Type 2 Cepheids in the Milky Way Galaxy and the Magellanic Clouds

Douglas L. Welch
Department of Physics and Astronomy, McMaster University, Hamilton, ON, L8S 4M1, Canada; welch@physics.mcmaster.ca

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Abstract Type 2 Cepheids are radially pulsating variable stars that have been recognized as a distinct class for sixty years. As the lower-mass and hence lower-luminosity counterparts of the classical Cepheids, Type 2 Cepheids have attracted less observational and theoretical attention in the intervening decades. Fortunately, the recent availability of long, high-quality photometric time-series has renewed interest in these variables. The results from the OGLE-III surveys of the Large and Small Magellanic Clouds have been particularly exciting, especially with respect to the identification of "peculiar W Virginis" stars which appear to be components of binary systems. It has also become apparent that the sample of Milky Way field Type 2 Cepheids in catalogues is highly contaminated with other classes of variable stars. In this review, I describe important developments in the study of Type 2 Cepheids and suggest research opportunities—many of which do not require the acquisition on new data.

1. Introduction

In September 1952 the universe as we understood it became much larger. Ever since the first Type 2 Cepheids were discovered in globular clusters, it had been assumed that they shared the same luminosity at a given period as (classical) Cepheids in the disk of the Milky Way. In reality, there was a 1.5 magnitude difference between the two. The surprising announcement of this realization by Baade at the Rome IAU was quickly buttressed by followup remarks by Thackeray who had arrived at the same conclusion using observations of Large Magellanic Cloud variables. (See Baade (1956) for the complete firsthand account of how these events unfolded.) Reviews of Type 2 Cepheids and related stars have been published by Wallerstein and Cox (1984), Harris (1985b), and, most recently, by Wallerstein (2002). There have been a number of developments since the last work including the release of variable star catalogs from long-term, wide-area photometric surveys such as OGLE-III. In what follows, I will concentrate on work reported since Wallerstein (2002). I delve a little further back to review binary Type 2 Cepheids due to the recent realization that binarity is an importance influence on the production of certain Type 2 Cepheids.

2. Nomenclature

For the purposes of this review, Type 2 Cepheids are defined as those stars which are normally classified as BL Her variables (with periods between 1 and 4 days, also abbreviated CWB), W Vir stars (with periods greater than 4 days but most frequently greater than 8 days and less than 20 days, abbreviated CWA), and RV Tau stars (periods between maxima greater than 20 days). Somewhat confusingly, the RV Tau stars are subdivided into RVA and RVB types where RVB indicates an additional very long-period (500+ days) modulation of the light curve. Studies of Type 2 Cepheids in the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC)—discussed later in this review—have revealed a smooth progression of properties between W Vir and RV Tau stars and so the adoption of a discriminating period is not physically motivated. While the alternating minima of different depths of RV Tau stars seemed a distinctive classification characteristic of the time, it has since been seen in the prototype W Vir itself (Templeton and Henden 2007) and in BL Her stars (Smolec *et al.* 2012). Its usefulness as a discriminating factor between classifications may be diminished, but the fact that the phenomenon is more widespread is a positive finding in terms of testing theory against observation. In any case, Buchler and Moskalik (1990) claim that the period-doubling behavior for the more luminous Type 2 Cepheids (W Vir/RV Tau) is the result of a 5:2 period resonance between the fundamental and the second overtone radial modes.

Historically, Type 2 Cepheids have often been referred to as "Population II Cepheids" but our understanding of their range of metallicities and their kinematics has evolved to the point where continuing to make use of such a title would mislead the reader.

While RR Lyr variables are closely related, space constraints prevent the discussion of their very considerable literature. The anomalous Cepheids (intermediate in mass and luminosity between Type 2 and classical Cepheids) are often discussed in Type 2 Cepheid papers but also will not be reviewed here.

3. Evolutionary context

The early detection of Type 2 Cepheids in globular clusters provided an immediate degree of evolutionary context for these stars although our physical understanding of stellar structure and evolution emerged much later. However, the brightest Type 2 Cepheids in globular clusters are still much fainter than the brightest stars of the field population and consequently the determination of abundance patterns at high spectral resolution relies dominantly on field stars.

Our current understanding of the evolution of Type 2 Cepheids (and their subtypes) was outlined by Gingold (1985) and references therein. It is assumed that these variables have masses similar to 0.6 $M_\odot$ when they begin to evolve away from the horizontal branch.

