Ground-Based and ISO Observations of Semiregular and Mira Variables

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Abstract We briefly compare various properties of Semiregular, Irregular, and Mira variables, and then discuss the importance of new observational and theoretical tools for understanding these groups of long period variables.

1. Introduction

A crucial stage during the late evolution of stars with main sequence masses between 0.8 and $8M_{\odot}$ is the Asymptotic Giant Branch (AGB). Stars in this evolutionary phase are characterized by several important phenomena: explosive He-burning (thermal pulses), the production of heavy elements via the s-process, pulsations with periods between 30 and 2,000 days, shock fronts propagating through the atmosphere, the formation of molecules and dust, and a mass loss of 10^{-7} –10^{-4} $M_{\odot}$ per year. All this has made them attractive targets for both professional and amateur astronomers (see the reviews by Habing 1996 and Mattei, this volume).

2. Variability types and molecular features

The variability classification of long period variables (LPVs) in the *General Catalogue of Variable Stars* (GCVS, Kholopov *et al.* 1985) is based on the amplitudes and regularity of the *visual* light curves. In order of increasing amplitude and regularity, the GCVS distinguishes between Irregular (L), Semiregular (SR), and Mira variables. In this paper we will exclude the SRc and Lc subtypes, which are thought to be supergiants.

The variations in the visual are strongly influenced by variations in the molecular features. If oxygen is more abundant than carbon (M stars), TiO and VO are the dominant molecules in the visual, while for carbon stars (C/O > 1) the molecular bands come from C_2 and CN (e.g., Jørgensen 1994). The TiO and VO bands are stronger and more temperature-sensitive than the bands of C_2 and CN. This has two important consequences with regard to the variability classification: (i) For the same bolometric amplitude, M stars can reach larger visual amplitudes than C stars. This is probably partly the reason for the higher fraction of SR and L variables among the C stars in the GCVS. (ii) The visual amplitudes of M stars are a complex function of the bolometric amplitude, the temperature amplitude, and the mean temperature of the star. This has to be taken into account when analyzing visual amplitudes in terms of general pulsational characteristics and fundamental stellar parameters (Mowlavi and Jorissen, this volume).

3. A brief comparison of oxygen-rich Lb, SRa, b, and Mira variables

In view of the small number of C-rich variables and the above-mentioned problems with variability classification, we will not include C stars in the following discussion. The comparison is mainly based on work carried out in Vienna during the last few years on SR and Lb stars. We make no distinction between the SRa and SRb subtypes (Kerschbaum and Hron 1992, 1994; hereafter KH92 and KH94, respectively—call them SRVs. Most of the results also hold for the Lb stars (Kerschbaum, Lazaro, and Habison 1996), although the available information is still somewhat limited.

3.1. Pulsational properties

The average periods of SRVs are significantly shorter than those of Miras, with an overlap between 100 and 200 days. SRV visual amplitudes are (by definition) smaller. From the available near-IR photometry one can conclude that this is probably also true for the bolometric amplitudes (KH94). The near-IR data also indicate that the temperature variations are smaller for SRVs. However, real IR light curves are still very sparse. The situation is clearer with regard to the velocity variations in the photosphere. The near-IR CO lines show typical velocity amplitudes of 5–10 km/s and 18–30 km/s for SRVs and Miras, respectively (Figure 1, taken from Lebzelter 1998). The SRVs apparently do not follow the period/luminosity and period/color relations of the Miras (KH92; Schultheis *et al.* 1998), but are cooler and more luminous than Miras at a given period.

Combining all this information, and considering that the masses of Miras and SRVs are comparable (KH92), it is likely that the SRVs are pulsating in a higher pulsation mode (or higher *modes*) than the Miras. Wood and Sebo (1996) found that for LPVs in clusters in the Large Magellanic Cloud (LMC), the amplitude alone is not enough to distinguish between fundamental and overtone pulsators. The fundamental mode pulsators can have amplitudes as small as the overtone pulsators. This is supported by results for SRVs in the galactic bulge (Schultheis *et al.* 1998) and in the LMC (Hughes and Wood 1990). These stars, which were classified as SRVs mainly on the basis of their small optical amplitudes, follow the period/luminosity and period/color relations of the Miras. Thus the galactic SRVs may also contain some intrinsic Miras, especially those with longer periods.

