THE NATURE OF THE TYPE C SEMI-REGULAR VARIABLES

D. G. Turner

Department of Astronomy and Physics, Saint Mary's University
Halifax, Nova Scotia B3H 3C3, Canada, *turner@ap.smu.ca*

ABSTRACT. The type C semi-regular (SRC) variables are M-type supergiants like Betelgeuse that undergo regular periodic brightness fluctuations superposed upon seemingly irregular trends. Many of the 55 recognized Milky Way M-type supergiants belonging to the class are multi-periodic, with radial pulsation almost certainly the source of their primary short-period luminosity changes. Noted here are additional characteristics of the stars, not supplied in the GCVS, that can be recognized in their growing archival inventories: amplitude for both long-term and short-term light variability increasing with luminosity, regular changes in mean brightness possibly tied to evolution, and a period-luminosity relation in need of further observational corroboration. As the immediate stellar precursors to many Type II supernovae and as auxiliary standard candles for the extragalactic distance scale, SRC variables are in need of more extensive observational studies to elucidate their many intriguing properties.

Key words: stars: variable: other — stars: late-type.

1. Introduction

Semi-regular variables are defined in the *General Catalogue of Variable Stars* (GCVS, Kholopov et al. 1985) as luminous stars of late spectral type that exhibit noticeable periodicity in their light changes accompanied by variations of a more irregular type. Type C semi-regulars, or SRC variables, are a small subset of the class restricted to M-type supergiants, typically of luminosity classes Ia to II. They may be related to the LC class of slow irregular variables in the GCVS that also comprise late-type supergiants.

There are 57 SRC variables in the GCVS, and 72 LC variables, compared with 490 classical Cepheids and 188 Cepheids of uncertain classification. This order of magnitude difference in numbers evident in the GCVS does not reflect the true space densities of the two types of stars. According to Pierce et al. (2000) and Jurcevic et al. (2000), long period variables, and SRCs in particular, are much more common than Cepheids in most galaxies, are more luminous than Cepheids, and also obey a period-luminosity relation that makes them inherently valuable distance indicators. The problem is that red supergiants tend to be relatively little studied and less well understood than their yellow supergiant kin. Complete light curves are not available for many of them.

Cool M-type supergiants are fairly rare massive stars that display the physical properties of highly evolved objects with progenitor masses of less than about 20 $M_\odot$ according to stellar evolutionary models by Meynet et al. (1993). The upper luminosity limit is established by the fact that more massive stars cannot evolve into the red supergiant region, but remain as hotter stars until their eventual explosion as Type II supernovae. The upper limit to red supergiant masses and luminosities is a recognizable feature in the H-R diagrams for luminous stars in other galaxies (Humphreys 1987).

Although it is expected that all M supergiants will eventually explode as Type II supernovae (Chevalier 1981), two of the most spectacular such events in recent years, SN 1987A in the Large Magellanic Cloud and SN 1993J in M81, apparently originated from B3 I and G8-K5 I progenitors with masses of $\sim$18 $M_\odot$ and $\sim$17 $M_\odot$, respectively (Sonneborn et al. 1987; Aldering et al. 1994). Presumably there was some evolution towards the hot side of the H-R diagram prior to the explosions, although the details are uncertain. If expectations are correct for existing members of the M supergiant population of the Milky Way, then it seems essential to learn more about the role played by SRC variables in the late stages of stellar evolution, since they are the likely progenitors of many future Type II supernovae in the Galaxy. The rapid rate of evolution for massive M supergiants assures that such events will continue to occur in the not-too-distant future. A detailed knowledge of the properties of individual members of the SRC class may therefore have fairly immediate applications.

