New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000397

Variable Red Giants

Franz Kerschbaum and Walter Nowotny

University of Vienna, Department of Astronomy, A-1180 Wien, Austria
email: franz.kerschbaum@univie.ac.at

Invited Talk

Abstract. The longest-known class of pulsating variable stars, namely pulsating red giants, is also the one that involves the most complex physical processes. Pulsation, mass loss, nuclear synthesis, mixing, atmospheric and circumstellar chemistry and dust formation all interrelate with one another and make both the observational studies and the modelling efforts quite challenging. The paper outlines some of the current key questions, and recommends observational strategies.

Keywords. stars: late-type, stars: AGB and post-AGB, stars: variables: other, stars: oscillation, stars: winds, outflows

1. Introduction

Within a publication mainly devoted to Venus and Mercury transits, Hevelius (1662) added *Quibus accedit succincta Historiola, novæ illius, ac* ***miræ*** *stellæ in collo ceti, certis anni temporibus clare admodum affulgentis, rursus omnino evanescentis.*† That text gave the first report of the early observations of a very special star, discovered by David Fabricius on 1596 August 13 in the constellation Cetus. After fading during the ensuing months it was seen to brighten again about ten years later, which was rated by observers of the 16^{th} or early 17^{th} century as very unusual behaviour. From then on it received increasingly more attention, and in 1639 Johannes Holwarda was the first to derive a period of 11 months. *o Ceti*, or (following Hevelius) *Mira*, proved to be the first pulsating variable to be discovered, and thereby opened a new line of astronomical research.

Today we know Mira as red giant star on the Asymptotic Giant Branch (AGB, Habing & Olofsson 2004; Kerschbaum *et al.* 2011). This article is focused mainly on AGB stars but also addresses similar time-variable phenomena of Red Giant Branch (RGB) and Red Supergiant stars.

Both AGB and RGB stars exhibit a wide range of time-variable observables: luminosity, colour, colour index and the whole spectral energy distribution, as well as spectral features like line or band strengths, line shapes and radial velocities. The period itself may also be variable, as too can be the light-curve's shape, the chemical composition, the overall morphology, the diameter, the mass loss . . . and many more features. Those observables and related derived quantities all vary on time-scales of a few days or even a few hours, up to 10^4 years. What a challenge to observational "time-domain" astronomy!

† "to which he has attached a short history of that new, wonderful star in the neck of Cetus, which is clearly visible during certain times of the year, but is afterwards completely invisible."

2. AGB Variables

2.1. *Pulsating atmospheres and mass loss*

The outer layers of very evolved stars on the AGB are strongly influenced by dynamical effects, and deviate significantly from those of less evolved red giants which on the whole show a hydrostatic configuration (Nowotny *et al.* 2010). Radial pulsations excited in layers below the photosphere lead to time-dependent variation of the atmospheric structure. On top of that, radiation pressure on dust particles which can form in the levitated cool layers cause an outflow of gas and dust. As the time-scale of pulsation differs from that of dust formation, the dynamic behaviour in the dust-forming region can differ from one object to another. Although it remains challenging to model the complex interplay of the physical processes present in the atmospheres of pulsating and mass-losing giants on the AGB, significant progress has been made in the last years (see Höfner 2009). Fig. 1 shows self-consistent dynamic model atmospheres simulating the dust-driven stellar wind occurring in the atmosphere of a C-type Mira. It starts with the initial hydrostatic model ($L_\star = 7000\,L_\odot$, $T_\star = 2600\,$K, C/O$\,=1.4$), and the dynamic effects are introduced by a variable inner boundary ($P = 490^{\rm d}$, $\Delta u_{\rm p} = 6\,{\rm km\,s^{-1}}$). As discussed in detail by Höfner *et al.* (2003) or Nowotny *et al.* (2010, 2011), it leads to a realistic description of the photometric variations ($\Delta m_{\rm bol} \approx 1^{\rm mag}$) and of the resulting mass loss ($\langle \dot{M} \rangle \approx 2.5{\cdot}10^{-6}\,M_\odot{\rm yr}^{-1}$, $\langle u \rangle \approx 7.5\,{\rm km\,s^{-1}}$).

