ANOMALOUS CEPHEIDS AND POPULATION II BLUE STRAGGLERS

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Abstract. Recent studies of anomalous Cepheids (ACs) and Pop II blue stragglers (BSs), including photometrically variable BSs (VBSs), are reviewed. The VBSs represent about 25% of the BSs, the majority of which are SX Phe short-period variables in the Cepheid instability strip. Mass estimates derived using various techniques suggest that both ACs and BSs are relatively massive (about 1.0-1.6 $M_\odot$). The recent discovery that two BSs in the globular cluster NGC 5466 are contact binaries, and the earlier discovery that one of the BSs in ω Cen is an eclipsing binary, provide direct evidence that at least some BSs are binary systems. If all BSs are binaries, and the time scale for coalescence is a few Gyr, then the majority are likely to be coalesced. Because ACs and BSs are found in the same stellar systems, and are probably related through their evolution, it is highly likely that most ACs are also coalesced binary systems. The fact that ACs and BSs are found only in low density environments, suggests that they were primordial binaries.

1. INTRODUCTION

Anomalous Cepheids and Population II blue stragglers have several features in common, most notably, proliferation in low density stellar environments (such as low central concentration globular clusters and Local Group dwarf galaxies), and relatively large masses, about 1.3 $M_\odot$ (Christy 1970; Zinn & Searle 1976). Since their discovery over 30 years ago, various single and binary star models have been proposed to explain the structure and evolution of both types of stars. One of the first and most obvious models is that they are massive single stars of intermediate age (i.e. a few Gyr). Such a model seems plausible for the BSs in open clusters (see Eggen & Iben 1988), and for the BSs and ACs in those luminous dwarf spheroidal galaxies that contain a substantial population of young stars (Mould 1983; DaCosta 1988), but is less convincing when it comes to explaining the large number of BSs that are found in about 15 Gyr old globular clusters, such as NGC 5466 (Nemec & Harris, 1987) and NGC 5053 (Nemec & Cohen 1988), that show little evidence of recent star formation. On the other hand, it is not necessary to assume that BSs and ACs are much younger than the systems in which they are found if they are relatively massive stars whose lifetimes were extended through mixing (McCrea, 1964; Wheeler 1979; Saio & Wheeler 1980; Da Costa & Demarque 1982; VandenBerg & Smith 1988).

McCrea (1964), and later van den Heuvel (1968) and Collier & Jenkins (1984), considered the possibility that BSs are close binary systems in which mass transfer has occurred between the evolving component stars. Under the assumption that the stars form with initially unequal masses, these studies found that a blue straggler sequence can be explained, and that the sequence could extend about 2.5 magnitudes above the main sequence turnoff. The influence of mass exchange on the orbital period of the binary system was also investigated. Renzini, Mengel & Sweigart (1977; hereafter RMS) were the first to demonstrate that a mass transfer model can explain both BSs and ACs, provided that the initial separation of the component stars is appropriate, i.e. during the red giant phase of the original secondary, mass is not transferred back to the the original primary (Norris & Zinn 1975). RMS predicted that because the frequency of stellar collisions in globular clusters increases with stellar density, ACs and BSs ought to be found preferentially in low density environments. They also predicted that the ratio of the number of BSs to ACs in the same stellar system should be greater than the ratio of the respective lifetimes, which they estimated to be in the range 1-10. This prediction provides a useful test of the binary hypothesis (see Nemec, Wehlau & Oliveira 1988; hereafter NWO). In the limiting case, it has been suggested that BSs are coalesced stars, which were originally detached binary systems (Zinn & Searle 1976; Webbink 1976a,b, 1979; Wallerstein & Cox 1984; Campbell 1986).

Further information on the theoretical models for ACs and BSs can be found in the reviews by Zinn (1980,1985), Hirshfeld (1980), Da Costa, Norris & Villumsen (1986), Nemec & Harris (1987), Harris (1987) and Da Costa (1988b). The emphasis of the present review is on recent observational developments concerning ACs (§2), BSs (§3), and variable BSs (§4).

2. ANOMALOUS CEPHEIDS

"The cause is hidden, but the result is well known."
Ovid (Metamorphoses IV, 287)

Baade & Swope (1961), van Agt (1967, 1968), and Swope (1968) recognized from their pioneering studies of the variable stars in the Draco, Ursa Minor and Leo II dwarf galaxies that there exists in these galaxies a population of Cepheid-like variables that does not follow the period-luminosity (P-L) relationships of Pop I and Pop II Cepheids. These stars have become known as "anomalous Cepheids" (Norris & Zinn 1975; Zinn & Searle 1976). Unlike globular cluster Cepheids, which typically have masses appropriate for single stars in post-horizontal-branch evolutionary phases, i.e. M approximately 0.6 $M_\odot$ (Böhm-Vitense et al. 1974), the pulsational periods of ACs require that their masses be about 1.2 to 1.8 $M_\odot$ (Christy 1970; Norris & Zinn 1975; Demarque & Hirshfeld 1975; Zinn & Searle 1976; Zinn & Dahn 1976).

Over 50 ACs are known, almost all of which are located in the nearest Local Group dwarf galaxies. The only AC to have been identified in a galactic globular cluster is V19 in NGC 5466 (Zinn & Dahn 1976, Zinn & King 1982). A list of ACs, and their properties, is given in Table IX of NWO. The only nearby dwarf spheroidal galaxy whose variable stars have been completely surveyed for periods is Ursa Minor.

Much work remains to be done identifying ACs in other nearby dwarf galaxies (such as the Fornax dwarf galaxy; Demers & Irwin 1987, 1989), as well as in more distant Local Group dwarf galaxies (such as the three dwarfs spheroidals in the direction of M31; van den Bergh 1972a,b). The ACs in other environments, such as the Small and Large Magellanic Clouds (see Smith & Stryker 1986) have been studied to some degree; however, further study would be valuable.

2.1 Periods, Luminosities and Pulsation Modes

The shortest and longest period ACs have periods of 0.26 day (V69 in Carina) and 2.37 day (V8 in Leo I), with a uniform distribution of periods throughout this range. Absolute B magnitudes of ACs, assuming that the mean M_B level of the RR Lyrae stars in each system is 0.80 mag, range from a high of $M_B = -1.7$ (again, V8 in Leo I) to a low of $M_B \sim +0.5$ (several stars).

Since the first anomalous Cepheids were discovered, the determination of their pulsation modes has been a major source of uncertainty in deriving their masses (see Wallerstein & Cox 1984; Cox & Proffitt 1988). By assuming that the degree of symmetry of the light curve depends on the pulsation mode and on the T_{eff} in the same manner for ACs as for RR Lyrae stars, Zinn & Searle (1976) suggested that among the ACs in the Draco dwarf galaxy, V141 and V157 pulsate in the fundamental mode, and V134 and V204 pulsate in the first-overtone mode. Support for this suggestion was provided by RMS, who showed that the location of the first-overtone blue edges (for models with helium abundance Y = 0.2 and 0.3, and an assumed mass of 0.65 $M_\odot$) were consistent with the above pulsation mode assignments.

It is often assumed that ACs define a single P-L relationship. Figure 1 shows the P-L diagram constructed by NWO (with minor changes, as noted in the figure caption), illustrating that the best studied ACs obey one of two distinct P-L relationships: $M_B = -2.294 \log P - 0.374$, (with a standard deviation of the individual points about the adopted regression line of only $\sigma = 0.11$ mag), or $M_B = -4.213 \log P - 1.498$ ($\sigma = 0.09$ mag). The small dispersions about the two lines suggest that the assumed M_B values (hence the distance estimates to the various dwarf galaxies) must be approximately correct. NWO associate the first of the two relationships with fundamental mode pulsation, and the second with first-overtone pulsation. The pulsation modes for the Draco variables mentioned above, and for V19 in NGC 5466, can be read from Figure 1. These agree with the modes determined by Zinn & Searle (1976) and Zinn & King (1982), respectively. Thus, it follows that period and M_B information alone may be sufficient for determining pulsation mode. If this is the case, the pulsation modes for the Sculptor, Fornax and Ursa Minor variables, which were previously unknown, can be read from the graph. Of course, at the lowest luminosities where the two lines merge the pulsation modes are uncertain.

