.1
160	19.9	c	9.4	2.5	-1.5

*Hγ is not measured on spectra obtained at Mount Stromlo. W(H) is otherwise the mean equivalent width of Hβ, Hγ and Hδ.

Since there is only a slight gravity dependence of the equivalent width of the Ca II K λ3933 line and of the equivalent width of the Balmer lines Hβ and Hδ in the temperature range of the RR Lyrae stars, it is possible to construct a series of relations between W(K) and $[W(\text{H}\delta) + W(\text{H}\beta)]/2$ with [Ca/H] as the dominant parameter which not only described the locus of an RR Lyrae star in the (K line, Balmer line)-plane but also defines the loci of RR Lyrae stars at random phases with a common [Ca/H]. The basic data used in the construction of this relation were outlined by Rodgers (1974); the relation as defined for atmospheres with $\log g = 3.0$ and 2.5 and young disk compositions is shown in Figure 1 together with the corrected data for the ω Cen variables derived from Table 2. There is in the spectra of ω Cen stars a strong interstellar K line component of 1.2 Å equivalent width (Rodgers 1972). This value has been subtracted from the data in Table 2 to be used in the determination of [Ca/H]. Since, in all cases observed, the K line is on the damping portion of the curve of growth, [Ca/H] is simply the logarithm of the square of the ratio of line widths in the cluster variables to those measured in young disc stars.

Table 2 displays the chemical inhomogeneity of ω Cen. An individual result has an uncertainty of ±0.2 in [Ca/H]; however, the data indicate a lowest value of $[\text{Ca/H}] = -1.6 \pm 0.2$ with individual stars having (Ca/H] ranging up to -0.4 ± 0.2. The membership of the stars 84, 85, and 119 was confirmed by radial velocity measurements which agreed with the cluster velocity of $+236 \text{ km s}^{-1}$ to within the measuring error ($\pm 25 \text{ km s}^{-1}$) for a single plate and an assumed velocity curve of cluster variables.

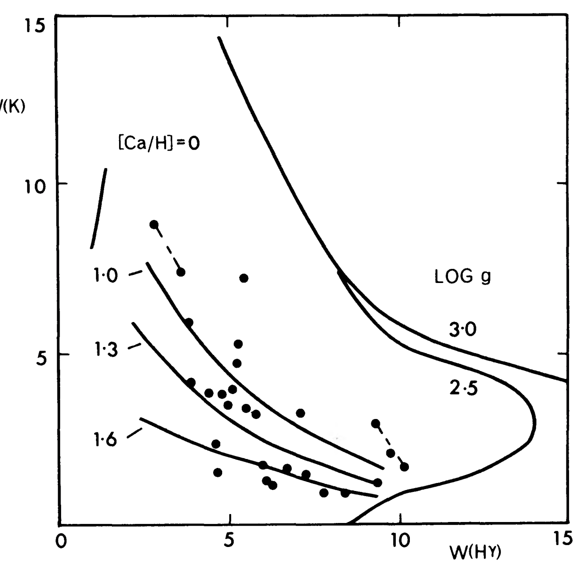

FIG. 1.—The equivalent width of the photospheric K line is plotted against the mean equivalent width of Hδ and Hβ for the ω Cen cluster variables (*dots*). The two full lines marked $\log g = 3$ and 2.5 indicate the loci of cluster variables with Population I compositions. The full line marked $[\text{Ca/H}] = -1.6$ shows the locus for stars calcium deficient by this amount.

IV. DISCUSSION OF THE COMPOSITION SPREAD

The most relevant photometric study of the giant branch of ω Cen is that by Cannon and Stobie (1973). They confirmed Geyer's observations of the excess width of the giant branch and showed that extrinsic causes of the effect were unlikely. Differential reddening, as a cause, is not supported by the tightness of their two-color relation unless $E(B - V)/E(U - B) \approx 2.0$. Differential reddening of 0.2 in $E(B - V)$, required to thin down the giant branch, is not supported by the distribution of blue horizontal-branch stars in the $(U - B, B - V)$-plane observed by Newell *et al.* (1969) wherein a maximum *differential* reddening in ω Cen of $E(B - V) = 0.03$ is indicated.

Cannon and Stobie do not address themselves to the intrinsic causes of the width of the giant branch in ω Cen, though several such causes readily spring to mind. The scatter, once present, in the giant branch probably smears out the demarcation of the asymptotic giant branch from the hydrogen shell-burning stage, and scatter in this prior stage can result from displacement of the Hayashi tracks for individual stars in ω Cen due to mass differences (i.e., noncoevality of the cluster stars), variations in the ratio of mixing length to scale height, composition differences, and perhaps the arcane results of varying rotational velocities as suggested by Caputo *et al.* (1974). It has been found by Dickens *et al.* (1972) that there are some M-type variables in the ω Cen giant branch, and Glass and Feast (1973) show that these stars form an extension of the branch to lower temperatures and lower luminosities. Glass and Feast argue that the similarity of TiO strengths in these stars to Population I objects at the same temperature does not indicate a range of composition in ω Cen since the TiO probably produces its own continuum opacity. In effect they are saying that the TiO is saturated. However, TiO band strengths change rapidly in the temperature range of these stars, so the band or blended line opacity/continuum opacity ratio must also vary rapidly with temperature. This situation does not occur in the case of saturated absorption in which the band strength is determined by the source function at $\langle\tau\rangle \approx 0.6$ and at the stellar boundary. The Stromlo cool-giant model atmosphere calculations show that the ratio of these functions does not change greatly with temperature, and we conclude the TiO bands are not saturated. Therefore there *is* a composition variation in ω Cen. For the purpose of the Ca abundance in horizontal-branch stars in ω Cen this discussion may not be completely relevant since it is possible, as pointed out by Dickens *et al.* (1972), that anomalous abundances of C and hence O affect the TiO abundance. Nevertheless, the simplest interpretation of the M stars in ω Cen is that they are of near Population I composition and lie along the appropriate Hayashi line. Such an Hayashi track may well be defined by the giant branch of a cluster like NGC 6356.