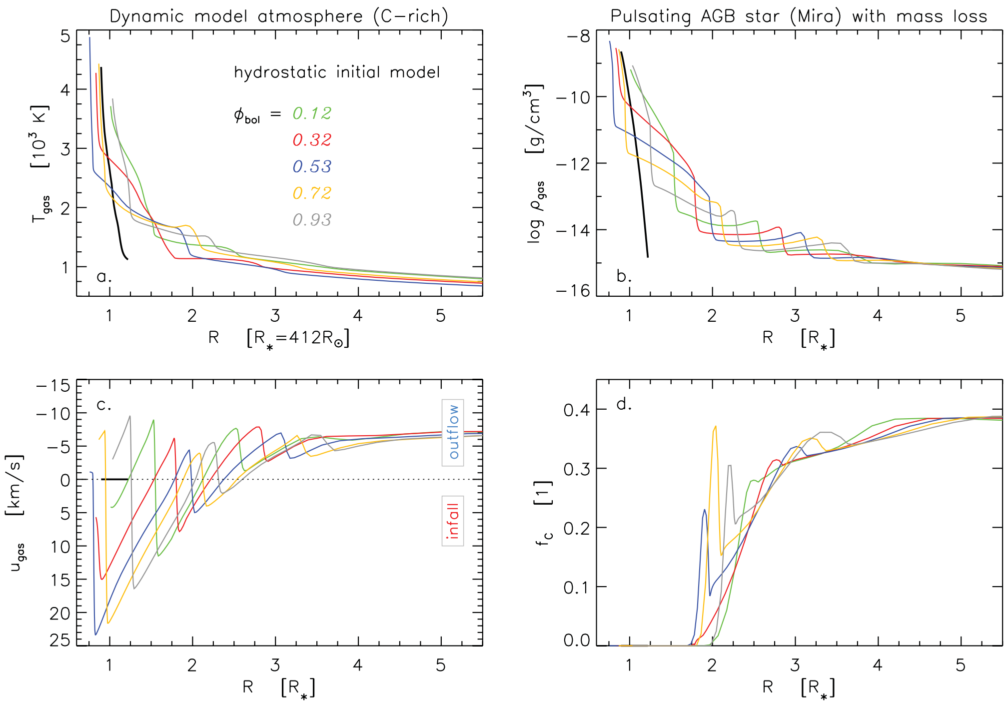

Figure 1. Radial structures of a model atmosphere resembling a typical Mira variable with dusty outflow. A few selected phases ($\phi_{\rm bol}$) during a pulsation cycle are compared with the corresponding hydrostatic model atmosphere (thick black). From Nowotny *et al.* (2010).

2.2. *Multi-colour light curves*

A fundamental approach to characterise a variable AGB star and to test modelling efforts as decribed above is the monitoring of the photometric variations throughout the

https://doi.org/10.1017/S1743921312000397 Published online by Cambridge University Press