3.2. Atmospheric structure

The near-IR colors of SRVs indicate that their atmospheres are less extended than those of Miras (KH94; Bessell *et al.* 1989). For stars with periods below about 80 days, a hydrostatic atmosphere seems to be a good approximation. The weaker or absent Balmer emission lines (KH92), and the smaller or absent line splitting observed for the IR CO lines (Hinkle *et al.* 1997) are evidence for weaker shock fronts in SRVs. This might be expected from the discussion in section 3.1 above.

3.3. Circumstellar matter and mass loss

The average mass loss rates (gas and dust) and wind velocities of SRVs are lower than for Miras (Kerschbaum, Olofsson, and Hron 1996; Hron *et al.* 1997a). SRVs with periods below about 80 days show no significant mass loss. However, the mass loss rates and wind velocities of the SRVs with longer periods are comparable to those of Miras with periods shorter than about 400 days. This means that there is no clear relation between mass loss and period or pulsation mode for these stars. Thus the pulsation does not seem to be the dominant factor for driving the mass loss. For similar mass loss rates, there is also a great similarity between the 10-μm dust features of Miras and SRVs, but for SRVs with thinner dust shells there seems to be a much stronger influence of the atmospheric structure on the dust composition than for Miras (Hron *et al.* 1997a).

3.4. Fundamental stellar parameters and evolutionary status

The galactic scale height and number densities of Miras and SRVs are comparable (KH92), which means that their average initial masses must be quite similar. The SRVs are *on the average* hotter and less luminous than the Miras, and also the content of such dredge-up products as technetium is lower for the SRVs (Lebzelter and Hron 1995). This would indicate that the SRVs are in an evolutionary phase preceding the Mira stage. However, the observational data are not very conclusive. Data from the Hipparcos mission (Grenon 1999) and the determination of carbon isotopic ratios should help to clarify this point.

4. New frontiers

4.1. Variability characteristics of SR and Lb variables

Lebzelter *et al.* (1995) have shown that the light curves are quite poorly known for about 40% of the SRVs in the GCVS. If the same is true for the Lb stars, many of these stars may be SRVs with undersampled light curves. This would also explain the large similarity between SRVs and Lb variables in many aspects. The small amplitudes of the SRVs and Lb stars make them difficult targets for visual observations. A comparison of simultaneous AAVSO data and observations with the Phoenix 10-inch robotic telescope (APT) illustrates this (Figure 2).

For a better understanding of the evolutionary status and the interior structure of SRVs and Lb stars, their variability characteristics (frequencies, amplitudes, possible frequency changes) have to be known. This requires long-term observations with accuracies better than a few 0.01 magnitude. Such data sets existed for only a few stars until now (e.g., Cristian *et al.* 1995). Therefore we have recently started a long-term photoelectric program with the Vienna University twin APT (Strassmeier *et al.* 1997). In view of the limited observing time at professional telescopes, photoelectric and CCD observations by amateur astronomers are an extremely useful extension of such a program. In addition, an analysis of systematic effects in the AAVSO data, as discussed during this conference, is definitely worthwhile.

Full advantage could then be taken of the very long time base available for many AAVSO program stars. Finally, the Hipparcos photometry (Grenon 1999) is also an important data source.

4.2. New model atmospheres

The atmosphere of an LPV is a very extended and highly dynamic structure due to pulsations and the formation of dust and molecules. Classical model atmospheres, however, assume a hydrostatic configuration without dust. Thus it is not surprising that synthetic spectra and colors computed from such classical model atmospheres are not really in agreement with observations (e.g., Aringer *et al.* 1997 and Figure 3, top and bottom panels).