It is obviously of interest to compare the observed P-L relationships (Figure 1) with the P-L relations predicted by the fundamental equations of stellar pulsation appropriate for ACs. The best theoretical estimates of the coefficients in the pulsation equations are those given by Cox (1987), which for the King Ia composition ($Y = 0.299$, $Z = 0.001$) including the effects of convection, are:

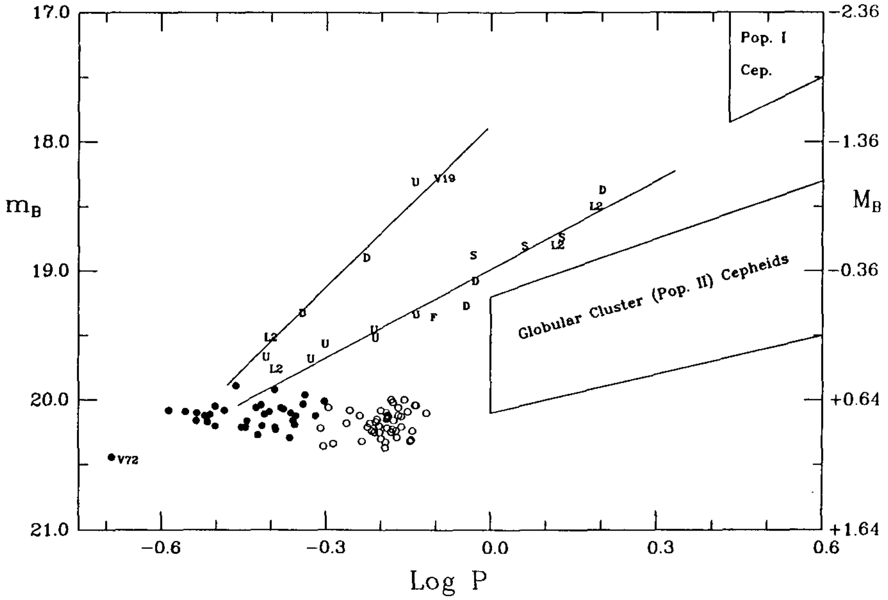
$$\log P = 11.331 - 0.655 \log M/M_\odot + 0.829 \log L/L_\odot - 3.430 \log T_{eff}$$

for the fundamental mode, and

$$\log P_1/P_0 = -0.4227 + 0.0438 \log M/M_\odot - 0.0240 \log L/L_\odot + 0.0806 \log T_{eff}$$

for the ratio of the first-overtone to fundamental-mode periods. In the absence of bolometric corrections for the anomalous Cepheids, the

Figure 1. Log P vs. M_B for 21 well-studied ACs. Also shown in the figure are the RR Lyrae stars in Ursa Minor, and schematic outlines of where Pop I and Pop II Cepheids would lie. (Note: Several minor errors were made in Table IX and Figure 13 of NWO. For the three Sculptor variables, V25, V26 and V119, the $<m_B>$ should have been 19.10, 18.96 and 19.03, and the M_B should have been -0.48, -0.62 and -0.55:, respectively. For the 9 Carina ACs the M_B should have been -0.05, -0.13, -0.68, -1.03, -0.06, +0.10, -1.21, -0.93, +0.15. For V149 in Carina, $<m_B>$ should have been 20.35; and, for NGC5466-V19 M should have been -1.07. The equations of the P-L relations given above are the corrected equations. The main conclusions reached by NWO are unchanged).



observed (log P)-M_B relations cannot be directly compared with the model results. However, luminosities are known from spectroscopic observations for NGC 5466-V19, and for the ACs in Draco (Searle & Zinn 1976). Assuming the pulsation modes given above, the following P-L relations were derived:

$$\log(L/L_\odot) = 2.226 + 1.412 \log P,$$

with $\sigma = 0.003$, for the three fundamental-mode ACs in Draco; and

$$\log(L/L_\odot) = 2.537 + 1.436 \log P,$$

with $\sigma = 0.007$, for NGC5466-V19 and the two first-overtone ACs in Draco. Note that the two lines are approximately parallel, and that the observed slope is in approximate agreement with the slopes 1.24 and 1.21 predicted for the first-overtone and fundamental modes, respectively.

2.2 Light Curves of Anomalous Cepheids

The pulsation of ACs in the fundamental and first-overtone modes is expected to lead to a dichotomy in the morphology of their light curves. To investigate this, the Fourier decomposition technique (see Simon & Lee 1981) is presently being used to evaluate the shapes of the light curves of ACs (Simon & Nemec, in preparation). Some preliminary results for the ACs in Ursa Minor are given in Table 1. Column (7) gives R_{21}, which is the ratio of the second largest to the largest amplitude of the fitted sinusoids. In other types of stars, such as dwarf Cepheids (see Fernley et al. 1987), it is found that the R_{21} ratio is large for fundamental mode pulsators, and small for first-overtone pulsators. The same appears to be true for ACs. The five stars in Table 1 with large R_{21} ratios do, in fact, lie along the fundamental mode relationship in the P-L diagram, and the star V6 lies along the first-overtone P-L line. The two stars V59 and V80 stand out in that they have intermediate R_{21} values, which makes it difficult to assign a mode. In Figure 1 it is also difficult to assign a mode since they have relatively low luminosities. The light curve of V59 is

Table 1.
Fourier coefficients for anomalous Cepheids in Ursa Minor

Star (1)	Pulsation Mode (2)	Period (days) (3)	A_B (4)	<B> (5)	R_{21} (6)	Φ_{21} (7)	R_{31} (8)	Φ_{31} (9)	Φ_{41} (10)
59	F	0.389981	1.59	19.70	0.37	3.91	0.08	1.87	0.64
1	F	0.470	1.13	19.64	0.57	3.93	--	--	--
80	?	0.498746	0.52	19.50	0.28	4.68	0.10	4.34	--
11	F	0.675	1.53	19.43	0.41	3.68	0.22	1.77	--
56	F	0.612494	1.65	19.34	0.50	3.67	0.35	1.58	--
6	H	0.725586	0.93	18.26	0.16	4.34	0.10	2.23	--
62	F	0.729	1.68	19.33	0.46	3.87	--	--	--

asymmetric and appears to be that of a fundamental mode pulsator. V80 has been problematic for some time; Kholopov suggested that it might be an eclipsing binary, but this remains to be seen. Further observations of V59 and V80 may help resolve these problems.

2.3 Masses of Anomalous Cepheids

The derivation of masses for ACs, using the fundamental equation of stellar pulsation, and T_{eff} and log g information, depends on knowledge of the pulsation modes of the stars. Zinn & Searle (1976) derived masses for the ACs in Draco, assuming pulsation modes based on T_{eff} , L, and an examination of the associated light curves, and derived masses ranging from about 1.0 to 1.8 $M_\odot$. Hirshfeld (1980), Wallerstein & Cox (1984) and Cox & Proffitt (1988) analyzed the same data and confirmed the masses derived by Zinn & Searle. However, the mass estimates would have been considerably different if the assumed pulsation modes were incorrect. For example, if the pulsation is in the first-overtone or the second-overtone mode, and not the fundamental mode, the derived mass drops by a factor of about 1.6 or about 2.5, respectively, from the fundamental mode value. Thus, uncertainy in the pulsation mode translates into a large uncertainty in the corresponding mass.

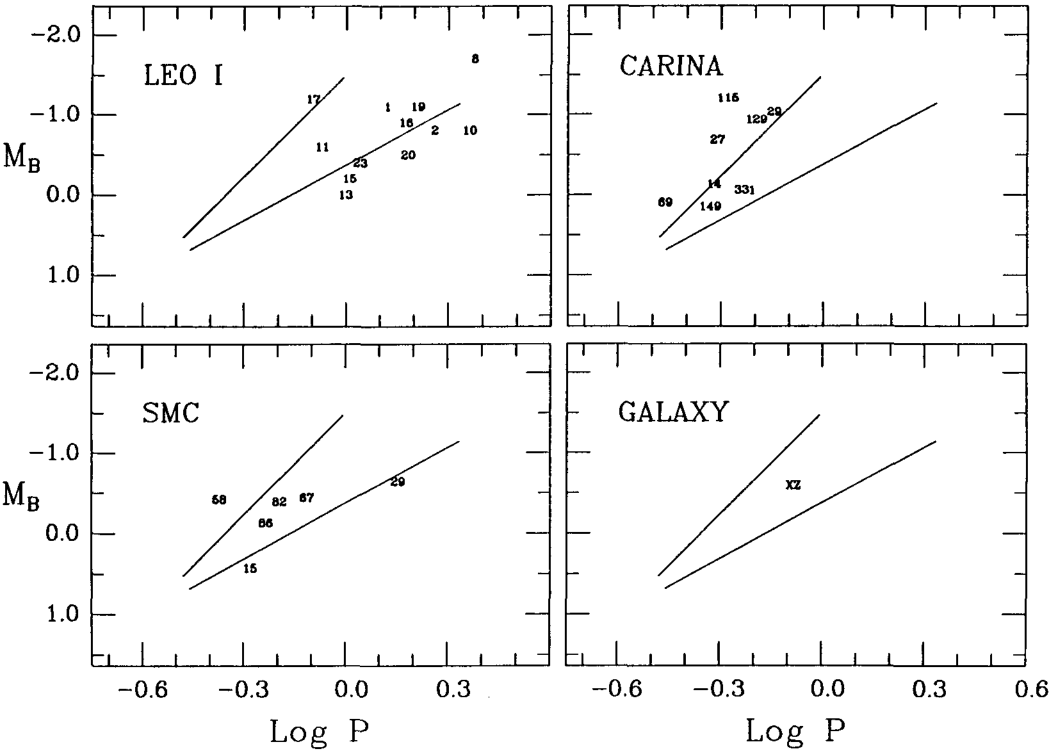
With the recent observation that fundamental and first-overtone pulsators separate in the P-L plane, and the development of Fourier methods for discriminating between the two groups, the pulsation modes, and hence the masses, of ACs can now be derived with confidence. Using the T_{eff} and log g values given by Searle & Zinn, and pulsation modes based on the P-L diagram, NWO determined that the minimum, maximum and mean masses for the five ACs in the Draco dwarf galaxy are 1.04, 1.77 and 1.38 $M_\odot$, respectively. These agree well with the earlier mass estimates, but the uncertainty is now much smaller (assuming that the T_{eff} and log g are accurate).