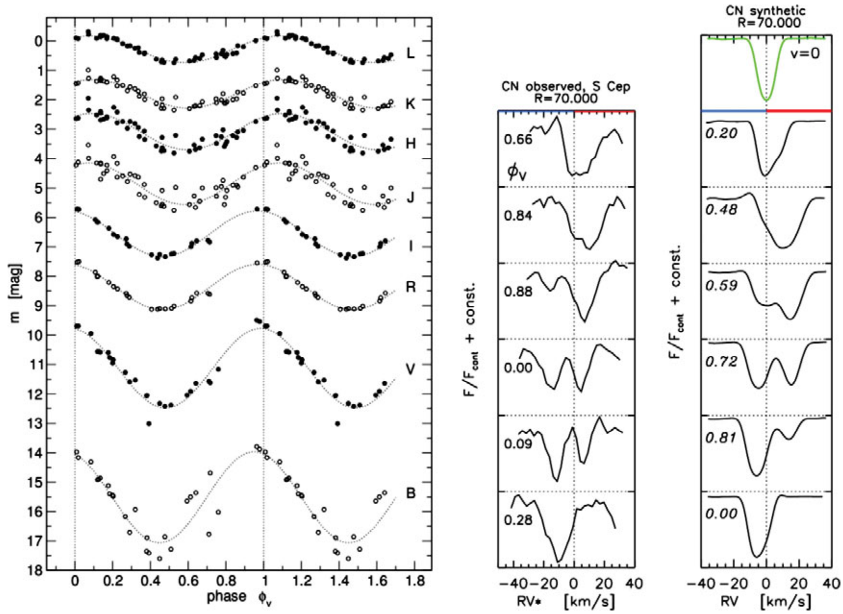

Figure 2. Left panel: Observed photometric variations of the C-type Mira RU Vir in various broad-band filters from the visual to the NIR (right-hand ordinate). Measurements from different periods (open/filled circles) are merged into a combined light cycle; each data point is then plotted twice. Dotted lines represent sinusoidal fits. From Nowotny *et al.* (2011). Two right hand panels: A comparison of observed (middle) and synthetic (right) line-profile variations. The plotted CN lines, which can be found near 2 μm in high-resolution spectra of long period variables, show characteristic behaviour throughout the light cycle, with line doubling around phases of maximum visual light. From Nowotny *et al.* (2010).

light-cycle from the visual to the NIR, thus covering the bulk of the spectral-energy distribution. Nowotny *et al.* (2011) compiled such multi-colour light curves exemplarily for the Mira RU Vir by adopting data from Eggen (1975; *BVRI*) and Whitelock *et al.* (2006; *JHKL*); the result is shown in Fig. 2.

2.3. *Velocities and line-profile variations*

Another interesting way to investigate dynamic effects in AGB stars is to study line-profile variations in high-resolution spectra of such objects. The complex velocity fields in AGB atmospheres (cf. Fig. 1c) strongly influence molecular line profiles (shapes, time-dependent shifts in wavelength, multiple components), see Fig. 2. Radial velocities derived from Doppler-shifted spectral lines provide information about velocities in the corresponding line-forming region. Time-series high-resolution spectroscopy (mainly in the NIR) thereby allows one to probe the atmospheric kinematics, such as the propagation of shock waves within the atmosphere (Hinkle *et al.* 1982; Nowotny *et al.* 2010).

2.4. *Pulsation, spatial resolution*

The large physical size and high absolute IR luminosity of AGB stars make them ideal targets for high-resolution spatial observations to resolve their stellar diameters. That ultimatively provides critical tests for current modelling efforts and our understanding of the stellar physics. As typical examples, Woodruff *et al.* (2008) were able to monitor the angular diameters of AGB variables at various wavelengths, probing different atmospheric layers and even dust-forming zones by means of near-infrared aperture masking using the Keck I Telescope. Paladini *et al.* (2009) estimated time- and wavelength-dependent interferometric observables like visibilities and uniform disk radii from their dynamical model atmospheres. Wittkowski *et al.* (2011) compared their VLTI-AMBER spectroscopy to self-excited dynamical model-atmosphere diameters (Ireland *et al.* 2011), demonstrating the potential of near- and mid-infrared interferometers like the VLTI.

2.5. *Changing periods*

For variables whose observational history can sometimes exceed a century (Mattei *et al.* 2002), research into long-term changes in period and possibly also in regularity or light-curve shape is feasible. Wood related observed changes in the periods of some well-studied Mira variables to the effects of a recent thermal pulse (Wood, 1975). Later, Wood & Zarro (1981) interpreted such changes as long-term luminosity evolution, though the explanation by Zijlstra *et al.* (2004) of a chaotic feedback of atmospheric opacity and pulsations takes a completely different line. However, a systematic study by Uttenthaler *et al.* (2011), searching for the dredge-up of the radio-active *s*-process element Technetium in stars that show such period changes, ruled out a link to recent thermal pulses.

2.6. *Period-Luminosity Relations*

Correlation between pulsational period, luminosity and colour index (PL or PLC) in Mira variables has been known since the 1960s (Osvalds & Risely 1961; Feast, 1963). Owing to missing or uncertain distances of field stars, the first tight PL relation was found for Miras in the LMC (Glass & Lloyd Evans 1981). Wood *et al.* (1999) then demonstrated multiple PL(K) relations from large MACHO and OGLE datasets. The distributions in these sequences have been related to (*inter alia*) radial modes, binarity, non-radial pulsation modes, convection, mass loss and chromospheres (Wood, 2010). The well-populated, tight sequences of the fundamental and first overtone radial-pulsation modes proved to be useful for distance measurements, both in the Milky Way field and in extragalactic systems.