2. Observational Characteristics

Observational data on the light curves of SRC variables are often limited owing to the long temporal cycles in their brightness levels. The American Association of Variable Star Observers (AAVSO) maintains

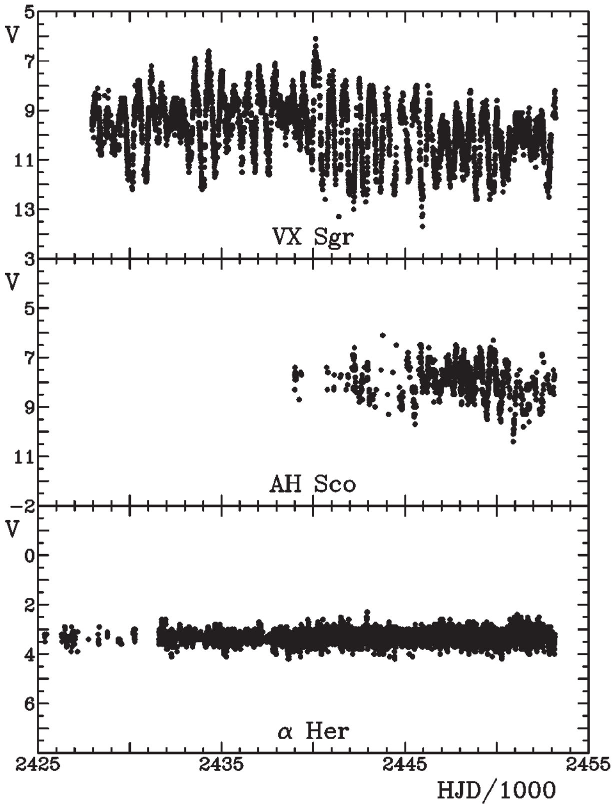

Figure 1: Light curves for the SRC variables VX Sgr, AH Sco, and α Her constructed from AAVSO visual observations (Waagen 2005).

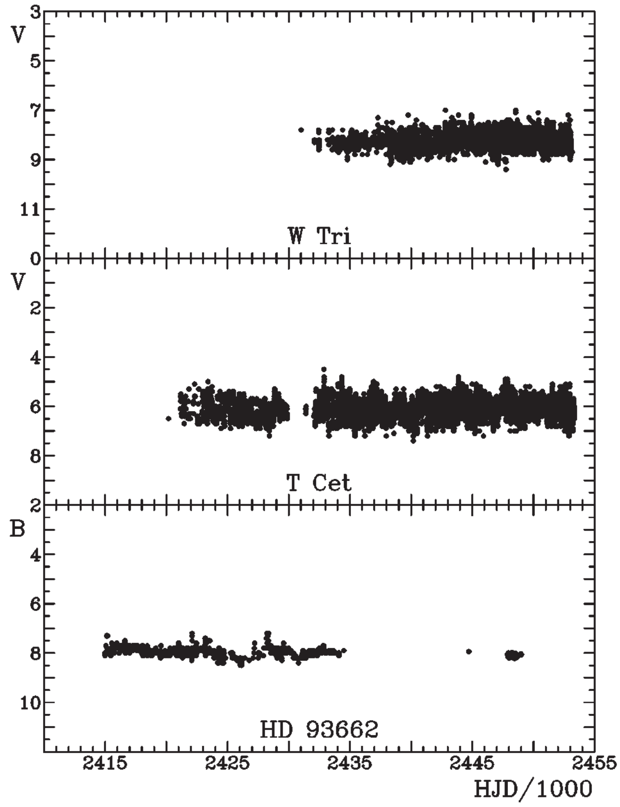

Figure 2: Light curves for the SRC variables W Tri and T Cet constructed from AAVSO visual observations (Waagen 2005), and for the bright M giant HD 93662 from photographic observations (Turner et al. 2005).

extensive databases for a large fraction of listed variables, and they provide instructive information about the light characteristics of individual class members.

Light curves, from Waagen (2005), are illustrated in Figs. 1 and 2 for a sample of SRC variables, all plotted at identical scales to illustrate the dependence of light amplitude on luminosity class for the stars. The nature of the amplitude dependence is illustrated in Fig. 3, and is tied to information available from AAVSO observers and spectral types in the GCVS. Note how light amplitudes increase as surface gravity decreases (towards type Ia supergiants, with emission-line Ia supergiants considered here to be more luminous), a natural consequence of an effect tied to the ability of radial pulsation to counteract the force of gravitational attraction at the star's surface.

Note in Fig. 1 the regular cyclical variations ($P = 757^{\rm d}$) of VX Sgr (M4-10 Iae) superimposed upon longer-term variations in mean light level. The regular cyclical variations ($P = 769^{\rm d}$) of AH Sco (M4-5 Ia-Iabe) are similar to those of VX Sgr, but of smaller amplitude. The star is also less luminous. The variations ($P = 116^{\rm d}$) in α Her (M5 Ib-II) are of small amplitude and the brightness level is essentially constant. The driving force for the variability is less effective against gravity in α Her than in more luminous M supergiants.