Despite the fact that the uncertainty due to error in the assignment of the pulsation mode has essentially been eliminated, there remain two controversies concerning the masses of ACs. First, the fact that the derived maximum mass, 1.77 $M_\odot$, is larger than twice the mass of the main sequence turnoff stars in Draco argues against the binary hypothesis. However, as noted by Cox & Proffitt, the discrepancy can be explained if there is an error in T_{eff} . They calculate that an increase in the measured T_{eff} of only 100 K is sufficient to reduce the derived mass to 1.6 $M_\odot$, which is consistent with the binary hypothesis. On the other hand, Wallerstein & Cox (1984) see no inconsistency if ACs were formed by the coalescence of two or more stars. The second controversy surrounds the minimum mass quoted above. Hirshfeld (1980) found that computer models predict that only those core helium-burning stars with masses between 1.3 and 1.6 $M_\odot$ can enter the instability strip. In this case, the estimated minimum mass for ACs is lower than expected. Again, it is necessary to appeal to errors in the T_{eff} or log g data, or errors in the assumptions of the models (e.g., Hirshfeld's models also show that helium abundance variations make a big difference), or a combination of both, to explain the apparent discrepany. The identification of double-mode ACs (if they exist), and the derivation of independent mass estimates using the Petersen diagram, might help resolve these issues.

2.4 Anomalous Cepheids as Distance Indicators

Figure 2 (adapted from NWO) shows the log P-M_B diagrams for the ACs in the Leo I dwarf galaxy (Hodge & Wright 1983), in the Carina dwarf galaxy (Saha, Monet & Seitzer 1986), in the Small Magellanic Cloud (Graham 1975), and in the field of the Galaxy (Teays & Simon 1985). Assuming that the fundamental and first-overtone P-L relationships given in §2.1 hold for all ACs (in all systems), and the scatter seen in Figure 2 can be reduced with improved accuracy of the apparent B magnitudes, it should be possible to estimate distances to the respective systems accurate to better than ±0.10 magnitudes. If ACs are found in the And I, II and III dwarf galaxies, the P-L method can be used to determine their distances, which are, at present, poorly known.

Figure 2. P-L diagrams for the ACs in Leo I, Carina, the Small Magellanic Cloud, and in the field of our Galaxy. The lines are the fundamental and first-overtone P-L relationships defined by well-studied ACs.



3. POPULATION II BLUE STRAGGLERS

Thirty-five years ago the first halo population BSs were discovered, in the globular cluster M3 (Sandage 1953). Over 300 BSs are now known in at least 17 globular clusters; several have been identified in the halo field of the Galaxy; and large populations are known in nearby dwarf spheroidal galaxies. In general, dedicated efforts have not been made to identify complete samples of BSs in individual clusters. Deep photometric investigations have identified relatively complete samples within a given surface area, but the areas surveyed have tended to be small and to not represent a large range of projected radial distances from the cluster centers.

Table 2 lists the number of BSs that have been identified in 17 globular clusters, and in the four nearest dwarf galaxies. The globular clusters are ordered according to increasing central concentration, $c=\log(r_t/r_c)$ (Peterson & King 1975). Column (3) contains the number of BSs that have been observed in the cluster, column (4) notes whether or not the

Table 2.
Stragglers in Globular Clusters and Dwarf Galaxies

Cluster (1)	c (2)	N(BSs) (3)	Center? (4)	Reference (5)
Pal 15	0.60	15	Yes	Seitzer & Carney (1988, unpubl.)
Pal 5	0.7	9	Yes	Smith et al. (1986)
Pal 14	0.75	5	Yes	Da Costa, Ortolani & Mould (1982)
E3	0.75	16	Yes	van den Bergh et al. (1980)
		16	Yes	McClure et al. (1985)
		17	Yes	Hesser et al. (1984)
NGC 5053	0.75	24	Yes	Nemec & Cohen (1988)
Pal 4	0.76	18	Yes	Christian & Heasley (1986)
NGC 5897	0.82	24	Yes	Nemec, Richer & Fahlman (1989)
NGC 288	0.89	9	(Yes)	Buonanno et al. (1984a)
Pal 12	0.90	12	Yes	Harris & Canterna (1980)
Pal 3	0.97	10:	Yes	Gratton & Ortolani (1984)
NGC 7492	0.98	5	Yes	Buonanno et al. (1987)
Pal 13	1.00	6	Yes	Carney & Inman (unpublished)
NGC 5466	1.25	48	Yes	Nemec & Harris (1987)
NGC 2419	1.38	few	No	Christian & Heasley (1988)
		few	No	Nemec & Rich (1985)
M71	1:50:	6	No	Arp & Hartwick (1971)
		50:	Yes	Richer & Fahlman (1987)
N2808	1.76	20	No	Buonanno et al. (1984b)
M3	1.90	30:	No	Sandage (1953)
		53	No	Buonanno et al. (1988)
Ursa Minor	-	28	-	Olszewski & Aaronson (1985)
Draco	-	100:	-	Carney & Seitzer (1986)
Sculptor	-	35:	-	Da Costa (1984)
Carina	-	100:	-	Mould & Aaronson (1983)

central region of the cluster was observed, and column (5) contains the reference to the published c-m diagram. In each cluster (or galaxy) the number of BSs is a lower bound for the true number of BSs, since only NGC 5466, NGC 5053, and possibly E3, have been systematically searched for BSs over their entire surface areas, and even in these three systems the incompleteness due to crowding at faint magnitude levels is not insignificant.

The binary hypothesis, as formulated by RMS, predicts that BSs (and ACs) ought to be found preferentially in low density environments, where the expected frequency of two- and three-body stellar encounters is low. The RMS argument is based, in part, on the calculations of Hills and Day (1976), which showed that less than one collision is expected to have occurred over the entire lifetime of a globular cluster with a very-low central concentration, and $\gtrsim$2000 collisions may have occurred in the centers of the densest globular clusters (such as M80 and M15). It follows, therefore, that one test of the RMS hypothesis is to determine whether or not BSs (and ACs) are more likely to be found in low density environments. For the test to be unbiased, a large number of representative globular clusters would have to be surveyed, and the absence and presence of BSs at all distances from the cluster centers would have to be investigated. At present, such information exists for only a few of the most open globular clusters in Table 2 (such as NGC 5053, NGC 5466 and E3), and is not available for most clusters. High resolution observations will be required to identify BSs in the most dense regions of globular clusters.

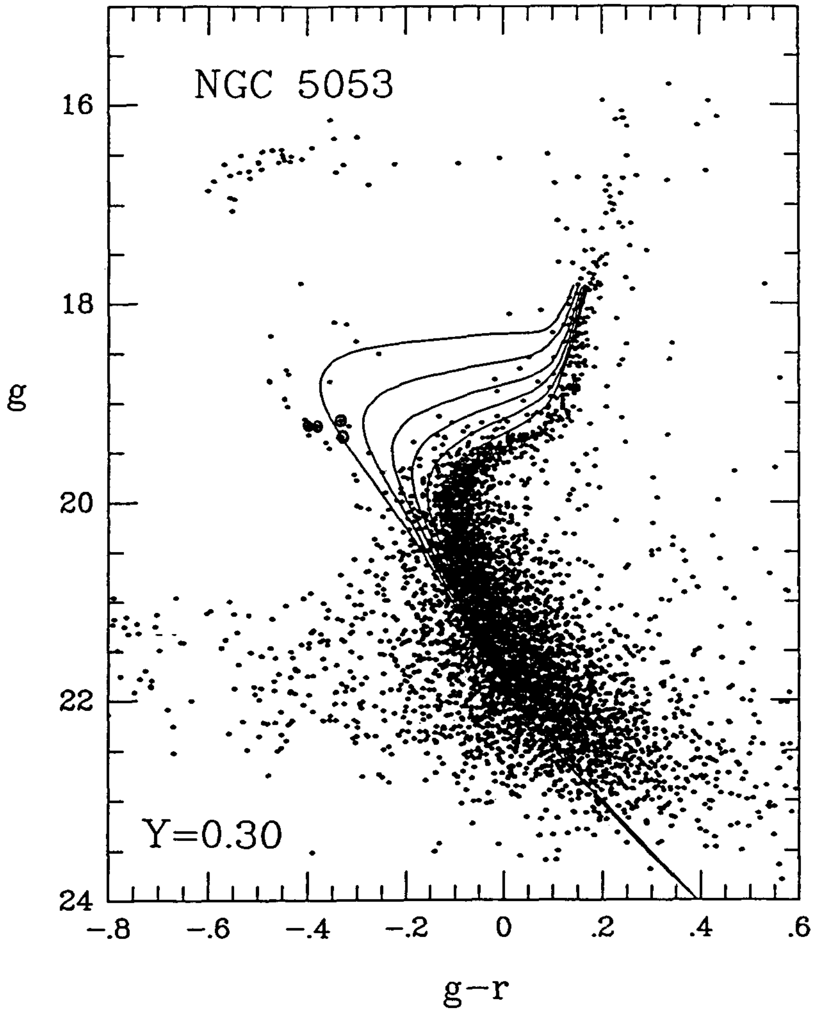
Although the available data on the statistics of BSs is incomplete and biased, Nemec & Harris (1987), using a subset of the data in Table 2, computed that the mean central concentration of globular clusters with BSs is $\langle c \rangle = 1.15$, with $\sigma = 0.12$. This was compared with the mean concentration for 117 globular clusters in Webbink's (1985) catalog ($\langle c \rangle = 1.53$, $\sigma = 0.17$), and with the mean central concentration for the globular clusters that do not apparently contain BSs ($\langle c \rangle = 1.91$, $\sigma = 0.18$). Recognizing that these mean central concentrations for clusters with and without BSs are highly uncertain, Nemec & Harris concluded that "the available numbers appear to support the RMS hypothesis that there is a correlation between central concentration and the presence of blue stragglers". The newer information contained in Table 2 gives no reason for altering this conclusion. In fact, factoring it in reduces the mean central concentration for the globular clusters that contain BSs to $\langle c \rangle = 1.04$, with $\sigma = 0.09$.

