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REVIEW OF "MULTICOLOR PHOTOMETRY OF LONG PERIOD VARIABLES" BY MENDOZA (1967)

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RESUMEN

Presento una reflexión sobre el artículo seminal de E. E. Mendoza, 1967, BOTT, 4, 28, 114 de fotometría *UBVRIJHKLM* de una muestra amplia y diversa de variables de largo período, incluyendo sus observaciones y resultados. Describo brevemente nuestra comprensión actual acerca de la naturaleza e importancia de estas estrellas y el trabajo correspondiente de nuestro grupo.

ABSTRACT

I reflect on E. E. Mendoza, 1967, BOTT, 4, 28, 114 which is a landmark paper on *UBVRIJHKLM* photometry of a large and diverse sample of long period variables, including his observations and results. I briefly describe our present understanding of the nature and importance of these stars, and the relevant work of my group.

Key Words: infrared: stars — stars: AGB and post-AGB — stars: carbon — stars: fundamental parameters — stars: late-type — techniques: photometric

1. INTRODUCTION

In 1967, Eugenio E. Mendoza (Mendoza 1967) published a pioneering paper on the optical and especially infrared photometric properties of a large sample of red giant stars – among the most complex stars in "the astrophysical zoo". He used the photometry to derive fundamental properties of the stars: effective temperatures, and bolometric corrections, as well as to classify them by temperature and composition. Mendoza had been a collaborator with Harold Johnson, who was *the* pioneer of multicolor photometry, and the developer, with W. W. Morgan, of the *UBV* photometric system.

All red giants (and supergiants) are variable in brightness, due to pulsation and probably other causes. They are collectively called Long Period Variables (LBVs), and they include: (i) Mira stars: red giants with visual amplitudes of 2.5 or greater; (ii) SR/SRa/SRb stars: red giants with smaller amplitudes and less-regular variation; (iii) L/La/Lb stars: red giants with little or no periodicity; and (iv) Lc stars, red supergiant variables. Percy et al. (2009a) recently showed that there is a smooth transition from SR to L type red giant variables. The red giant and supergiant variables are also closely related. Whether there is a smooth transition from Mira to SR variables is an open question.

Red giants are further divided into spectroscopic composition types, which reflect their composition: M (normal), S (oxygen-rich), and C (carbon-rich), the latter with N and R sub-types, according to the relative strengths of the CN and C_2 bands. Each composition type is divided into temperature subtypes.

2. MENDOZA'S OBSERVATIONS

Mendoza obtained 2839 observations of 67 stars, at wavelengths ranging from 0.36 to 10.2 microns (Johnson filters *UBVRIJHKLMN*). The numbers of *M* and especially *N* observations was very small. Observations were obtained with a variety of telescopes, including the Tonantzintla telescope, and the 21″, 28″, and 60″ telescopes at the University of Arizona's Catalina Observatory. The 67 stars included M, SR, and L variable star types, plus some suspected variables and constant stars. All three composition types (M, S, and C) were included. Almost all of the stars were red giants, but a few supergiants may have been included, since some of the stars lacked MK spectral types.

Some of the brighter and better-known target stars included T Cas, R And, o Cet, S Ori, R Gem, R Hya, and the enigmatic IR source NML Tau, now known to be a Mira star, IK Tau. The stars have periods ranging from over 400 days, down to a few weeks in the case of the small-amplitude red variables such as R Lyr, RR UMi, and ρ Per.

On average, each star was observed 5–15 times. Given the complex time variability of these stars, these multiple observations provided some degree of phase averaging, especially at the longer wavelengths, where the amplitude of variability is smaller.

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Since different filters required different photometers and telescopes, the observations in each of the 11 filters were not contemporaneous. The observations are not extensive enough to determine periods, but they provided some information about the amplitudes.

3. MENDOZA'S RESULTS

In 1967, infrared photometry was a rather arcane topic, outside the observational mainstream. Yet for cool stars such as LPVs, it was absolutely essential for studying the bulk of the stellar spectrum.