Considerable progress has been made in this field in the last few years. Bessell *et al.* (1989) were the first to compute spectra for M-stars based on dynamic model atmospheres. The atmospheres were constructed in a way similar to what is described by Willson (1999), but they do not contain dust. Dynamic models with dust formation have so far only been constructed for carbon stars (see Höfner *et al.* 1997), due to the complexity of dust formation for $C/O < 1$. Synthetic spectra for multiple phases of the light curve, based on the models of Höfner *et al.*, were presented by Loidl *et al.* (1997), and they are shown in the middle panel of Figure 3. The agreement with the observations is better than for the static model atmospheres, but further improvements of the models are necessary.

Dynamic model atmospheres with dust formation are also important for interpreting existing and future high angular resolution observations of LPVs (Windsteig *et al.* 1997; Karovska 1999).

4.3. Variability in the infrared

Observations in the IR sample basically all atmospheric layers of an LPV, and thus they provide important information about the processes going on in the atmospheres. However, photometric and especially spectroscopic data about the variations in the IR are still very sparse (e.g., Whitelock *et al.* 1997) due to the Earth's atmosphere and the limitations of available detectors. The great progress in the last decade in IR detector technology has made ground-based IR observations almost as easy and efficient as observations with optical CCDs. This will provide much more photometric and spectroscopic data for LPVs.

Another major step forward is the very successful ESA satellite ISO, with its unprecedented photometric and spectroscopic capabilities between 2 μm and 200 μm. The first exciting results have been published in a special issue of *Astronomy and Astrophysics* (November 1996). Figure 4 shows spectra of two LPVs taken for an observing program of the Vienna group (Hron *et al.* 1997b) with the Short Wavelength Spectrometer (SWS). Observations with such a wavelength coverage would have taken several observing runs with ground-based and airborne telescopes, and even then the resolution and sensitivity would have been much worse. The total observing time for one such ISO spectrum was only 30 minutes! The spectra show a rich variety of features in molecules and dust, some never observed before. The observing program also yields spectra at different pulsational phases, and the data will thus help to improve the dynamic model atmospheres discussed previously.

5. Concluding remarks

New observational and theoretical methods will considerably improve our understanding of the complex processes going on in the atmospheres of Irregular, Semiregular, and Mira variables. The long-term observations provided by amateur astronomers are, however, still extremely important for planning and interpreting observations with modern instruments, and as constraints for theoretical models.

6. Addendum, 2006

For the progress related to ISO spectra, model atmospheres, and atmospheric kinematics you may consult the website of the Vienna AGB-group and the publications listed there: http://www.univie.ac.at/agb/.

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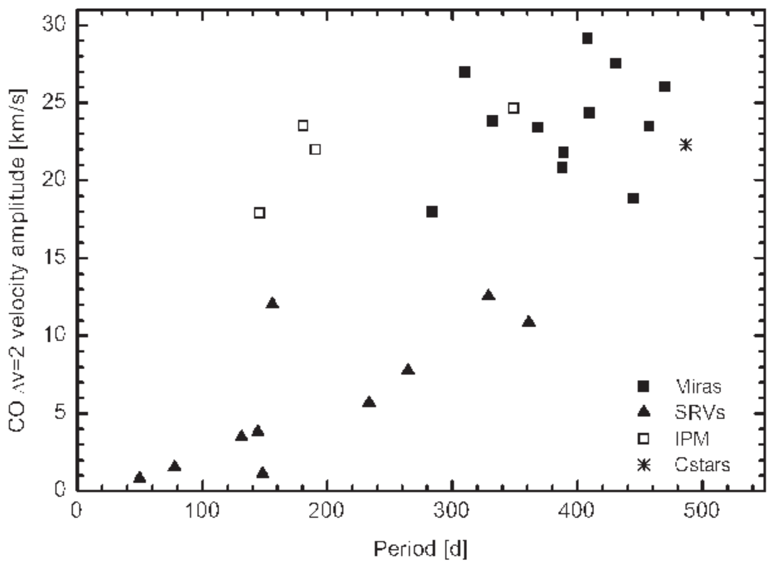

Figure 1. Velocity amplitudes as derived from CO lines in the near IR for different LPVs (from Lebzelter 1998). IPM stands for intermediate population (metal-poor) Miras.