The discussions that follow focus on three important issues concerning BSs: the morphology of blue straggler sequences (§3.1), the mean dynamical mass of a sample of BSs (§3.2), and field Pop II BSs (§3.3).

3.1 Morphology of Blue Straggler Sequences

Figure 3 shows a deep c-m diagram for NGC 5053 (Nemec & Cohen 1988), fitted with theoretical isochrones appropriate for the Thuan-Gunn photometric system (Bell & VandenBerg 1987). The isochrones correspond to the evolutionary tracks of single stars having ages of 6, 8, 10, 12, 14 and 16 Gyr, and an assumed helium abundance Y = 0.30. Most of the 24 BSs clearly lie along a sequence that is an extension of the main sequence. The five most luminous BSs appear to define a redward turnoff. If the BSs in NGC 5053 are coeval, and one extrapolates the isochrones shown in Figure 3 to younger ages, a fit of the isochrones to the observed blue straggler sequence gives an age 2 to 4 Gyr. This is in sharp contrast to the mean age of the majority of the cluster stars, which is about 18 Gyr. The theoretical models (appropriate for single, unmixed stars) also indicate that at the "blue straggler turnoff" the BSs have a mass about 1.5 $M_\odot$, compared with 0.8

Figure 3. A c-m diagram for NGC 5053 (from Nemec & Cohen 1988).



$M_{\odot}$ for the main sequence turnoff stars.

The apparent blue straggler turnoff seen in NGC 5053 is not unique. In M3, redward turnoffs are seen in both the Sandage (1953) and the Buonanno et al. (1988) c-m diagrams. Blue straggler turnoffs are also seen in the c-m diagrams for NGC 5466 (Nemec & Harris 1987), the Draco dwarf galaxy (Carney & Seitzer 1986), and the old open cluster NGC 188 (McClure & Twarog 1977). Presently, not enough data exists to investigate trends; however, as the number of known BSs increases, and photometry improves, the morphology of the sequence will become better revealed. Eventually, measurements of the structure along the blue straggler sequence should provide important information for modelling the evolution of BSs.

Another aspect of the morphology question concerns the globular cluster E3 (van den Bergh, Demers & Kunkel 1983; Frogel & Twarog 1983), and its population of about 10 unexplained "yellow stragglers" (Hesser et al. 1984). In the c-m diagram, the yellow stragglers (YSs) are situated above the flat portion of the main sequence turnoff, and are redder than the BSs. The additional detection in E3 of a sequence of main-sequence binaries about 0.75 mag above the standard main sequence (McClure et al. 1985), lends support to the binary hypothesis explanation for both YSs and BSs. A search for short-period variability among the blue and yellow stragglers, and among the candidate main sequence binaries in E3, might be a most profitable endeavor. Yellow stragglers appear also to be present in NGC 2808 (Buonanno et al. 1984b) and in NGC 7492 (Buonanno et al. 1987).

3.2 Mass Segregation and Dynamical Masses of Blue Stragglers

The masses of BSs, like the masses of ACs, can be calculated in a number of ways. One of the most direct methods is based on elementary kinetic theory and the principle that in a stellar system that is in thermal equilibrium there will be equipartition of kinetic energy among the stars, and mass segregation (i.e., the massive stars will be more centrally concentrated than the less massive stars). In practice, by comparing the observed radial distributions of any two samples of stars, one can determine if one sample is, on average, more massive than another. To compute the amount of the mass difference, it is necessary to compare the observed distributions with projected radial distributions (for stars of different masses) calculated with theoretical models of the stellar system. In globular clusters, where relaxation times range from about 0.1 Gyr in the centers of the most dense globular clusters, to about 5.0 Gyr in the centers of the least dense clusters, mass segregation is expected to occur. And, if BSs are more massive than the main sequence turnoff stars, then one expects them to be more centrally concentrated than the turnoff stars.

Dynamical masses for the relatively complete samples of BSs in the globular clusters NGC 5466 and NGC 5053 have been computed in just this manner. In NGC 5466, Nemec & Harris (1987) found the 48 BSs to be more centrally concentrated than the subgiant stars in the same magnitude interval. (The subgiants were chosen for comparison purposes because they have approximately the same mass as the main sequence turnoff stars, and they were believed to be as incomplete a sample of stars as the BSs). By fitting multi-mass King models to the observed cumulative radial distribution function, the mean mass of the NGC 5466 BSs was determined to be 1.3 ± 0.3 $M_\odot$. In NGC 5053 (Nemec & Cohen 1988) a similar result was found for the 12 most luminous BSs, suggesting a mean dynamical mass for them of 1.3 ± 0.3 $M_\odot$. That the 12 lowest luminosity BSs showed no evidence for central concentration is attributed to a range of masses of the BSs, with the lower luminosity BSs having lower masses than the higher luminosity BSs.

In retrospect, one can see that the brightest BSs in Palomar 12 also appear to be located in the central region of that cluster (Harris & Canterna 1980). An increased central concentration of BSs has also been seen in the old open cluster M67 (Mathieu & Latham 1986). In M67 the BSs follow the radial distribution of the spectroscopic binaries. The mean dynamical mass is about 2.0 $M_\odot$ for the BSs in M67, compared with about 1.2 $M_\odot$ for the main sequence turnoff stars. Of course, with all of these mass estimates a critical factor is that the models must adequately represent the real clusters, and this means correctly estimating, among other things, the amount of dark matter in the clusters. The fact that the M3 BSs discovered by Sandage (1953) are not centrally concentrated (Sandage & Katem 1968) can readily be explained by the lack of dynamical equilibrium in the outer regions of M3 (see Chaffee & Ables 1983; Peterson, Carney & Latham 1984), and the relatively high frequency of stellar collisions in the central regions of M3 (Hills & Day 1976).

3.3 Field Pop II Blue Stragglers

The identification of nearby (and therefore bright) field Pop II BSs is obviously important, and several candidate stars have been identified (Bond & MacConnell 1971; Eggen 1970). However, the list includes mostly variable stars, such as VW Ari, SU Crt and BS Tuc (these latter two stars both have broad lined spectra and may be detached binary systems). Carney & Peterson (1981) concluded that the only known non-variable BSs brighter than V = 12 mag, with metal abundances less than 0.1 solar, are BD-12° 2669 and BD+25° 1981.

4. VARIABLE BLUE STRAGGLERS

Potentially the most valuable development in the study of Pop II BSs has been the discovery of short period (44 min to 5 hr) photometric variables among known BSs. These include: several SX Phe variables (or Pop II dwarf Cepheids) in the halo of the Galaxy (§4.1); at least 14 SX Phe stars in the globular clusters ω Cen (§4.2), NGC 5466 (§4.3), NGC 5053 (§4.4), M3 (§4.5), and in the Draco dwarf galaxy (§4.6); two W UMa-like contact binaries in NGC 5466 (§4.7); and, an eclipsing binary in ω Cen (§4.8).

Table 3 summarizes the pulsational and photometric properties of the known variable BSs. Column (1) contains the star name; column (2) gives either the pulsational or the orbital period; column (3) contains the logarithm of the period (days); column (4) contains the amplitude of the photometric variations (V filter); columns (5), (6) and (7) contain the mean V mag, the mean B mag, and the mean B minus the mean V color of the star; and column (8) lists the absolute V magnitude.