Note in Fig. 2 that the variations ($P = 592^{\rm d}$) in W Tri (M5 II) are small, and the mean light level of the star is relatively stable. The light variability ($P = 288^{\rm d}$) of T Cet (M5-6 II) displays an amplitude closer to that of class Iab SRC variables than class Ib-II stars. Finally, the star HD 93662 (M1 II) has $P = 5756^{\rm d}$ (Turner et al. 2005), but does not display the cyclical nature typical of SRC variables. Its variability is more typical of starspot or chromospheric activity. A similar object may be the newly-discovered SRC variable BD+20°1171, which appears to display light fluctuations on an even longer time scale (Brukhanov 2001).

Another source of archival observational data is the Harvard College Observatory Photographic Plate Collection, which contains images dating from roughly 1890 to the mid 1990s. Harvard plates are relatively untapped for the study of SRC variables to our knowledge, but are very useful for obtaining information on light variability and period changes in members of the class less frequently observed by AAVSO members.

Examples are shown in Fig. 4 for the southern SRC variables CL Car (M5 Ia), which has $P = 512^{\rm d}$, and IX Car (M2 Iab), which has $P = 357^{\rm d}$. Note how the

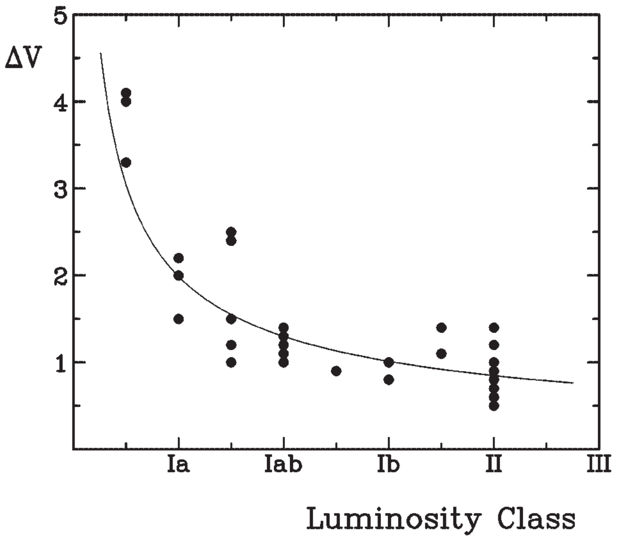

Figure 3: The trend in pulsational V amplitude as a function of spectroscopic luminosity class for SRC variables, as derived from AAVSO observations and GCVS data. Emission-line type Ia M supergiants are assumed to be more luminous than regular Ia supergiants. A possible trend line is illustrated.

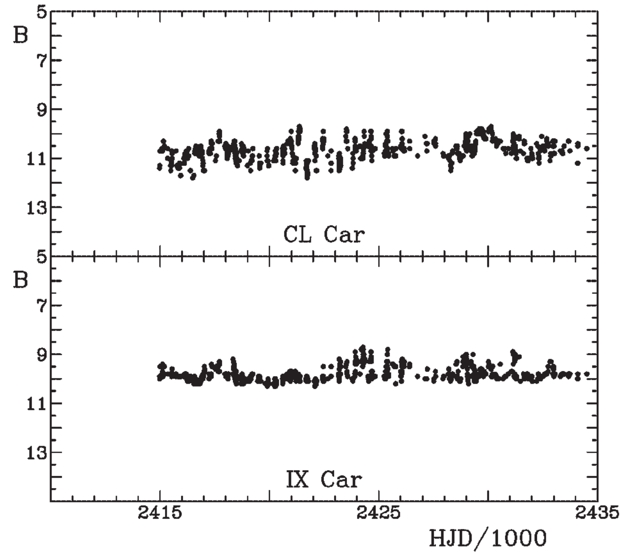

Figure 4: Light curves for the SRC variables CL Car and IX Car constructed from eye estimates off plates in the Harvard College Observatory Photographic Plate Collection.

photographic amplitude of IX Car increases as the star brightens. A separate study of the northern SRC variable BC Cyg in the open cluster Berkeley 87 is presented by Rohanidazegan et al. (2005).