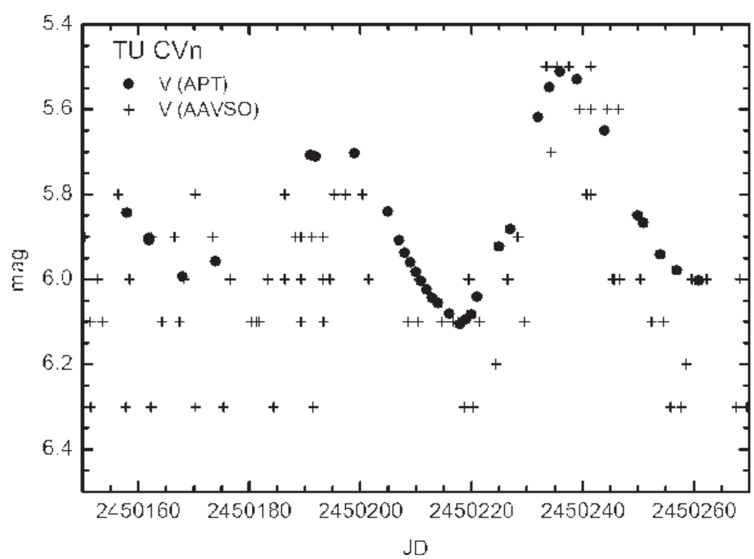

Figure 2. Comparison of AAVSO data and observations with a 10-inch APT. The offset between the AAVSO and APT data is probably a systematic effect in the AAVSO data.

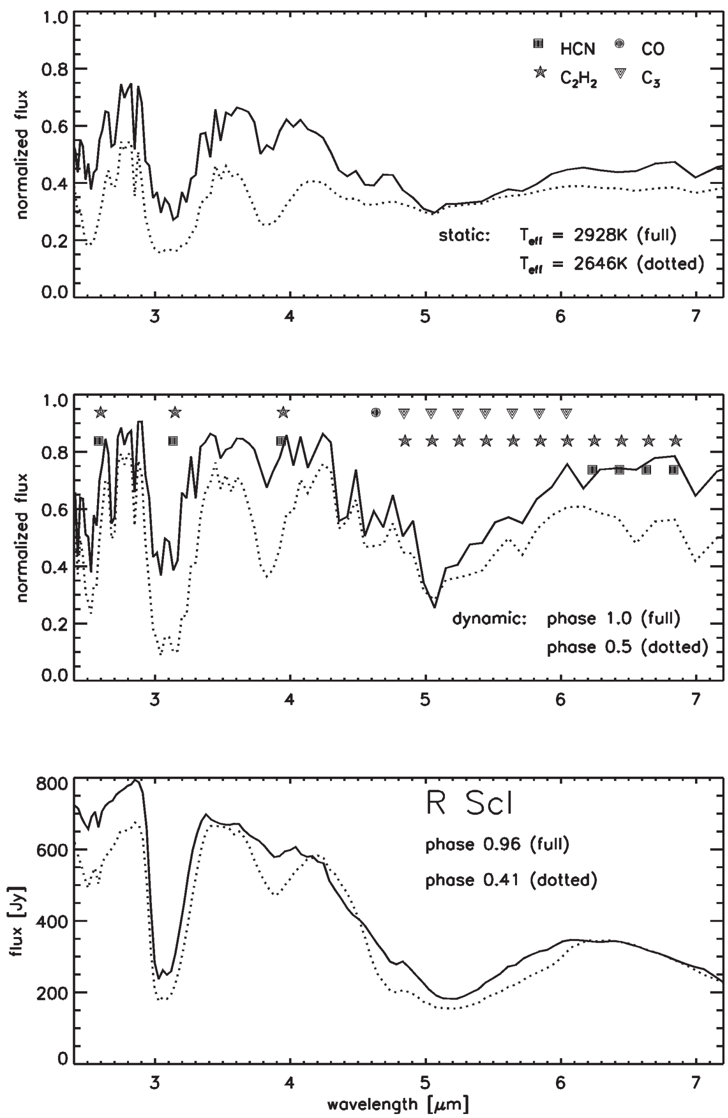

Figure 3. Synthetic and ISO spectra for carbon stars. The synthetic spectra are from Loidl *et al.* (1997). The upper panel shows spectra based on hydrostatic model atmospheres; the T_{eff} values approximately correspond to the expected values for maximum (full line) and minimum light (dotted line) for R Scl. The middle panel uses dynamic model atmospheres by Höfner *et al.* (1997) for two phases. A computer animation of the spectral variations over the light cycle is available from the author. The symbols denote different molecular features. The lower panel shows ISO-SWS spectra of the SRb star R Scl, rebinned to a resolution of 100.