Table 3.
A Summary of Properties of Known Variable Blue Stragglers

Star (1)	Period (days) (2)	log P (3)	A_V (4)	<V> (5)	<B> (6)	<B>-<V> (7)	M_V (8)
ω Cen (Jorgensen and Hansen 1984)							
E39	0.057	-1.252	0.25	17.03	17.34	0.31	3.11
NJL 220	0.047	-1.328	0.50	17.04	17.33	0.29	3.12
NJL 79	0.063	-1.201	0.38	16.79	17.12	0.33	2.86
NJL 5	1.38*	0.139	0.50	15.96	16.22	0.26**	2.9
NGC 5466 (Mateo et al. 1988)							
NH38	0.054	-1.268	0.44	18.79	19.07	0.28	2.79
NH29	0.040	-1.398	0.12	18.93	19.15	0.23	2.93
NH27	0.051	-1.292	0.12	18.84	19.08	0.24	2.84
NH35	0.0504	-1.298	0.51	18.96	19.27	0.31	2.96
Anon.1	0.0455	-1.342	0.30	19.32	19.49	0.18	3.32
NH19	0.42*	-0.356	0.4	18.67	18.79	0.12	2.67
NH30	0.33*	-0.481	0.38	19.42	19.64	0.22	3.42
NGC 5053 (Nemec et al. 1988)							
NC14	0.0379	-1.421	0.08	19.42			3.53
NC11	0.0357	-1.447	0.25	19.55			3.63
NC7	0.0347	-1.460	0.12	19.20			3.37
NC13	0.0369	-1.433	0.13	19.41	19.73	0.32	3.59
M3 (DaCosta 1987)							
Anon	0.031	-1.51	0.08	18.0:	18.2:	0.2:	3.34
Field SX Phe Stars							
BL Cam	0.039	-1.409	0.50	13.10		0.21	3.2
DY Peg	0.073	-1.137	0.54	10.25		0.24	2.2
SX Phe	0.055	-1.260	0.50	7.0	7.24	0.24	2.7
CY Aqr	0.061	-1.215	0.70	10.78		0.22	2.5
KZ Hya	0.060	-1.225	0.80	9.97		0.22	2.6

* Orbital period, ** At maximum light (phase 0.25)

4.1 Field SX Phe Variables

SX Phoenicis, discovered by Eggen (1952a,b), is a seventh magnitude, high proper motion (0.8"/yr) star with an ultra-short period and a variable amplitude ($A_V \sim 0.3-0.6$ magnitudes). Walraven (1955) showed that it pulsates simultaneously in the fundamental mode (P_0 = 0.05496 day) and in the first-overtone mode (P_1 = 0.04277 day), with a ratio of its two pulsation periods (P_1/P_0 = 0.7782) that is not unlike that for Pop I double-mode δ Sct variables (Fitch 1970; Fitch & Szeidl 1976; and Cox, King & Hodson 1979). SX Phe has long been recognized as the brightest example of the class of low-metal abundance, high-amplitude Pop II dwarf Cepheids, other members of which include BL Cam, CY Aqr, KZ Hya and DY Peg. (The existence of low-amplitude field Pop II dwarf Cepheids remains questionable - see McMillan et al. 1976; Carney & Peterson 1981; and Halprin & Moon 1983). A list of 178 dwarf Cepheids in the field of the Galaxy has been compiled by Halpren & Moon (1983), while Frolov & Irkaeav (1984) have attempted to identify which of these are Pop II stars. Properties of selected field Pop II dwarf Cepheid candidates are summarized in Table 3.

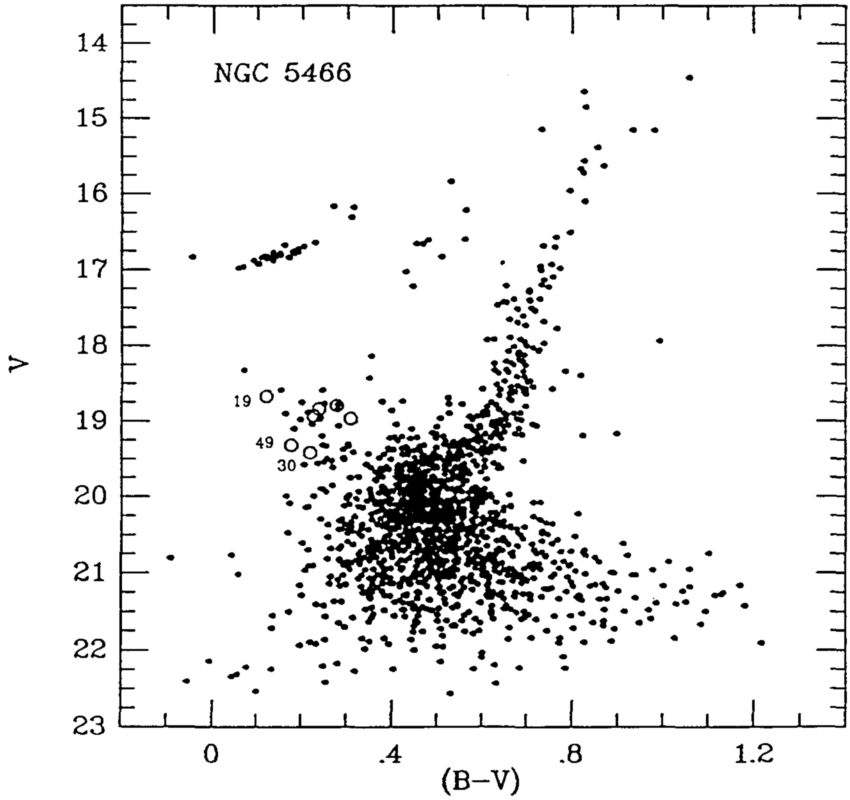
The evolutionary status of SX Phe variables, like that of ACs and BSs, is controversial. Bessell (1969) proposed that they might be low-mass (0.5 $M_\odot$), post-helium-flash Pop II stars. Another hypothesis is that they are short period δ Scuti (or AI Velorum) variables with relatively large masses (1.5 to 2.5 $M_\odot$) similar to those of δ Scuti stars. The most likely explanation (Eggen 1970, 1971, 1979) is that they are variable BSs (VBSs), analogous to Pop I δ Scuti variables. These hypotheses, and others, are discussed by Bessell (1969), McNamara & Feltz (1978), Breger (1980), Fernley et al. (1987), and Eggen & Iben (1988).

The pulsation periods of SX Phe stars allow several different mass estimates to be made, depending on the available information. One can compute the theoretical mass (using P and T_{eff}), the pulsation mass (using P, L and T_{eff}), the mass relative to the RR Lyrae stars in the same system (using P, and Teff and m_{bol} relative to the RR Lyraes), and, if the star is also double-periodic, it may be possible to compute its mass using the Petersen method. The reader is referred to Cox, King & Hodson (1979) and Jorgensen & Hansen (1984) for detailed discussions of these mass estimation techniques. If SX Phe stars are VBSs, then they are particularly valuable for improving our understanding of BSs. The masses determined for individual SX Phe stars provide an important check on the dynamical mass estimate discussed above (which provides only a mean mass for an appropriately selected sample of BSs), and the evolutionary mass estimate derived by a comparison of theoretical isochrones with position in in the c-m diagram. By establishing the physical characteristics of SX Phe stars (and other faint variable stars in globular clusters), many key questions regarding BSs will almost certainly be answered.

4.2 Variable Blue Stragglers in ωCentauri

The first VBSs to be identified in a globular cluster were the three Pop II dwarf Cepheids found in ωCen. Niss, Jorgensen & Laustsen (1978) surveyed approximately 25% of ωCen's surface area and identified 29 candidate short-period variables. Two of the stars, NJL 79 and NJL 220, and a third star not in the NJL catalog, E39, were subsequently found to be "dwarf Cepheids" with periods between 0.047 and 0.063 day (Jorgensen 1982; Jorgensen & Hansen 1984; Da Costa & Norris 1988). A fourth star, NJL 5, is an eclipsing binary (see §4.9). All four stars lie in the blue straggler region of the ωCen c-m diagram (Da Costa, Norris and Villumsen 1986), which also includes five BSs that appear to be photometrically constant to 0.03 mag (DaCosta & Norris 1988; Da Costa 1988, personal communication).

Figure 4. A c-m diagram for NGC 5466 (from Mateo et al. 1988) based on one pair of 300 sec B and V Palomar 60-inch CCD exposures. The blue straggler sequence is obvious above and to the left of the main sequence turnoff. The open circles denote the mean V magnitude and (B-V) colors of the seven variables found in NGC 5466. Note that there is little doubt that these variables are each also blue stragglers.



Depending on the assumed pulsation modes of the three dwarf Cepheids (see §4.7), estimates of their pulsation masses range from 2.24 $M_\odot$ for NJL 220, to 0.57 $M_\odot$ for NJL 79 (Jorgensen 1982), and 0.72 $M_\odot$ for E39 and 0.74 $M_\odot$ for NJL 220 (Jorgensen & Hansen 1984). The mean mass, computed relative to the RR Lyrae stars, is 1.2 ± 0.2 $M_\odot$. Since the pulsation modes of these stars are not known (the fundamental mode was assumed), the uncertainties are large. Properties of the four VBSs in ωCen are summarized in Table 3. Clearly, there is little to distinguish the three dwarf Cepheids from the field SX Phe stars, and NJL 5 stands out as an exceptional stellar system.