3. Pulsation in the SRC Variables

Stothers (1969) used stellar evolutionary models to confirm pulsation as the origin of variability in M supergiants, noting the existence of a period-luminosity relation for cluster and association members. Glass (1979) found that SRC variables in the Large and Small Magellanic Clouds also follow a *PL* relation, which was confirmed using data for additional LMC SRC variables by Feast et al. (1980). Wood et al. (1983) used a deeper survey of long period variables in the LMC and SMC to separate M supergiant variables from variables belonging to the asymptotic giant branch (AGB). As noted by Wood et al. (1983), the masses of M supergiant variables are clearly much larger than those of AGB variables.

Kinman et al. (1987) further developed the usefulness of SRC variables as extragalactic distance indicators, and noted that those in the LMC follow the same *PL* trend as SRC variables in M33, making them excellent distance indicators. The most recent use of SRC variables as standard candles has included studies by Pierce et al. (2000) and Jurcevic et al. (2000) to re-establish a Galactic calibration of the *PL* relation to determine the distances to the LMC and M33.

It is possible to establish a period-luminosity relation for SRC variables using the few that are members of open clusters and associations, but the optical calibration relies heavily on the adopted scale of effective temperatures and bolometric corrections. Infrared calibrations are provided in the references cited above. An optical calibration tied to M supergiants in the region of h and χ Persei (Per OB 1) and Berkeley 87 is presented in Fig. 5. The relationship is similar to the *PL* relation for Galactic Cepheids, but displays more scatter. The calibration sample may contain a few objects that are not physical members of Per OB1, or perhaps some M supergiants pulsate in overtone modes. Further tests are needed to resolve the problems inherent in the existing sample. A *PL* relation for SRC variables predicted from period-radius and effective temperature relations is included for reference purposes in Fig. 5.

4. Discussion

Existing information on SRC variables is relatively incomplete because of the limited availability of observational data for them covering time intervals of a century or more. Uncertainties about class members raise a number of as-yet-unanswered questions. Do all SRC variables pulsate, or are there other mechanisms at work causing variability, particularly in low amplitude variables? Does circumstellar dust and/or gas play a role? Do luminous SRCs pulsate in the fundamental mode, or do some pulsate in overtone modes? What causes the slow changes in mean brightness of stars like BC Cyg, VX Sgr,and S Per? Is there a bet-

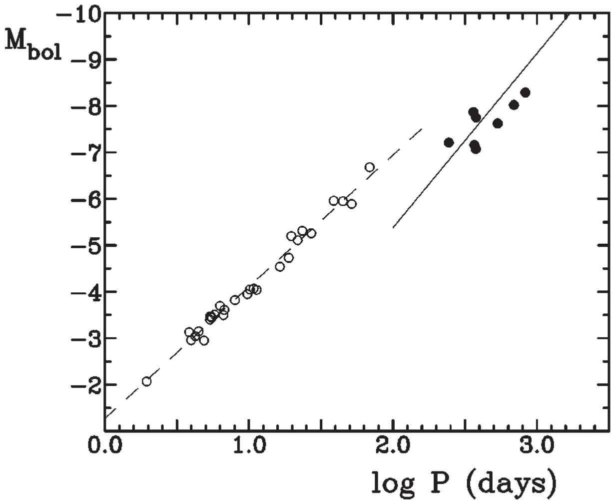

Figure 5: A period-luminosity relation for SRC variables in Per OB1 and Berkeley 87 (filled circles) constructed from *BV* data for the stars in conjunction with their known reddenings. Shown for comparison is the Galactic calibration of the Cepheid period-luminosity relation (open circles). The solid line is a calibration based upon theoretical considerations, the dashed line a fit for cluster Cepheids.

ter method of classifying the SRC variables to account for differences in the nature of their variability?

Future work should probably include continuous spectroscopic or infrared observations of SRC variables over complete pulsation cycles to confirm the apparent colour changes, detailed light curves for SRC variables in a larger sample of open clusters, possibly the construction of more advanced pulsation models for red supergiants, and the development of a larger sample of SRC variables with comprehensive, that is, 100-year baseline, light curves. The last noted is possible through additional archival studies.

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