

CEPHEIDS OF THE DISK AND HALO

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HISTORICAL REVIEW

In 1888, soon after the Great Blizzard swept New York and Boston, E. C. Pickering sent his brother, W. H. Pickering, to a mountain in California as a possible site for a large telescope to be run by the Harvard College Observatory (Pickering 1889). With a 13-inch refractor they found the seeing to be exceptionally good on Wilson's Peak and hence discovered a variable star near the center of M3. It is now known as #154 and has a period of 15 days. The prototypical population II Cepheid in the field, W Virginis, had been discovered in 1866 by E. Schönfeld. However, it was 50 years after Pickering's discovery that differences between W Vir and other Cepheids were recognized by Joy (1937) who called attention to the star's high velocity, high proper motion, and the presence of hydrogen emission lines during rising light (though he did not mention its high galactic latitude). The importance of the dichotomy among the Cepheids was recognized by Baade (1952) when he suggested that the Cepheids in the globular clusters were intrinsically different from the field stars and could not be used to calibrate the period luminosity relation of classical Cepheids. Incidentally, Baade's correction to the distance scale raised the age of the Universe from 1.8×10^9 years to about 3.6×10^9 years.

Following many discoveries of Cepheids in globular clusters by Dr. H. S. Hogg the first general survey of light curves was by Arp (1955) who obtained photographic light curves in m_{pg} and m_{pv} for 18 Cepheids in the globular clusters observable from Mt. Wilson. A repetition using CCD's would be very useful to establish changes in periods over the 40 year interval since Arp's survey. The spectroscopic survey by Joy (1949) has never been repeated and would provide high quality data if redone with CCD's and a modern classification scheme to derive metallicities as well as radial velocities. In the general field, photoelectric light curves have been published for many Cepheids by Kwee and Braun (1967), Harris (1981) and Diethelm (1986). Some image tube spectroscopy is available by Harris and Wallerstein (1984) for the longer period stars but only a few complete velocity curves were covered and almost no observations at $H\alpha$ were obtained for any of the stars. Such surveys could be carried out with telescopes of about one meter size; large instruments are not necessary.

POPULATION CHARACTERISTICS

There is no entirely adequate definition of population II Cepheids. Some reasonable ones are:

1. Variables in globular clusters with periods between one and forty days and similar stars found elsewhere.
2. Variables with periods between one and forty days that would lie at least 350 parsecs (or some other specified distance) from the Galactic Plane if classified as classical Cepheids.

Of course, a few type II Cepheids will lie close to the plane and a few classical Cepheids may lie far from it if they are derived from run-away B stars. Also there is no reason to relate the classification of a variable star to the spin period of the earth; perhaps a period of 0.77 days is more significant because that is the upper limit in period of normal RR Lyrae stars in the field (Preston 1959).^{*} The phrase "similar stars" in the definition leaves open to judgement which property must be similar. Lastly is the question of whether or not to include the RV Tau stars or which subgroup of RV Tau stars should be included.

It is easiest to define type II Cepheids by their location in the color-magnitude diagram than by their light curves, spectra, etc. They lie very nearly 1.5 mag below the classical Cepheids; but this definition is useful only for stars of known distance (Wallerstein and Cox 1984).

In the real world, where do we find them?

1. Globular Clusters: About 46 type II Cepheids are known in globulars (Harris 1985, Table 1). Only globulars with blue horizontal branch stars have Cepheids; clusters like 47 Tuc do not. Within the globulars the Cepheids group themselves by period. Stars with 1-5 day periods and 12-35 day periods are common. There is one star in the gap, M10 #3, with a period of 7.9 days. It is subluminous for its period and its membership and period should both be verified. For periods beyond about 25 days the light curves show alternating minima much like RV Tau stars with ω Cen #1 and M2 #11 appearing to be "real" RV Tau stars, *i.e.*, they misbehave as well as alternate.
2. Our Galaxy: In the field of our Galaxy we see all the above plus additional stars that confuse the classifier. For periods of 1-5 days both metal-weak and metal-strong spectra are common. Stars in this group have been further subdivided according to colors, which indicate metallicity, into three subgroups (Diethelm 1990). Stars with low metallicities, *i.e.*, $[\text{Fe}/\text{H}] \simeq -2$ are rare. Type II Cepheids with periods of roughly 6-11 days are all normal or possibly rich in metals. They are absent in globulars (except for M10 #3) and must constitute a disk population or else be outliers of the Galactic bulge population. In the 12 to roughly 35 day interval of period stars similar to those in the globulars are found but metal-rich stars are also seen in

* The globular cluster Omega Centauri has RR Lyrae stars of longer period.