One of the benefits of the multicolor approach is that it is possible to classify the stars, photometrically, according to *both* temperature and composition type – M, S. or C. The temperature affects the shape of the continuum; the composition type affects the presence and strength of molecular bands in the filter bandpasses. For instance: in stars of composition type M, there are strong titanium oxide bands in the V passband. In principle, the multicolor photometry could provide an estimate of the reddening, but Mendoza assumed that the reddening would be close to zero.

In the $(V-R)-(B-V)$ plane, there is a clear separation of the M, S, and C types and, for each type, there is a temperature sequence that extends for several magnitudes – much larger than the observational error, or the scatter due to intrinsic variability. In fact, the narrowness of some of the sequences is quite impressive, considering the variability of the stars, their variety and strength of composition types, and perhaps their populations.

Equally important: the 11-color photometry provides a measure of both effective temperature Te and bolometric correction BC, since the 11 filters cover most of the spectra of these cool stars. Te and BC allow a direct comparison between the observed magnitudes and theoretical models. The effective temperatures mostly lie between 1800 K and 3200 K; they are comparable with more recent results for M types (e.g. van Belle, Thompson, & Creech-Eakman 2002); for carbon stars, they are very slightly lower than those found by e.g. Bergeat & Chevallier (2005). Separate $BC-Te$ relations are given for the three chemical types. The bolometric corrections range from -3 to -6 in most stars, to -12 in the most extreme stars; with a very few exceptions, these values are consistent with more modern ones. Mendoza's Table 4 lists the "tentative" effective temperatures and bolometric corrections as a function of chemical type and spectral type.

4. SUBSEQUENT DEVELOPMENTS

The interest and importance of the LPVs has continued to develop since Mendoza's time. They are understood as being the late nuclear-burning evolutionary stage of stars with masses less than about two solar masses, which makes them a very common phenomenon. The star first evolves up the giant branch in the H-R diagram, fusing hydrogen in its core, and later in a shell around the core. Following the helium "flash", the star evolves up the asymptotic giant branch, fusing helium, initially in its core, and later in a shell. In each case, pulsational instability sets in at an effective temperature of about 4000 K. Warmer giants, such as Arcturus, can also pulsate, but in a manner, and by a mechanism more similar to that in the sun.

The period and amplitude increase with decreasing temperature. The largest-amplitude pulsators are the Mira stars, with visual amplitudes of 2.5 magnitudes or more, by definition. The bolometric amplitudes are much smaller, and are better represented by the infrared amplitudes; the visual amplitude is artificially enhanced by the effect of TiO absorption in the V band.

In Mira stars, the pulsations increase the density of the atmosphere, and the mass loss of gas and dust. Radiation pushes on the dust, carrying the gas along with it. Within about 200,000 years, the star loses most of its envelope, and the core is exposed as a white dwarf (see Wang, Willson, & Kawaler 2008, for instance). The hot white dwarf excites emission in the expanding envelope, producing a planetary nebula. The complex forms of planetary nebulae indicate that mass loss is not always radially symmetric: rotation, binarity, and possibly magnetic fields must be involved, somehow.

Red giants are highly convective, and convection is a poorly-understood process in astrophysics. It is responsible for bringing the products of nucleosynthesis to the surface in S and C stars, but the details are not yet clear. Detailed comparisons between observed abundances, and abundances predicted by nucleosynthesis theory will be helpful, but challenging. Mendoza (1967) was motivated, in part, by the possibility of using his photometry to measure and classify LPVs by oxygen-to-carbon ratio. Nowadays, abundances are generally determined spectroscopically, often by comparing observed line strengths and shapes with models (spectral synthesis). For LPVs, constructing such models is difficult.

Convection also challenges our understanding of pulsation in these stars, since the interaction between pulsation and convection is not simple. Cool stars in general are discussed in the proceedings of a recent conference, picturesquely titled "The Biggest, Baddest, Coolest Stars" (Luttermoser et al. 2009). See also Xiong & Deng (2007) for a specific discussion of pulsation modelling of red giants.