4.3 Variable Blue Stragglers in NGC 5466

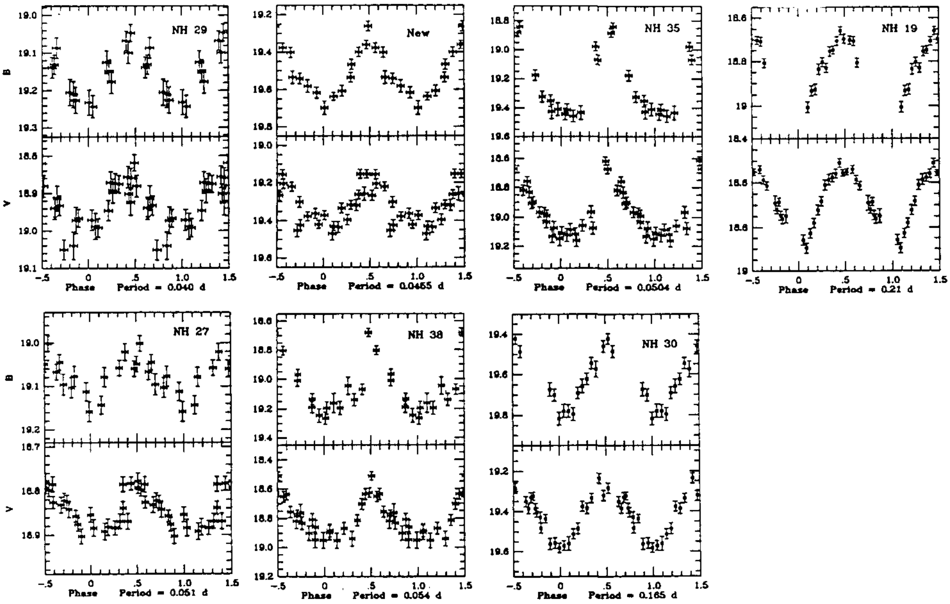
With four out of nine BSs in ωCen known to be either dwarf Cepheids or eclipsing binaries, it was obviously of interest to establish whether or not a comparable fraction of the recently discovered BSs in NGC 5466 (Nemec & Harris 1987) and NGC 5053 (Nemec & Cohen 1988) are variable. CCD programs to monitor the variability of the BSs in these two systems, and to search for short-period variables, are underway (Nemec et al. 1988a; Mateo et al. 1988a, b). To date, hundreds of short exposure frames have been taken by a team of observers using the Palomar Observatory 60-inch telescope, the Canada-France-Hawaii 3.6-meter telescope, and the Steward Observatory 90-inch telescope. Over 30 hours of observing time has been devoted to this project over a two year period. A preliminary report on the results of both surveys is given here.

Mateo et al. (1988a) have recently discovered seven short-period variable stars among the BSs in NGC 5466 (Nemec & Harris 1987). The stars have periods ranging from 0.04 day to 0.21 day (0.42 day if the variations are interpreted as orbital motion), and amplitudes between 0.12 mag and 0.51 mag. Figure 4 identifies the seven variables in one of the Mateo et al. c-m diagrams, and light curves for the seven stars are plotted in Figure 5. (One of the variable BSs was not in the NH-catalog of BSs in NGC 5466, and was labelled "Anon. 1" by Mateo et al. In Figures 4 and 7 it has been labelled "49" to indicate that it is the 49th known blue straggler). With the exception of Nos. 19 and 30, which deserve special mention and are discussed in §4.8, the periods, amplitudes and light curves of the five shorter-period variables resemble those of SX Phe variables, i.e. the light curves are Cepheid-like, showing some flatness at minimum light and some asymmetry. Basic information on the seven VBSs is summarized in Table 3. The B-V color range of the five SX Phe variables is from 0.18 to 0.31 (and is only from 0.23 to 0.31 if No. 49 is excluded). The variables tend to be among the brighter BSs in NGC 5466. Photometrically constant BSs appear to sit side-by-side in the c-m diagram with the variables. Of course, these "non-variable" stars may turn out to vary, with amplitudes $\lesssim$0.10 mag. (Eggen 1970 has shown that non-variable and variable old disk BSs share a common location in the c-m diagram).

4.4 SX Phe Variables in NGC 5053

The search for photometric variables among the 24 BSs in NGC 5053 (Nemec & Cohen 1988) has resulted in the recent discovery of four SX Phe stars, with periods ranging from 0.0347 to 0.0379 day, and V amplitudes in the range 0.19 to 0.35 mag (Nemec et al. 1988). All four stars are (in projection) in the innermost region of the cluster. Preliminary details are given in Table 3, and light curves for the four stars are plotted in Figure 6. In the NGC 5053 c-m diagram shown in Figure 3, the four stars occupy a small region about half way down the blue straggler sequence. It is curious that none of the highest luminosity BSs (i.e. those with g ≈ 18.5, g-r ≈ -0.30) appears to be variable, since these appear to lie between the RR Lyrae stars and the SX Phe stars in the instability strip. As was also the case in NGC 5466, variable and non-variable BSs appear to be mingled together at a similar position in the c-m diagram. The range in the <V>-magnitudes of the four SX Phe stars is relatively small, from 19.27 to 19.53 mag, and the range of mean colors is also small, from g-r about -0.40 to -0.33. This localization of the four variables in the c-m diagram offers the hope that perhaps with identification of more SX Phe stars in NGC 5053, and in other systems, and determination of their colors and luminosities, the edges of the instability strip will become well established.

Figure 5. Light curves for the VBSs in NGC 5466 (from Mateo et al. 1988).



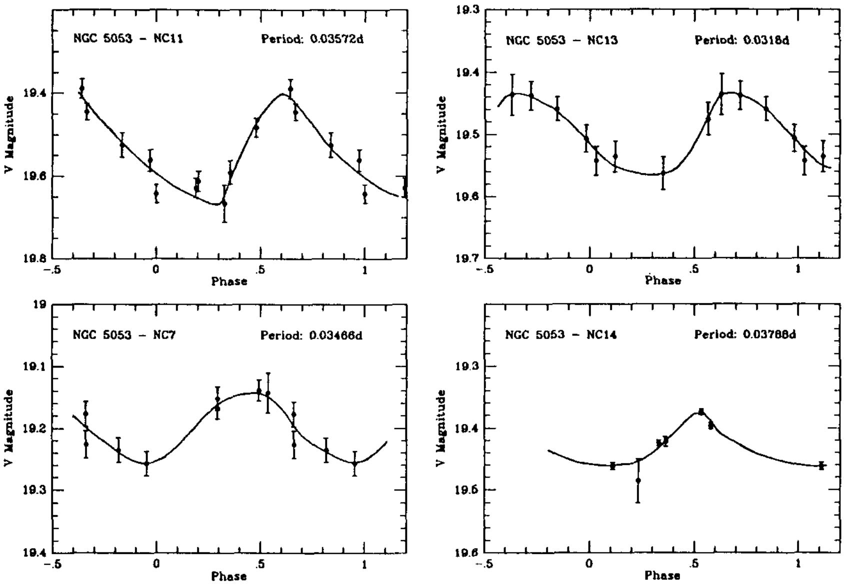
4.5 SX Phe Variables in M3

As discussed above, about 30 BSs can be identified in Sandage's (1953) c-m diagram for M3. More recently, Buonnanno et al. (1988) note that they have identified 53 BSs in their 10,000 star c-m diagram for M3. Da Costa (1987) reports that photometry has been obtained for 11 BSs in M3, and that one of the monitored stars appears to be variable, with a pulsation period about 44 min (P = 0.031 day), and a B-amplitude about 0.07 magnitudes. The published light curve for Da Costa's variable is sinusoidal in shape, and there is every reason to believe that it is an SX Phe star. Adopting <B> = 18.56, and assuming <B-V> = 0.30 and $(m-M)_0$ = 14.83, the absolute V magnitude of this star is M_V = 3.3. If the 44 min period is confirmed, this variable would be the shortest period SX Phe star known. Its very low amplitude suggests that precise photometric measurements will be necessary if other such VBSs are to be identified in M3, and in other stellar systems. A complete search for BSs over the entire surface area of M3, and further study of the BSs that have already been identified, would be of great value.

4.6 Variable Blue Stragglers in Nearby Dwarf Galaxies

The Ursa Minor, Draco, Sculptor and Carina dwarf galaxies, in addition to their populations of ACs, contain substantial populations of BSs. The (total) number of BSs in Ursa Minor, Draco and Sculptor is estimated to be about 300, 700 and 1400, respectively (Olszewski & Aaronson 1985; Carney & Seitzer 1986; Da Costa 1984). Counting only those BSs brighter than M_V = +2.5, Da Costa (1988) has determined that

Figure 6. Light curves (in V) for the four SX Phe variables in NGC 5053 (from Nemec et al. 1988).



these three galaxies contain, respectively, 45, 70 and 200 BSs bright enough to produce ACs. Mould & Aaronson (1983) argue that the stars in the blue straggler region of their Carina c-m diagram may be of intermediate age (about 7.5 Gyr).

It is noteworthy that Carney and Seitzer (1986) have found that one of the luminous Draco BSs appears to be either a dwarf Cepheid or an eclipsing binary. Given that Draco, Ursa Minor, Sculptor and Carina have such large populations of BSs, a search for more such variables would be of great value for determining whether the physical properties of the VBSs in these galaxies are similar to those of the VBSs in globular clusters, and for establishing the connection with the many other kinds of chemically peculiar stars, including CH and CN stars, in dwarf galaxies (see Zinn 1981, Smith & Dopita 1983, Stetson 1984). Given that the V mags of the BSs in these three systems range from 21 to 23 mag, such a search is currently within reach of large ground-based telescopes with CCD cameras.