2.7. *Extragalactic AGB stars*

In the tradition of the pioneering work by Glass & Lloyd Evans (1981) on LMC Miras, the next challenge was to work outside the local group. The most distant application of Mira PL-relations was made by Rejkuba (2004 and references therein) on Cen A halo long-period variables. They confirmed an intermediate-age population there, and compared the distances from a Mira PK-relation and the RGB tip at 4 Mpc. In fact they agree very well, to within 0.05 mag. There is a rich future for the up-coming E-ELT era!

Within the local group, Whitelock *et al.* (2009) and Menzies *et al.* (2011) have recently monitored the dwarf spheroidals in Fornax and Sculptor in the near infrared. Accurate distances could be derived for both galaxies, and also clues about the star-formation history. Lorenz *et al.* (2011) monitored in total more than 700 long-period variables for two years in the dwarf spheroidals NGC 147 and NGC 185, leading not only to improved distances for the systems but also to the classification of the variables into fundamental- and overtone-mode pulsators of defined atmospheric chemistry. The different star-formation history of the galaxies was related to the differing distribution of variability classes.

2.8. *Long-term changes in mass loss*

While it is well established that mass loss increases on average during AGB evolution (Habing 1996), there is also observational evidence (Olofsson *et al.* 1988) for more episodic processes. Interferometric mm-CO maps of so-called detached shells are intriguing examples of that (Olofsson *et al.* 2000). Similar structures are also evident from dust emisson (Kerschbaum *et al.* 2010; Decin *et al.* 2011) or scattered light (Mauron *et al.* 2000). The corresponding mass-loss modulations happen on time-scales of 10^2–10^4 years, i.e. much longer than pulsational ones and shorter than thermal inter-pulse times.

3. Asteroseismology and Exoplanet Missions

Somewhat similar to the realisation of valuable output from monitoring projects like OGLE or MACHO which were not originally designed for research into red variables, astroseismology and exoplanet space missions are now also revolutionizing this field by the unprecedented availability of high-cadence, high-precision photometric data sets.

Using observational data from CoRoT, Lebzelter (2011) investigated a sample of long-period variables for the small amplitude variations that are sometimes claimed on unusually short time-scales (hours or days instead of months or years) and found a quite low rate of such events: only 0.15 per star and year.

For RGB stars the KEPLER mission is proving to be extremely fruitful. Because of the large sample sizes, ensemble seismology of hundreds of objects is now possible (Huber *et al.* 2010), and also supports statistically meaningful conclusions. By analysis of the mode spacings, Bedding *et al.* (2011) succeeded in differentiating between H-shell- and He-core-burning objects for the first time. After long searches Gravity-Mode period spacings have also eventually been identified (Beck *et al.* 2011).

Whereas KEPLER focuses on relatively small fields and faint objects, the new mission BRITE-constellation (Kuschnig *et al.* 2009) to be launched in early 2012 will be devoted to objects brighter than about $V = 5\,\mathrm{mag}$, thus allowing easy follow-up observations with medium-sized telescopes and interferometers. The Canadian-Austrian-Polish cooperation will use 6 nanosats with 3-cm-aperture telescopes to make high-precision and high-cadence observations in two filter bands. Short-term phenomena that can be expected in late-type giants include flares, convection signatures, spots, acoustic-, mixed- and gravity modes, and dimmings related to mass loss.

4. "Wish list" for Variable Red Giants

The multitude of time-variable observables and the complex, interrelated physical phenomena in the field of red variables put special constraints on observational data. A few general desiderata are mentioned below.

- Multi-wavelength monitoring is often a key to successful comparisons with theoretical models.
- Do not neglect the red, and especially the near infrared. Simultaneous visual data are preferable for studying variable light-curve shapes and amplitudes in general. "Phased" material is less useful.
- In the field of asteroseismology both ground- and space-based surveys often monitor their fields for only relatively short periods. In order to increase the usefulness of such data for studies of red variables too, we urge that they monitor for longer than a few months—or return to the same field later.
- Photometry should be carefully cross-calibrated, and supplied with transformations, to enable the data to be combined with vintage material.
- Historic photographic plates constitute a valuable tool for probing long-term amd maybe even evolutionary-scale variations. Please make that information available in an astrometric- and photometrically calibrated form!
- Don't neglect bright objects! They are perfect for follow-up work at high spectral and spatial resolution.