the field especially in the direction of the Galactic center. From the data in Table II of Harris and Wallerstein (1984) some correlations of metallicity with position in the Galaxy are evident. For stars with $|Z| > 2$ kpc $[\text{Fe}/\text{H}] = -1.3 \pm 0.26$ ($n=10$); for $2.0 > |Z| > 0.9$ kpc $[\text{Fe}/\text{H}] = -0.9 \pm 0.19$ ($n=10$); for $0.9 > |Z| > 0.4$ kpc $[\text{Fe}/\text{H}] = -0.3 \pm 0.12$ ($n=18$); for $|Z| \leq 0.4$ kpc $[\text{Fe}/\text{H}] = -0.1 \pm 0.12$ ($n=12$); while for the Galactic bulge, defined by $|\ell| < 20^\circ$ and $|b| < 20^\circ$, $[\text{Fe}/\text{H}] = -0.6 \pm 0.14$ ($n=16$).

Around 35 days the same transition to RV Tau characteristics takes place as in the globulars. In the field, however, the metal-poor RV Tau stars similar to those seen in globulars are rare. More common are the strong lined stars which often show exceptional strength of CN bands or TiO bands near minimum. Also present are a group of weak-lined stars like AC Her which show strong CN near minimum light. The populations and origins of the last two groups of stars are unknown.

3. The Magellanic Clouds: About 20 type II Cepheids have been recognized in the LMC and four in the SMC. All have periods of the W Vir subtype; fainter short period Cepheids of type II have not yet been recognized. Clearly all such candidates deserve study with CCD detectors to overcome the crowding problem, determine absorption corrections and derive metallicities. The only modern data for these stars are some JHK photometry by Welch (1987).
4. Fornax System: At least two Cepheids of the W Vir type have been found in this loose elliptical. Interestingly it is the only loose elliptical companion to our Galaxy that contains globular clusters. One of the Cepheids is very likely to be a member of one of the globulars (Light, Armandroff and Zinn 1986).
5. Andromeda Nebula: A total of 16 candidates have been located by Baade and Swope (1963, 1965) in their Cepheid fields. Because they are close to their limiting magnitude and seem to show peculiar lightcurves they call them "population II variables" rather than Cepheids; some may be RV Tau stars or semi-regular variables. Obviously multi-color CCD data are called for in these crowded fields at magnitudes of 21-23.

EVOLUTION

The calculation of the evolution of stars into the Cepheid instability strip of the HR diagram is not an easy task. Most of the calculations have been carried out by Gingold and reviewed by him (Gingold 1985). The calculation must start with a model on the zero-age horizontal branch. Such models are parameterized by total mass, core mass, $[\text{Fe}/\text{H}]$, $[\text{CNO}/\text{Fe}]$ and perhaps envelope He abundance. Hence, much computing time is necessary. Since the abundance of nitrogen can exceed that of oxygen in strong CN stars such as those in M22 (Brown, Wallerstein and Oke 1990) clusters with a strong dichotomy in CN strength may have differing evolutionary paths for otherwise similar stars. With so many parameters and the likelihood of helium flashes a lot of computing time is required.

There are three paths by which a post-horizontal branch star can cross the instability strip:

1. Very blue HB stars with thin hydrogen envelopes may evolve toward larger radii and higher luminosity temporarily until the hydrogen burning shell consumes most of the envelope. They then turn back to the blue in the HR diagram and begin their descent into oblivion as white dwarfs. During this evolution they may cross the instability strip twice or may turn around within the strip. All of this occurs at low luminosity yielding pulsation periods less than about five days. The fact that short period Cepheids in globular clusters show either increasing or constant periods indicates that most are evolving to the red (Wehlau and Bohlender 1982).
2. Stars with sufficiently thick hydrogen envelopes reach the asymptotic giant branch (AGB) and advance up it to larger radius. After a while helium shell flashes develop and during the shell flash the radius shrinks and the star makes an excursion to higher effective temperature thereby entering, or possibly even crossing, the instability strip. Such stars should pulsate with periods in the range of roughly 12-25 days and may be the commonly seen W Vir stars in globular clusters. It is unclear how often an individual star will make this excursion nor is the time scale of events and, hence, predicted period changes easy to calculate because of the sudden onset of convection during the helium flash. Standard mixing length theory cannot be expected to handle sudden events with very large initial temperature gradients. In fact the convection itself may bring additional fuel into the burning shell and, hence, strongly effect the subsequent evolution.
3. After evolving up the AGB a star will eventually deplete its hydrogen envelope by a combination of mass loss and shell burning. The remaining star will shrink and begin its long march to the hot subdwarf and white dwarf region. On its way it must once again cross the instability strip, now at higher luminosity and longer period, roughly 25-50 days, where the RV Tau stars are found. This phase of evolution must be rapid since RV Tau stars are rare in globular cluster and only one post RV Tau star at sufficiently high luminosity has been recognized in a globular cluster, RGO 24 in ω Cen. All such stars should show increasing periods, as do several RV Tau stars in the general field. The presence of detached cool dust shells in field RV Tau stars (Jura 1986) confirms this picture for some field stars and one star in a globular cluster (Cardelli and Nook 1989).