Visible and infrared photometry of LPVs has continued. Olin Eggen, and subsequently Robert Wing have used narrower-band filters to measure both the continuum and molecular bands to classify these stars. Of course, the technical aspects of infrared photometry have also developed considerably since Mendoza's time. There are infrared photometers and cameras for ground-based telescopes, and the *IRAS*, *ISO*, and especially the *Spitzer* space telescopes have revolutionized the field.

Nowadays, it is possible to determine effective temperatures and bolometric corrections for stars by creating model atmospheres and fitting them to the observed spectra whereas, in 1967, the creation of realistic model stellar interiors and atmospheres was just beginning. Still, it is virtually impossible to model the atmospheres of the coolest LPVs in detail. The atmospheres are dynamic, and sufficiently cool that molecular opacities are very important. On the other hand, with infrared photometers on the ground and in space, it is relatively easy to measure the flux distribution of LPVs at any phase of their variation.

For a comprehensive recent account of variable star observation and theory, see Guzik & Bradley (2009). For a less-technical account, see Percy (2007).

5. MY OWN INTERESTS AND WORK

My own work on LPVs has included Mira stars, and especially the much more numerous small-amplitude red variables; the latter work has recently been reviewed by Percy et al. (2009b). Most of the work has been done by undergraduate students, and outstanding senior high school students in the University of Toronto Mentorship Program (Percy 2008), so it has a strong educational component: students develop and integrate their science and math skills, by doing real science, with real data. Much of the data comes from the International Database of the American Association of Variable Star Observers (AAVSO); it is obtained by skilled amateur astronomers. Our results are usually presented at AAVSO meetings, and/or published in the *Journal of the AAVSO* with the students as co-authors; this provides motivation for the students, and important feedback and recognition for the observers who produce the data at little or no cost to the scientific community.

Our work on Mira stars, for instance, was made possible by many decades of visual observations of almost 400 stars by the AAVSO. It includes studies of random cycle-to-cycle period fluctuations in these stars (Percy & Colivas 1999), which amount to a few percent of a period per cycle. We were also able to detect, marginally, the slow evolutionary period changes in these stars (Percy & Au 1999). Templeton, Mattei, & Willson (2005) have made a more comprehensive study of the period changes in these stars, and identified 57 individual stars, out of 547, which seem to show detectable evolutionary changes; they are probably undergoing helium shell flashes.

The work on small-amplitude red variables is based mostly on observations from the AAVSO photoelectric program, and from a robotic telescope, and includes: (i) the determination of periods and amplitudes of several dozen bright stars; both period and amplitude increase with decreasing temperature; (ii) identification of pulsation modes; they are low-order radial modes; (iii) study of multiperiodic pulsators; some stars show two or three or possibly more radial modes; masses can thereby be estimated in these stars; (iv) long-term variability, specifically the "long secondary" periods that have been found in about a third of such stars, and whose cause is unknown, though recent work (Wood & Nicholls 2009) suggests that they may have some connection with enhanced mass loss; (v) very long-term variability; (vi) wavelength dependence of amplitude; the amplitude decreases with increasing wavelength for both the primary and "long secondary" periods; (vii) period fluctuations and variability; this is difficult to study in these small-amplitude, semi-regular variables, and (viii) red supergiant variability; these stars show complex variability which may be strongly affected by convective cells on their surface, and possibly by rotation. See Percy et al. (2009a,b) for specific references.

6. FINAL REFLECTIONS

It has been a pleasure to review this paper, and to recall the pioneering work of Mendoza, and his efforts to measure and understand the characteristics of these complex, extreme, important variable stars. His paper continues to be referenced, as recently as 2008. It is also interesting to recall those earlier times when graphs had to be drawn, tables had to be typed, and papers had to be typeset!

My own career extends back to Mendoza's time and, for many years, I myself did photometry – though of the simple *UBV* kind, rather than the much more complex infrared kind. Nowadays, most astronomers use instruments, including photometers, which they do not have to understand, except in a general way. Mendoza worked at a time when photometers, especially infrared photometers, were in their infancy. Like human infants, these photometers required understanding, and "tender, loving care". Our understanding of LPVs would not have developed as it has, without his contributions.

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