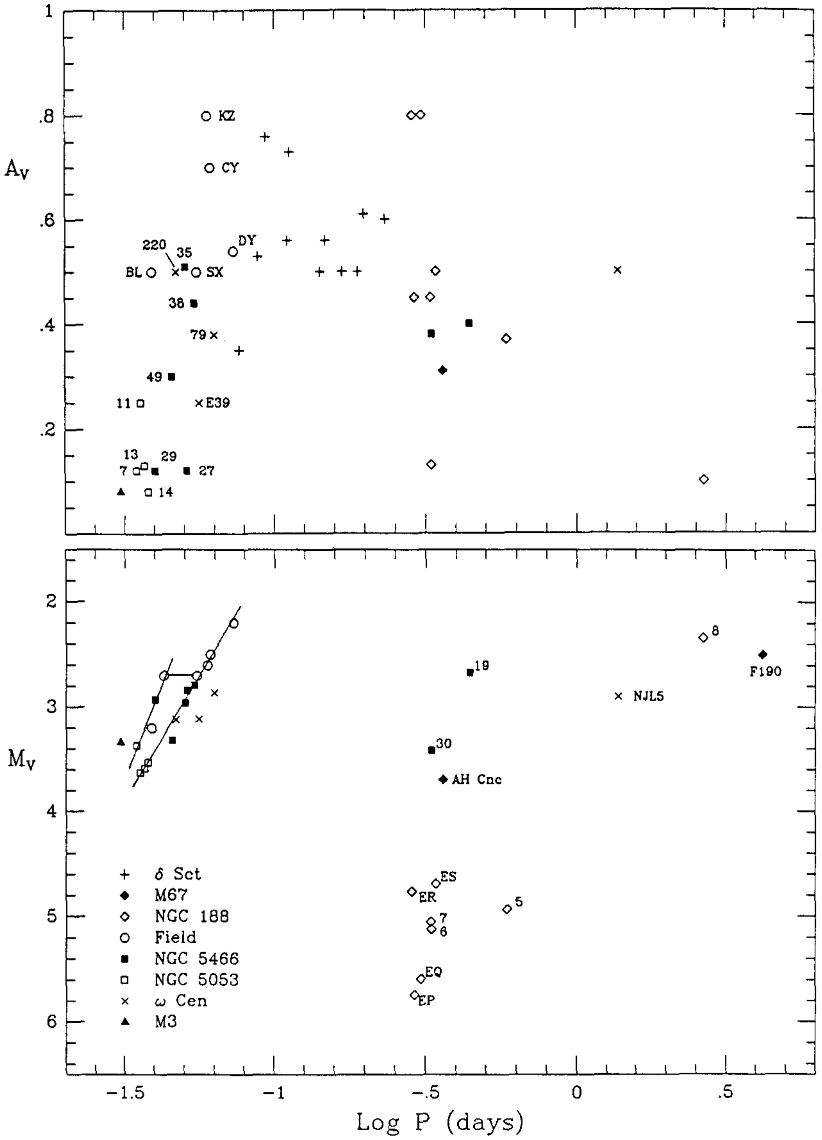
4.7 Pulsational Properties of SX Phe Stars

With the identification of relatively large numbers of SX Phe stars it should be possible to establish P-L and P-A relationships, and determine pulsation modes for the stars. The lower panel of Figure 7 shows all the variable BSs in NGC 5466, NGC 5053, M3, and ω Cen, plotted in a (log P)-(M_V) diagram; the upper panel shows the corresponding (log P)-(A_V) diagram. Also plotted in the diagrams are the field SX Phe variables DY Peg, CY Aqr, KZ Hya, SX Phe and BL Cam, the known W UMa contact binaries in the old open cluster NGC 188 (age 5 to 11 Gyr), and two variable BSs in M67 (age about 3 Gyr). Several large amplitude δ Scuti variables also are represented in the upper panel (for comparison with the SX Phe stars). A number of interesting points are raised by these diagrams:

(1) The VBSs in the globular clusters do not constitute a homogeneous sample, but divide into three types of variables: SX Phe stars, contact binaries, and eclipsing binaries. The SX Phe variables have M_V between +2 and +4, and periods in the range 44 to 110 min; the contact binaries appear to be found over a wide range of luminosities, with orbital periods in the interval 0.28 to 0.41 day; the eclipsing binaries have relatively long orbital periods. The contact and detached binaries are discussed in §4.8 and §4.9, respectively.

(2) All the known SX Phe stars define an approximately linear relationship between log P and M_V. Upon closer inspection, it appears that the scatter might be systematic. Excluding NJL 79 and E39 in ω Cen, which appear to have longer periods at a given luminosity than the bulk of the SX Phe stars, No. 29 in NGC 5466, BL Cam, No. 7 in NGC 5053, and Da Costa's star in M3, tend to have shorter periods at a given luminosity than the bulk of the variables. Since the periods are short and well determined, the greatest uncertainties are in the absolute V magnitudes. However, with the exception of BL Cam, these four outlier stars are in well-studied clusters, and hence the M_V values should be

Figure 7. (Lower panel) Period-luminosity diagram for variable blue stragglers. Nos. 19 and 30 in NGC 5466 are plotted with the assumed orbital periods. Both the fundamental and the first-overtone periods are plotted for SX Phe (connected with a line). Contact and detached binary systems are labelled. (Upper panel) Period-amplitude diagram for the SX Phe variables, the binary systems, and for selected δ Sct stars. The SX Phe stars and the δ Scuti variables are labelled.



secure. Thus, the scatter appears to be real. For the stars with periods short for their luminosities, including SU Crt, one explanation of the large scatter at a given luminosity might be that they are oscillating in a higher pulsation mode. Given that we know that SX Phe pulsates simultaneously in the fundamental and first-overtone modes, and not in the first- and second-overtone modes (in which case the period ratio would be expected to be much larger), it is reasonable to postulate that the four high-amplitude SX Phe variables are first-overtone pulsators. Further evidence for this is that the shapes of the light curves for all four short-period stars are sinusoidal, which is to be expected for first-overtone pulsators. Support for the notion that some SX Phe stars pulsate in the first-overtone mode comes from Fourier decomposition studies of field dwarf Cepheid light curves (Antonello et al. 1986; Fernley et al. 1987), which show that dwarf Cepheids with $R_{21} < 0.30$ are first-overtone pulsators, and those with $R_{21} > 0.30$ are fundamental mode pulsators. When more photometry becomes available, it will be of considerable value to subject the data on the globular cluster SX Phe stars to a Fourier decomposition analysis. Assuming that the SX Phe stars can be sorted into fundamental and first-overtone pulsation modes, the possible relationships are as plotted in Figure 7.

(3) Pulsation in different modes does not explain NJL 79 and E39 in ω Cen. For these two stars, a number of possibilities come to mind (none of which is appealing): (a) the two stars may have incorrect luminosities. However, if this is the case, and their periods are correct (which they seem to be), the adopted M_V values are too faint by about 0.5 magnitudes; (b) if the two stars are fundamental mode pulsators, then the bulk of the SX Phe stars would have to be first-overtone pulsators, and the stars with periods short for their luminosities would have to be second-overtone pulstors. Although there seems to be no theoretical reason why SX Phe stars cannot pulsate in modes from the fundamental up to the fifth-overtone (see Figure 1 of Stellingwerf 1979), a problem with this interpretation is that the period ratio for SX Phe would then be anomalous; (c) the two stars are binary systems. Here however, the light curves are those of dwarf Cepheids, and not contact binary systems (see next section). Given that ω Cen is famous for its chemical inhomogeneity and other anomalies, more work is necessary to understand these stars.

(4) The P-A diagram (upper panel of Figure 7) shows that all of the shortest period SX Phe stars have amplitudes less than about 0.3 mag, and as the periods become longer the amplitudes increase (up to about 0.5 mag). The largest amplitude SX Phe variables are KZ Hya, CY Aqr, GP And and DY Peg, all of which are intermediate metal-abundance variables (some of which are old disk stars). Traditionally, SX Phe variables have been identified by their high space motions, low luminosities, high galactic latitudes, and low metal abundances. Because most of the field SX Phe variables that are known have amplitudes larger than about 0.40 mags, it is commonly thought that SX Phe variables, in general, have large amplitudes. Figure 7 also shows several large-amplitude δ Scuti variables. Recognizing that this sample

of Pop I dwarf Cepheids excludes most δ Scuti stars, which have relatively small amplitudes, and is not representative of δ Scuti stars in general, Figure 7 nevertheless suggests that most (and maybe all?) large amplitude dwarf Cepheids with periods longer than about about 0.08 day are Pop I dwarf Cepheids. The reader is referred to Figure 1 of Breger (1980) for the over-all period distribution of δ Scuti stars.