CHEMICAL COMPOSITION

Variable stars offer both a challenge and an opportunity in the derivation of their chemical compositions. The challenge is obvious because the real star and the adopted model atmosphere are not likely to be as similar as they are for nonvariable stars. In addition to the fact that the pulsation is likely to upset the normal temperature gradient in the star, the boundary temperature may be effected by pulsationally induced mass loss, the effective gravity may

be upset by the pressure wave and the “elevator effect” when the atmosphere is falling into the star, and worst of all the radiation field may be effected by a shockwave either within or below the visible atmosphere. Radiation from the shock, especially Lyman lines of H and perhaps strong resonance lines of He may be scattered into the atmosphere where they can cause departures from LTE in the ionization. Selective excitation of certain levels that are well known in long period variables may be occurring at more subtle levels, *i.e.*, to weaken an absorption line rather than turn it into an emission line, in Cepheid atmospheres.

However, there are compensating factors. The change in effective temperature around the cycle permits the reliability of the analysis to be evaluated because the composition must remain constant as the atmospheric parameters change.

The rewards of successful analyses of Cepheid atmospheres are great because Cepheids, both of types I and II, are probes of our Galaxy at large distances where other methods of analysis are difficult to pursue and where other stellar types are at uncertain distances.

A. Metal Abundances

The standard parameter for metallicity in most population studies is $[Fe/H]$ where the brackets indicate the logarithmic difference with respect to the sun. Recently the use of $[O/H]$ has been noted as a more fundamental parameter, which it is, but the oxygen abundance is often more difficult to measure. Five type II Cepheids have been analyzed for $[Fe/H]$ yielding values from +0.1 to -1.0 (summarized by Luck and Bond 1989). Clearly none is as metal-poor as the globular clusters in which Cepheids are found, *i.e.*, $[Fe/H] = -1.2$ to -2.0 . For five RV Tau stars Luck and Bond find $[Fe/H]$ ranging from -0.8 to -1.4 , but the complexity of their atmospheres introduces a substantial uncertainty in those numbers, especially for the so-called “strong-lined” RV Tau stars U Mon and R Sct.

Using field Cepheids of known metallicity and Cepheids in globular clusters of known metallicity it is possible to calibrate photometric systems which can then be applied to many stars (Harris 1981). For the longer period stars the Washington system of photometry yields reasonably accurate $[Fe/H]$ values though it loses sensitivity for the short period, and hence, hotter stars. Other systems such as the Strömgren system or the Walraven system may be preferable for the hotter stars (*e.g.*, Diethelm 1990). There remains the question of identifying both calibration standards and Cepheids with $[Fe/H] \lesssim -2.5$ since some red giants and a few subdwarfs are known to have such large metal deficiencies.

B. O/Fe Values

The oxygen abundance is particularly important in all population II stars because it is usually less depleted than is iron and, hence, is an important contributor to the continuous opacity at depths below which helium is completely ionized and above which oxygen itself is completely ionized. Furthermore, oxygen is representative of the CNO group whose abundance determines the rate of hydrogen burning in the hot shell between the outer hydrogen envelope and the intermediate helium region in HB and AGB stars.

Oxygen abundances have not been obtained for any type II Cepheid. The coolest stars might show the [OI] line at 6300 Å near minimum light. The highly excited lines at 7775 Å and 8446 Å should be present in short period Cepheids but suffer such large departures from LTE even in nonvariable stars that they are not likely to be useful for abundance in variables.

C. The Carbon Abundances

Though RU Cam, a high latitude Cepheid of period 22 days, was long known to be an R-type star at minimum light, its significance was not understood until Lloyd Evans (1983) called attention to its membership in a group of seven carbon-rich type II Cepheids. The relationship between these stars – two with periods near two days and five with periods between 20 and 32 days – to the carbon-rich RV Tau stars is unclear. Recent observations of one of the coolest of the group, DI Car, by Lloyd Evans (private communication) shows that it has strong isotopic bands and, hence, a low ratio of $^{12}\text{C}/^{13}\text{C}$. A preliminary analysis of RU Cam also showed high ^{13}C (Wallerstein 1968). Quantitative analyses of these stars with modern detectors and appropriate models may be very rewarding, though surely very difficult. These carbon-rich Cepheids are clear evidence that they are post-helium-flash stars. For the stars of period 20-32 days they confirm Gingold's calculations – perhaps with a little extra mixing; but the origin of the excess carbon in the stars with periods near two days is not evident.