Acknowledgements

The authors thank the *Austrian Science Fund (FWF)* for supporting this work under project number P23586-N16 and P21988-N16.

References

Beck, P. G., *et al.* 2011, *Science*, 332, 205
Bedding, T. R., *et al.* 2011, *Nature*, 471, 608
Decin, L., *et al.* 2011, *A&A*, 534, A1
Eggen, O. J., 1975, *ApJS*, 29,77
Feast, M. W., 1963, *MNRAS*, 125, 367
Glass, I. S. & Lloyd Evans, T., 1981, *Nature*, 291, 303
Habing, H. J., 1996, *A&A Rev.*, 7, 97
H. Habing and H. Olofsson (eds.) 2004, *Asymptotic Giant Branch Stars* (Berlin: Springer)
Hevelius, J., 1662, *Mercurius in Sole visus Gedani* (Danzig: Simon Reiniger), p. 146
Hinkle, K. H., *et al.* 1982, *ApJ*, 252, 697
Höfner, S., *et al.* 2003, *A&A*, 399, 589
Höfner, S., 2009, *ASPCS*, 414, 3
Huber, D., *et al.* 2010, *ApJ*, 723, 1607
Ireland, M. J., Scholz, M., & Wood, P. R., 2011, *MNRAS*, in press
Kerschbaum, F., *et al.* 2010, *A&A*, 518, L140
F. Kerschbaum, T. Lebzelter and R. F. Wing (eds.), 2011, *Why galaxies care about AGB stars II: Shining examples and common inhabitants* (San Francisco: *ASPCS*), 445
Kuschnig, R., Weiss, W. W., Moffat, A., & Kudelka, O., 2009, (San Francisco: *ASPCS*), 416, 587
Lebzelter, T., 2011, *A&A*, 530, A35
Lorenz, D., *et al.* 2011, *A&A*, 532, A78
Mattei, J. A., Menali, H. G., & Waagen, E. O. 2002, *AAVSO Monograph 15*, XIII + 14.
Mauron, N. & Huggins, P. J., 2000, *A&A*, 359, 707
Menzies, J. W., *et al.* 2011, *MNRAS*, 414, 3492
Nowotny, W., *et al.* 2010, *A&A*, 514, 35
Nowotny, W., *et al.* 2011, *A&A*, 529, A129
Olofsson, H., *et al.* 2000, *A&A*, 353, 583
Olofsson, H., Eriksson, K., & Gustafsson, B. 1988, *A&A*, 196, L1
Osvalds, V. & Ristey, A. M. 1961, *Publ. Leander McCormick Obs.*, 11, 147
Paladini, C., *et al.* 2009, *A&A*, 501, 1073
Rejkuba, M. 2004, *A&A*, 413, 903
Uttenthaler, S., *et al.* 2011, *A&A*, 531, A88
Whitelock, P., *et al.* 2006, *MNRAS*, 369, 751
Whitelock, P., *et al.* 2009, *MNRAS*, 394, 795
Wittkowski, M. *et al.* 2011, *The Messenger*, 145, 24
Wood, P. R. 1975, in: W.S. Fitch (ed.), *Multiple Periodic Variable Stars*, IAU Coll. 29 (Dordrecht: Reidel), p. 69
Wood, P. R. 2010, *Mem.S.A.It.*, 81, 883
Wood, P. R. & Zarro, D. M. 1981, *ApJ*, 247, 247
Wood, P.R., *et al.* 1999, in: T. Le Bertre, A. Lèbre and C. Waelkens (eds.), *Asymptotic Giant Branch Stars*, Proc. IAU 191 (San Francisco: *ASPCS*), p. 151
Woodruff, H. C., *et al.*, 2008, *ApJ*, 673, 418
Zijlstra, A. A., *et al.* 2004, *MNRAS*, 352, 325