Maas *et al.* (2007) studied 19 Type 2 Cepheids and found a number of abundance patterns. BL Her stars were found to have an overabundance of Na by up to a factor of 5 while the W Vir stars show no such anomaly. This careful and pivotal study also contains an excellent discussion of the evolutionary options available to core helium-burning blue horizontal branch stars heading towards the instability strip from the hot side. The Na anomaly suggests that BL Her stars do not normally end up becoming W Vir or RV Tau stars later in their evolution. Assuming single-star evolution, they suggest that the BL Her stars result from a phase of high-temperature CNO processing which both leave them with enhanced Na and "deposits" them at the red end of the blue horizontal branch, resulting in a single pass through the instability strip. W Vir stars are thought not to have experienced such high-temperature CNO processing and start their journey off the horizontal branch nearer the blue end of the blue horizontal branch. W Vir stars then may pass through the instability strip on their way to the asymptotic giant branch (AGB) but have an additional excursion back and forth across the instability strip at higher luminosity due to helium shell flashes and/or internal structure readjustments on the AGB.

The traditional interpretation of the "no man's land" in period, between about 4 and 10 days, where Type 2 Cepheids are rarely found therefore maps back to the horizontal branch and the way in which evolutionary tracks diverge from each other as the stars evolve to cooler temperatures and higher luminosities.

4. Type 2 Cepheids in binary systems

In the Milky Way field, there are presently five Type 2 Cepheids known to be members of binary systems.

AU Peg is a 2.4-day BL Her star with a rapidly changing period. Precision radial velocites obtained by Harris *et al.* (1979) led them to conclude that AU Peg was a component of a spectroscopic binary with a period of order 50 days. Harris *et al.* (1984) obtained additional photometry and spectrscopy and concluded that AU Peg was in a 53.32-day orbit, that it had an [*Fe/H*] = +0.1 and that it must be very close to filling its Roche lobe. AU Peg appeared to be redward of the instability strip and thus binarity was implicated as a possible source of excitation of pulsation as well as a driver of the rapid period change. Vinkó *et al.* (1993) published additional photometry and found the period change to be non-linear. Furthermore, they disputed the tidal excitation interpretion in the earlier work, suggesting instead that AU Peg was simply near the red edge of the Instabilty Strip. Vinkó *et al.* (1998) obtained R = 11,000 optical spectroscopy of a number of Type 2 Cepheids and found that AU Peg was unique among them in revealing a P Cygni profile in its Hα line—indicating outflow. More recently the entire Type 2 Cepheid interpretation of AU Peg has been challenged by Jurkovic *et al.* (2007), who instead conclude that AU Peg is a double-mode pulsator (fundamental/first overtone) and a classical Cepheid despite its high galactic latitude and the enormous distance from the disk that such an interpretation would require. An interesting alternative explanation is that AU Peg is the first example of a double-mode Type 2 Cepheid.

Harris and Welch (1989) obtained new radial velocities and determined orbital characteristics for the single-lined spectroscopic binaries IX Cas and TX Del. They also pointed out that both stars had near-solar metallicities. The periods of IX Cas and TX Del, 9.2 and 6.2 days, respectively, are in a period range where few Type 2 Cepheids are known. Balog and Vinkó (1995) argue that the radius of TX Del is too large to be a Type 2 Cepheid and instead should be considered a classical Cepheid, despite the 1.2 kpc height above the disk that would require.

ST Pup is a 18.47-day W Vir star which was found by Gonzalez and Wallerstein (1996) to be in a spectroscopic binary with orbital period 410.4 days. Although it has a $[Fe/H] = -1.47$, it has a depletion pattern very similar to the longer-period stars in the sample of Maas *et al.* (2007) with the exception of an unexpectedly high Ca abundance.

Antipin *et al.* (2007) found the first galactic Type 2 Cepheid in an eclipsing binary: TYC 1031 01262 1. At present, there is no estimate of the Cepheid's metallicity, and no radial velocity observations suitable for determining other orbital characteristics are known to have been obtained.

Of the five systems discovered to date, it is noteworthy that three of the four that have had their composition estimated have near-solar or above-solar metallicities and have short orbital periods and distances. The most straightforward interpretation of this correlation is that there has been mass transfer from a more evolved companion prior to the current instability strip pass.

5. Type 2 Cepheids in Milky Way globular clusters

Clement *et al.* (2001) produced a catalog of all variable stars known in Milky Way globular clusters. Fifty-eight Type 2 Cepheids were identified at the time once two anomalous Cepheids are removed from their count. They note that all clusters containing Type 2 Cepheids have $[Fe/H] < -1.0$ and all except one have $[Fe/H] < -1.25$.

A recent census of Type 2 Cepheids in Milky Way globular clusters south of Declination −30° was provided by Matsunaga *et al.* (2006). Their new discoveries combined with previous work result in forty-six variables in twenty-six southern globular clusters. Their ten new discoveries bring the total number of Type 2 Cepheids in globular clusters to sixty-eight.

6. Type 2 Cepheids in the Milky Way field

The sample of Type 2 Cepheids associated with Milky Way globular clusters is likely to be complete or near-complete, since such stars are among the very brightest cluster members and, along with the horizontal branch RR Lyrae pulsators, have large photometric amplitudes.