D. S – Process Abundances

To those who are concerned with the big problems of the helium abundance in the Universe or the enrichment of our Galaxy in oxygen and iron, the origin of the s-process elements must sound like a description of torpedo boat actions during the battle of Jutland. However, the s-process elements provide important clues to stellar evolution especially when they are convected to the stellar surface. In the type II Cepheids a deficiency of the s-process elements relative to iron appears to be present (Luck and Bond 1989). They have reanalyzed Kappa Pav, quoted other analyses of four type II Cepheids and added several RV Tau and related variables to their data base. They show [s/Fe] ratios of roughly -0.7 for [Fe/H] ratios between 0 and -1.5 . Such values of [s/Fe] are more commonly seen in nonvariable red giant with [Fe/H] in the range of -2 to -3 . In my opinion these deficiencies are only apparent because both europium and scandium partake in them and neither is an s-process element as shown by their lack of enhancement in Ba stars and S stars. Most likely the deficiencies are due to excess second ionization probably due to scattered Lyman photons originating in the stellar shockwave, a possibility which Luck and Bond discuss. Their alternative hypothesis that these stars are now drastically hydrogen deficient and originally had [Fe/H] in the -2 to -3 range is difficult to sustain in view of the H/He ratio in W Vir which we will now discuss.

E. The Helium Abundance

Only in highly evolved hot subdwarfs and in planetary nebulae is it possible to derive the helium abundance in old stars. However, the presence of

helium emission from the shockwave in W Vir stars permits an analysis of the He/H ratio provided that the shock velocity can be obtained by an analysis of the observed radial velocities and the radiative transfer of the hydrogen lines, which are optically thick, can be handled. Following a very preliminary effort in that direction that yielded a ratio of He/H in the range of 0.1 to 0.3 (Wallerstein 1959) Raga *et al.* (1989) have performed a far more detailed analysis based on Palomar CCD spectra taken on four nights during rising light of W Vir. As with absorption line analyses the solution must be constrained to keep the abundance ratio constant with phase while permitting the physical conditions to change within expected limits. Their ratio of 0.12 with a possible range from 0.08 to 0.18 may be compared with the accepted ratio for the early Universe of 0.08 indicating a small but probably significant enhancement of helium in the atmosphere of W Vir. The range of He/H ratios in planetary nebulae are similar showing, perhaps, that the loss of the atmosphere of W Vir would yield a planetary of reasonable composition. The very high helium suggested by Luck and Bond is not confirmed. In fact, stars with atmospheres of 90% He would pulsate quite differently than do the type II Cepheids due to the difference in specific heats as compared with stars with the derived helium abundance of W Virginis.

I am pleased to thank the Sternwarte of the Institut für Astronomie und Astrophysik der Universität München for hospitality in May 1990 during which time this review was prepared.

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DISCUSSION

A. K. Dupree: Are there any indications of high temperature material in the W Vir stars? The presence of HeI, 10830 Å, ultraviolet emission or X-rays would indicate the level of excitation and assist in deriving the helium abundance?

G. Wallerstein: No W Vir star has been seen in X-rays. The X-ray source in the center of M15 is close to the only W Vir star in the cluster but most speculations favor a black hole or close binary for the X-rays. No one has looked for 10830 because all of these stars except for Kappa Pav are faint and even CCD detectors are not very sensitive there. Low resolution IUE spectra by E. Böhm-Vitense do not indicate emission lines except possibly for CIII] in ST Puppis. Ly- α is swamped by geo-coronal emission.

H. Harris: In order that the relative numbers of RV Tau stars and HB stars in globular clusters be consistent with their lifetimes, the RV Tau lifetime should be roughly 10^6 years. Perhaps the period changes do not indicate the evolutionary time scales, or perhaps fielded RV Tau stars have shorter lifetimes than those in clusters.

A. Wehlau: It is interesting that the one RV Tau star in a globular cluster to show an IR excess is in M28, the most metal-rich cluster to contain an RV Tau star.

A. Cox: Why are the UU Her stars, which appear to be of small mass and are located at high galactic latitude, not in the instability strip?

G. Wallerstein: Perhaps they have a high helium content, as suggested by Luck and Bond (1989). In any case, that might be a good problem for your next postdoc.