(5) In analyses involving the periods and amplitudes of SX Phe stars there are a number of potential problems. Many SX Phe and δ Sct dwarf Cepheids exhibit cycle-to-cycle amplitude variations, reminiscent of Blazhko variability in RR Lyrae stars. These variations are often caused by multi-mode radial pulsations, but many variations are complex and not understood. The brightest double-mode Pop II dwarf Cepheid is SX Phe, itself (which was discussed earlier). Some SX Phe stars, such as Nos. 27 and 35 in NGC 5466, have similar periods and luminosities, but there is a large difference in their amplitudes. One possibility is that these two stars have variable amplitudes and are doubly-periodic, and the observations have been made at high and low amplitude states. Other problems involve the question of non-radial pulsations, and the effects of rotation and magnetic fields. Certainly much more work is needed to identify and deal properly with the question of amplitude variations.

4.8 Contact Binary Systems Among Blue Stragglers

The long period VBSs in NGC 5466, Nos. 19 and 30, represent a type of variable star not previously seen in a globular cluster. They have periods considerably longer than those of the other VBSs in NGC 5466, light curves with shapes unlike those of the shorter-period variables in NGC 5466, and B-V colors ($0.1 < B-V < 0.2$) bluer than most of the SX Phe stars discussed above (see Figure 4). Mateo et al. (1988) conclude that both stars are contact binary systems, based on the relatively long periods, and the morphology of the light curves. The light curve of No. 19 is asymmetric, and at minimum appears to come to a sharp point. The light curve for No. 30 is almost symmetrical. The light curves of both stars resemble those of W UMa-type binary systems (see Eggen 1976; Kaluzny & Shara 1987). Under the W UMa contact binary hypothesis, the pointed minimum for No. 19 suggests that a partial eclipse may be occurring, possibly like that seen in Figure 17 of Binnendijk (1970). The flat bottom of the light curve for 30 is more suggestive of a much more complete eclipse in an edge-on system. This discovery provides direct evidence that at least some BSs are contact binaries. In Figure 7, the similar orbital periods of these two stars, and of the certain contact binary (and blue straggler) AH Cnc in M67 (Eggen 1976; Whelan et al. 1979), and of the lower-luminosity W UMa-type contact binaries in NGC 188 (Baliunus & Guinan 1985; Kaluzny & Shara 1987), lends considerable support to this interpretation. It is of added interest that the well-defined light curve of AH Cnc resembles those of 19 and 30. The fact that the two NGC 5466 stars are very luminous relative to these other binaries is not sufficient evidence to rule out the possibility that there are lower luminosity contact binaries in NGC 5466. A systematic survey of M67 to identify W UMa binaries similar to those found in NGC 188 would be helpful in determining the properties of these stars. Obviously, much more work needs to be done to exploit a comparison between the binary systems in old open clusters, and the newly discovered candidates in NGC 5466.

4.9 Detached Binary Systems Among Blue Stragglers

The eclipsing binary NJL 5 in ωCen, with an orbital period of 1.376 days and a well defined light curve (Liller 1978, Jensen & Jorgensen 1985), is a blue straggler in the ωCen c-m diagram (DaCosta, Norris & Villumsen 1986). Since NJL 5 is a radial velocity member of the cluster (Jensen & Jorgensen 1985), it is unique among BSs in globular clusters. The fact that the light curve indicates that the component stars are detached provides direct evidence that some BSs in globular clusters are detached binaries. The existence of only one such star suggests that detached (and eclipsing) binaries are relatively rare. Since ωCen also contains many spectroscopically peculiar stars, including six CH stars (see Cowley & Crampton 1985) which are probably spectroscopic binaries (see McClure 1985), and since CH stars and other chemically peculiar stars are also present in many dwarf spheroidal galaxies (see Mould 1983), it is not implausible that those BSs that are detached binaries (such as NJL 5) are the progenitors of such chemically peculiar giant stars. Circumstantial evidence for this is provided by a parallel situation among old disk stars: the Ba II stars, which are believed to be the old disk counterparts of the CH stars, are known to be detached binary systems (McClure, Fletcher & Nemec 1980; Böhm-Vitense, Nemec & Proffitt 1984; McClure 1985) and to probably have as their progenitors old disk BSs.

Detached binary stars with orbital periods similar to that of NJL 5 are also known in NGC 188 (Baliunas & Guinan 1985) and M67. It is enlightening to review these stars, since they are possible counterparts of NJL 5. Two candidate detached binaries are known in NGC 188: V8, which is a yellow straggler and V5, which sits below the subgiant turnoff in the c-m diagram of McClure & Twarog (1977). Kaluzny & Shara (1987), while recognizing that the 2.67 day period for V8 is somewhat uncertain, conclude that "the time scale and amplitude of the light variations suggest that V8 is either an RS CVn-type star or an FK Com-type star. (FK Com-type stars are rapidly rotating single giants exhibiting light variations of the order of 0.1 mag. Their variability is most probably due to the presence of large starspots on their surfaces)". Since coalesced W UMa binaries are believed to be the progenitors of FK Com stars (Bopp & Stencel 1981; Guinan & Bradstreet), it follows that a search for low-amplitude variability in yellow stragglers in different environments might be quite productive. The period of V5, 0.586 day, is "extraordinarily long for a contact binary of spectral type K2" (Kaluzny & Shara, 1987), and needs to be checked.

M67 is well-known for its large populations of BSs and spectroscopic binaries. The fact that the BSs follow the same radial distribution as the spectroscopic binaries (Mathieu & Latham 1986) implies that the mean mass of the BSs is similar to that of the spectroscopic binaries.

Periods for seven of the long period binaries in M67 (see Mathieu & Mazeh 1988) range from 4.2 day to 60.5 days. The shortest period variable, F190 (see Eggen & Iben 1988), has recently had its 4.2 day period confirmed (Latham et al. 1988, private communication). The location of F190 in the c-m diagram is similar to those of V8 in NGC 188, and to the high-luminosity BSs in NGC 5053 (Nos. 2, 3, 4, and 24 in Nemec & Cohen 1988). None of the NGC 5053 stars appears to be photometrically variable; however, the photometric reductions are not complete. Since F190 is a blue straggler, it is tempting to speculate that some of these long period binaries may have evolved from the BSs with the largest separations. Of course, the BSs that have coalesced could not be the progenitors.

5. CONCLUSION

The derived masses for ACs leave little doubt that they are stars with relatively large masses, 1.0 to 1.7 $M_\odot$. The recent discovery that there is a dichotomy in the P-L relationship for ACs, and the application of the Fourier decomposition method, help considerably in identifying the pulsation modes of ACs. This has all but eliminated what was previously a major source of uncertainty in the computation of the pulsation masses of ACs. In addition to facilitating mode identification, the fundamental and first-overtone P-L relationships for ACs can be used as distance indicators, provided that they are universal in nature.

Large numbers of BSs are now known in about 20 globular clusters, and in all the nearest dwarf galaxies. Although an unbiased statistical test has yet to be carried out, the RMS prediction that BSs should occur preferentially in globular clusters with low central concentrations appears to be supported by the observations. Observed blue straggler sequences tend to show evidence for a redward turnoff at high luminosities. In both NGC 5466 and NGC 5053, the mass of the BSs from dynamical consideratons is substantially larger than the mass of the main sequence stars. In NGC 5053, the most luminous BSs appear to have larger masses than the least luminous BSs.

Surveys of photometrically variable BSs indicate that about 25% of all BSs are variable, with periods ranging from about 45 min to 10 hours. At least 14 SX Phe stars, with periods between 45 min and 120 min and amplitudes between 0.1 and 0.6 mag, have been identified in four globular clusters. (There is some evidence that a similar star exists in the Draco dwarf galaxy). The shapes of their light curves and their P-L relationships, suggest that the pulsation modes of the SX Phe stars are probably the fundamental and the first-overtone modes. However, this conclusion is not certain since there are still some questions concerning the pulsation modes of NJL 79 and E39 in ωCen. The derived pulsation mass, and mass relative to the RR Lyrae stars, of the SX Phe stars in ωCen, NGC 5466 and NGC 5053, is consistently large, about 1.3 $M_\odot$. Thus, there is good agreement between the masses of non-variable BSs and the SX Phe stars.

Two contact binaries, with orbital periods of about 8 and about 10 hours, have been discovered in NGC 5466. These stars are similar to the W UMa contact binaries in the old open clusters M67 and NGC 188, and provide direct evidence that some BSs are binary systems. Further evidence for this conclusion is provided by the eclipsing binary NJL 5 in ωCen, which has an orbital period of 1.38 day. Almost certainly there are more contact binaries, eclipsing binaries and SX Phe stars to be discovered among BSs, and these will yield important information.

Finally, the observational evidence concerning the origin and evolution of Pop II BSs and ACs seems to favor the binary hypothesis. It is highly likely that both types of stars have as their progenitors primordial binary (or possibly multiple) systems. Direct observation of both types of stars in very low-density stellar systems, where collisions are extremely rare, argues strongly in favor of this theory. Because of angular momentum losses, and the tendancy for close binaries to coalesce on times scales of a few Gyr (Mochnachi, 1985), most BSs are likely to be coalesced systems. However, the observed diversity of variable star types among BSs indicates that at present there is a range of separations of the binary components.

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