The identification of a clean sample of true Type 2 Cepheids among Milky Way field stars has been much more problematic. The list of Harris (1985a) contained 152 field Type 2 Cepheids but was compiled prior to the microlensing, wide-field, and all-sky surveys. The surveys have been a two-edged sword in terms of improving our sample. They have both increased the number of Type 2 Cepheids known and dramatically improved the duration over which high-quality photometry exists but they have also introduced a significant number of false positive Type 2 Cepheid classifications.

A search of the Variable Star Index (Watson 2006) on May 6, 2012, revealed the numbers of Type 2 Cepheid classifications shown in Table 1. The first two variable types (CEP and CEP:) almost certainly contain "underclassified" classical Cepheids as well as Type 2 Cepheids. It is also this pair of classes which likely has the largest contamination of non-pulsating variables—stars that have rotation or orbital periods similar to Cepheids of both kinds.

While the LMC and SMC samples are likely near-complete, the mix of selection biases for the discovery of Type 2 Cepheids in the Milky Way field does not yet lend itself easily to numerical comparisons of subtypes between our galaxy and those in our companion galaxies.

Ed Schmidt's group at the University of Nebraska has been one of the most active in the study of field Type 2 Cepheids, with a number of careful photometric studies (Schmidt 2002; Schmidt *et al.* 2005a; Schmidt *et al.* 2005b; Schmidt *et al.* 2007; Schmidt *et al.* 2009) and spectroscopic studies (Schmidt *et al.* 2003b; Schmidt *et al.* 2003a; Schmidt *et al.* 2011). Schmidt *et al.* (2011) is an important synthesis of early work with numerous significant findings. It reports a uniform set of low-resolution spectra of 288 stars from Schmidt *et al.* (2007) and Schmidt *et al.* (2009)—the first large-scale attempt to produce spectral confirmation of classifications made with light curves. Although the authors expected to find about 560 new Type 2 Cepheids based on the estimates of Wallerstein (2002), they found only nineteen (elsewhere in the paper, the number twenty-three is stated.) This class of variable is easily mistaken for others based on light curves alone. Schmidt *et al.* (2011) also found that Type 2 Cepheids frequently had small (0.1 to 0.4 mag) amplitudes, contrary to conventional wisdom. This amplitude finding has been confirmed by OGLE-III for the LMC and SMC samples (discussed below). Of the "Cepheid Strip Candidates," as the new Type 2 Cepheid candidates are called, most have $-1.0 < [Fe/H] < 0.0$, suggesting an evolutionary path distinct from their counterparts in globular clusters. Although the numbers are small (and therefore the statistics are uncertain), the period distribution of the "Cepheid Strip Candidates" is quite flat in the traditionally underpopulated 4- to 10-day period range. This finding, too, is consistent with the OGLE-III surveys of the LMC and SMC and suggests that there is not such an evolutionary avoidance for this period range—the gap is at least partly due to photometric amplitude selection biases in discovery. The earlier correlation noted between Type 2 Cepheids in binaries and those with near-solar metallicities suggests that a significant fraction of the field population may be binary.

Another major study was that of Soszyński *et al.* (2011) who reported on the classical and Type 2 Cepheids of the OGLE-III microlensing survey fields in the galactic bulge. Of the 335 Type 2 Cepheids, there were 156 BL Her, 128 W Vir, and 51 RV Tau stars. This is the most uniformly observed and selected sample of galactic Type 2 Cepheids. Observations analyzed for this paper were acquired between 1997 and 2009.

7. Type 2 Cepheids in the Magellanic Clouds

Prior to the microlensing surveys of the 1990s few Type 2 Cepheids were recognized in the LMC and SMC.

The very first claim of a Type 2 Cepheid in either of the Magellanic Clouds was made by Tifft (1963) where 1.4300-day period was suggested for a star (6-31) in the field of the SMC which was possibly associated with the globular cluster NGC 121. Such a star would now be classified as a BL Her. Curiously, the star (now also cataloged as 2MASS J00262813-7136591) has not had further photometric follow-up. Payne-Gaposchkin and Gaposchkin (1966) reported only three "W Vir" stars in the SMC: HV 12901, HV 1828, and HV 206. The last of these had a period of 103.8 days which would fall into the period range of RV Tau stars by a more modern usage.

The first LMC Type 2 Cepheids, HV 5690 and HV 2351, were reported by Hodge and Wright (1969). Both were characterized by changing periods. Subsequently, Payne-Gaposchkin (1971) listed a total of seventeen "Population II Cepheids," including the two already discovered. The periods for the seventeen stars ranged from 11.439 to 50.87 days and ten of the stars have notes regarding observed period change. In the photographic surveys of the era, the shorter-period BL Her stars were below the detection threshold.