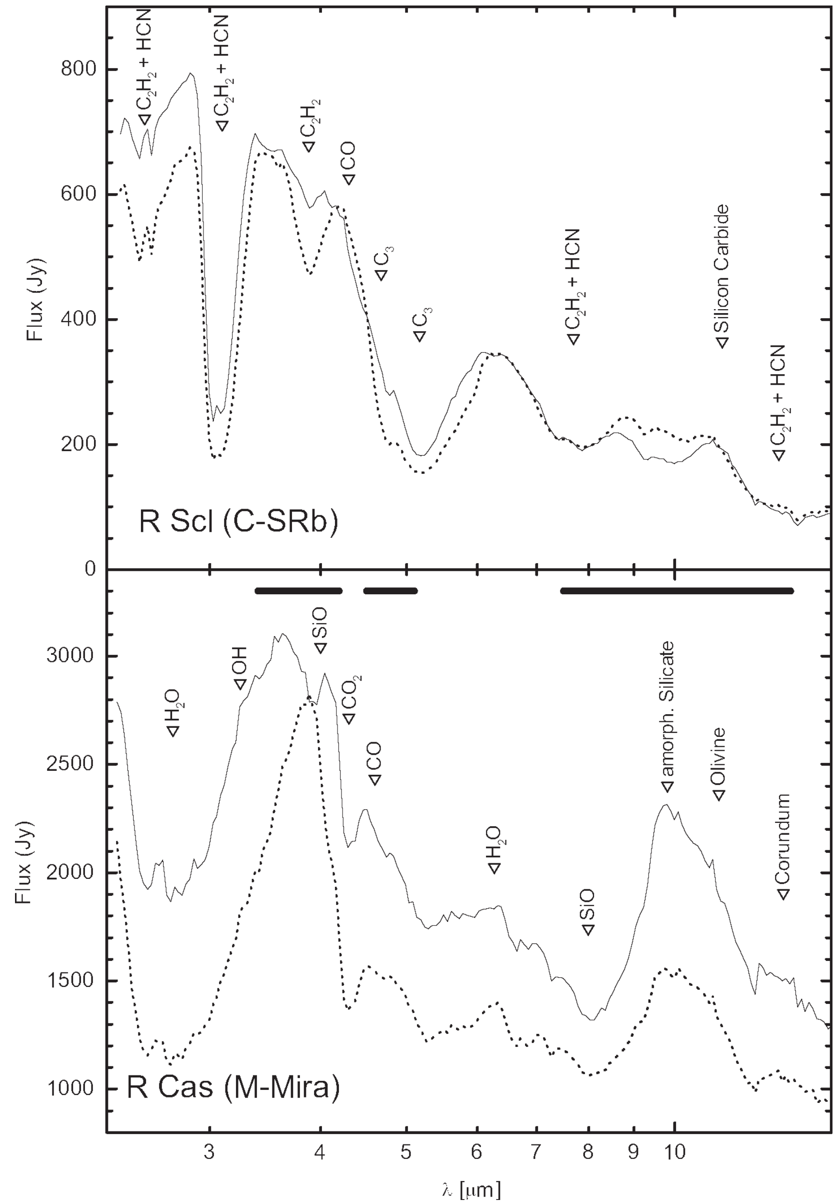

Figure 4. ISO-SWS spectra of two LPVs taken near maximum and minimum light (full and dotted lines, respectively). The most important molecular and dust features are identified, and the spectra are rebinned to a resolution of 100. The thick horizontal bars in the lower panel denote the wavelength regions where ground-based observations are possible.