We suppose (assuming again that RR Lyrae stars have not experienced significant internal mixing) the inhomogeneity in composition in ω Cen to be due to the enrichment of its intracluster gas by first-generation nucleosynthesis. We must ask why this phenomenon is apparent in ω Cen and not obvious in other clusters. Stars which do not fall on a unique giant branch can be mistakenly regarded as field stars. This is particularly so in clusters in which differential reddening is high. Little evidence on the composition of giant branch (and asymptotic branch) stars may be garnered from the ultraviolet excess, as this quantity is independent of the composition of halo giants for values of Fe/H significantly less than those found in 47 Tuc; this is clearly seen when giant branches for different clusters are compared in the two-color diagram.

Omega Centauri is among the brightest (and most massive) of the globular clusters. Two other giant clusters, 47 Tuc and NGC 6388, are of similar luminosity ($M_V \leq -9.5$), but both consist of stars which are markedly more metal-rich. It is easy to see that for these clusters metal enrichment during the cluster collapse would be of considerably less observable consequence than in ω Cen. Assume that in the enrichment process in ω Cen the heavy-element yield were sufficient to allow the formation of 5 percent of the cluster stars with solar metal content; then if this same yield were obtained in a metal-rich cluster, e.g., one in which $[Fe/H] = -0.3$, the effects on the Hess diagram of the cluster and the spectra of the individual giants would be much less pronounced.

It seems very likely that by analogy with the correlation between galaxy mass and nucleosynthesis yield, there is a similar relation between the mass and the yield in globular clusters. We therefore hypothesize that heavy-element enrichment occurs in the formation of globular clusters, that it is a function of cluster mass, and that it is most evident in massive, but initially metal-weak, clusters such as ω Cen. According to current wisdom, nucleosynthesis occurs through supernova events. If such events occurred during the formation of a globular cluster, there may be a problem in containing the metals synthesized during the event, because the escape velocity from the cluster is so much less than the characteristic supernova ejection velocities.

There are many implications of the composition spread in ω Cen. For example, Dickens and Woolley (1967) observe an overlap of variable and constant stars at the blue edge of the instability strip; it is likely that this effect arises from differential blanketing. Its presence, however, masks any indication of a range of helium abundance which may occur. Another obvious effect of the chemical inhomogeneity will be upon the luminosities and colors of stars on the main sequences and at the turnoff points in globular clusters.

In the current series of observations, we have not been able to observe the spectra of many RR Lyrae stars close to the cluster center, because of background problems. This has so far prevented us from investigating whether there is in fact a radial variation of composition. We expect that linear TV subtraction techniques recently developed here will allow us to pursue this problem further.

REFERENCES

Bessell, M. S. 1969, Ph.D. thesis, Australian National University.
Cannon, R. D., and Stobie, R. S. 1973, *M.N.R.A.S.*, **162**, 207.
Caputo, F., Castellani, V., and D'Antona, F. A. 1974, *Ap. and Space Sci.*, **28**, 303.
Chun, M., and Freeman, K. C. 1975, to be published.
Dickens, R. J., Feast, M. W., and Lloyd Evans, T. 1972, *M.N.R.A.S.*, **159**, 337.
Dickens, R. J., and Woolley, R. v. d. R. 1967, *R. Obs. Bull.*, No. 128.
Eggen, O. J., Lynden-Bell, D., and Sandage, A. R. 1962, *Ap. J.*, **136**, 748.
Freeman, K. C. 1974, ESO/SRC/CERN conference on Research Programs for the New Large Telescopes (Geneva), p. 177.
Gascoigne, S. C. B., and Burr, E. J. 1956, *M.N.R.A.S.*, **116**, 570.
Geyer, E. H. 1967, *Zs. f. Ap.*, **66**, 16.
Glass, I., and Feast, M. 1973, *M.N.R.A.S.*, **163**, 245.
Hyland, A. R., and Rodgers, A. W. 1974, *IAU Symposium 59, Stellar Instability and Evolution*, ed. P. Ledoux (Dordrecht: Reidel).
Iben, I. 1974, *Ann. Rev. Astr. and Ap.*, **12**, 215.
Martin, W. Chr. 1938, *Leiden Ann.*, Vol. **17**, Part 2.
Newell, E. B., Rodgers, A. W., and Searle, L. T. 1969, *Ap. J.*, **158**, 699.
Oke, J. B., Giver, L. P., and Searle, L. 1962, *Ap. J.*, **136**, 393.
Peterson, C. J., and King, I. R. 1975, *A.J.*, in press.
Rodgers, A. W. 1972, *Ap. J.*, **171**, 257.
———. 1974, *ibid.*, **191**, 433.
Rood, R. T. 1970, *Ap. J.*, **162**, 939.
Silk, J., and Siluk, R. S. 1972, *Ap. J.*, **175**, 1.

K. C. Freeman and A. W. Rodgers: Mount Stromlo and Siding Spring Observatory, Private Bag, Woden P.O., A.C.T., Australia, 2606