Welch (1987) obtained single-epoch, near-infrared (JHK) photometry of nine LMC and two SMC Type 2 Cepheids. Three of these with periods between 35.9 and 47.8 days showed K(2.2μm) excesses, indicating the presence of warm circumstellar dust.

The higher-quality, deeper CCD photometry acquired during the microlensing surveys dramatically improved our understanding of the Type 2 Cepheid populations of the LMC and SMC. The MACHO Project published its findings of Type 2 Cepheids (W Vir and RV Tau stars) in Alcock *et al.* (1998) which established the pattern of increased light curve variability with period and showed that there was no clear demarcation between the two classes. The existence of a common period-luminosity relation for the stars was also revealed.

The OGLE-III catalogs of LMC (Soszyński *et al.* 2008) and SMC (Soszyński *et al.* 2010) Type 2 Cepheids are the seminal observational works for these variables.

- In the LMC, 197 Type 2 Cepheids were found (64 BL Her, 96 W Vir, and 37 RV Tau—where the W Vir/RV Tau dividing period was taken to be 20 days).

- In the SMC, 43 Type 2 Cepheids were found (17 BL Her, 17 W Vir, and 9 RV Tau).

- "Exemplar" light curves for the LMC and SMC Type 2 Cepheids have been produced, providing definitive light curve shape classification. It is of interest to note that that light curve amplitude is the smallest in the period range 4–8 days where few Type 2 Cepheids were found in photographic surveys. The dearth of stars in that period range is thought to be due to evolutionary considerations, but amplitude-related discover selection biases may also have played a role.

- In both the LMC and SMC, a set of "Peculiar W Virginis" (hereafter, PCWA) stars were identified with distinctive light curve shapes (more symmetric) and bluer than their normal W Vir counterparts at the same period. The observed fraction of PCWA stars in eclipsing binaries or with ellipsoidal variation (4 of 16 in the LMC and 4 out of 7 in the SMC) is high enough to suggest that all such stars are in binary systems. A clear implication of this finding is that the production of PWCA stars is the result of binary interaction.

- In the LMC sample three of the seven Type 2 Cepheids in eclipsing systems have pulsation periods between 4 and 6 days where the frequency of Type 2 Cepheids is typically very low. Binary interaction may play an important role in populating this period range. If so, study of the few Type 2 Cepheids with similar periods in the Milky Way field may clarify whether such stars are always in binaries.

- The PCWA stars in the SMC all show multiperiodicity. Presumably the addition periods are the result of the Cepheid being non-spherical due to tidal effects.

While the Type 2 Cepheids in the LMC and SMC are too faint for detailed abundance work, they suggest additional avenues of exploration in the Milky Way field and bulge.

8. Opportunities

There is a surprising amount of discovery space available in the study of

Type 2 Cepheids. Here are some immediate suggestions for new observations and/or analysis:

- The great majority of photometry which exists for Type 2 Cepheids in globular clusters is photographic and imprecise. Since these stars are among the brightest in their clusters, they can be easily detected and measured with modern imagers in standard bandpasses. Profile-fitting photometry is needed in such crowded fields, but there are plenty of stars available to get the point spread function right.

- Suspected or uncertain Type 2 Cepheids in catalogs can be further assessed by examining the additional information now available in proper motion surveys, near-infrared colors, and cross-references with X-ray source catalogs. The rotation periods of spotted stars such as BY Dra and RS CVn variables frequently result in their misclassification as Type 2 Cepheids.

- There are few precise (± 2 km s^{-1}) radial velocities of field Type 2 Cepheids—a factor which limits our ability to understand both the frequency of binarity and the dynamical population from which they have been produced.

- No variable star catalog from a long-term photometric survey of the northen sky has yet been released. There are sure to be additional, relatively bright Type 2 Cepheids identified by such a survey and a program of routine photometry of newly-discovered stars will inevitably pay dividends.

- A re-classification of field W Vir stars into "normal" and "peculiar" is warranted as a result of the OGLE-III surveys of the LMC and SMC. It would be most interesting to investigate how metallicity and rates and directions of period change are correlated with these two classes of objects.

- The Type 2 Cepheids discovered in photometric surveys already have time-series available for period change analysis with hundreds to thousands of epochs. Patterns of non-pulsation modulation are waiting to be discovered and defined. The ellipsoidal modulation due to a tidally-distorted pulsator in orbit around a close companion can easily be teased out of available data - a purely photometric indication of binarity.

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Table 1. Counts of Type 2 Cepheid types in VSX.

Variability type	*N*	*Variability type*	*N*	*Variability type*	*N*
CEP	491	CWA:	19	RVA	72
CEP:	141	CWB	237	RVA:	3
CW	11	CWB:	24	RVB	26
CW:	2	RV	81	RVB:	1
CWA	240	RV:	35		