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THE PHYSICAL PROPERTIES OF RED SUPERGIANTS

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RESUMEN

La ubicación "observada" de supergigantes rojas en el diagrama HR ha estado variando con los modelos evolutivos a lo largo de los años, pero la nueva generación de modelos de atmósferas estelares MARCS ha conducido a mejores determinaciones de sus propiedades físicas y un mejor acuerdo con la teoría de evolución estelar. Resumimos brevemente nuestros descubrimientos.

ABSTRACT

The "observed" location of red supergiants in the HRD has been at variance with the evolutionary tracks for many years, but the new generation of MARCS stellar atmosphere models has led to improved determinations of their physical properties, and much better agreement with stellar evolutionary theory. We briefly summarize our findings.

Key Words: stars: atmospheres — stars: evolution — stars: late-type — supergiants

1. INTRODUCTION

Red supergiants (RSGs) are the He-burning descendants of 10-25$\mathcal{M}_\odot$ stars. They are not the most massive or luminous stars (those become LBVs and/or WRs) but their cool effective temperatures and relatively high luminosities result in their being the physically largest stars. These stars are fully convective, with the lowest temperatures determined by the Hayashi limit; cooler than this, stars are not hydrostatically stable.

When we began this project, there was a unpleasant discrepancy between the "observed" location of these stars in the HRD, and where the evolutionary tracks had them (Figure 1, left). The RSGs are a lot cooler, and more luminous, than the evolutionary tracks predict. Now, when there is a disagreement between theory and observation one usually points a finger at theory. Indeed, Figure 10 of Maeder & Meynet (1987) shows that the redwards extension (temperature) of the tracks does depend upon just how the mixing length is treated. Furthermore, the assumed opacity also controls how far to the red the tracks can go. However, you cannot raise or lower the tracks (luminosity) without fiddling with the mass-loss rates. Could it be that the "observations" were wrong? After all, we do not actually observe the effective temperatures or luminosities; instead, we obtain photometry and spectral types and do something to convert these to the physical properties of these stars. What if the conversion was wrong? The existing scales were based primarily upon lunar occulations of red *giants*, not *supergiants* (see discussion in Massey & Olsen 2003). The deep molecular bands that characterize M-type supergiants are highly sensitive to effective temperature, but older stellar atmosphere models were not up to the task of fitting these lines.

The situation was actually quite analogous to that of the O-type effective temperature scale with which many of us are familiar: in the 1960s there was recognition that without the non-LTE treatment of the hydrogen and helium lines, determining effective temperatures was rather hopeless. Fixing the problem required a blend of modeling advances with high quality observations. The Auer & Mihalas (1970) models, which included the NLTE, were used by Conti (1973a,b) to develop the first modern effective temperature scale.

In our case, it was the new generation of MARCS stellar atmospheres (Gustafsson et al. 1975; Plez et al. 1992; Plez 2003; Gustafsson et al. 2003) that provided the key theoretical improvement. We used a version that includes sphericity, 10^5 opacity sampling points, and improved atomic and molecular

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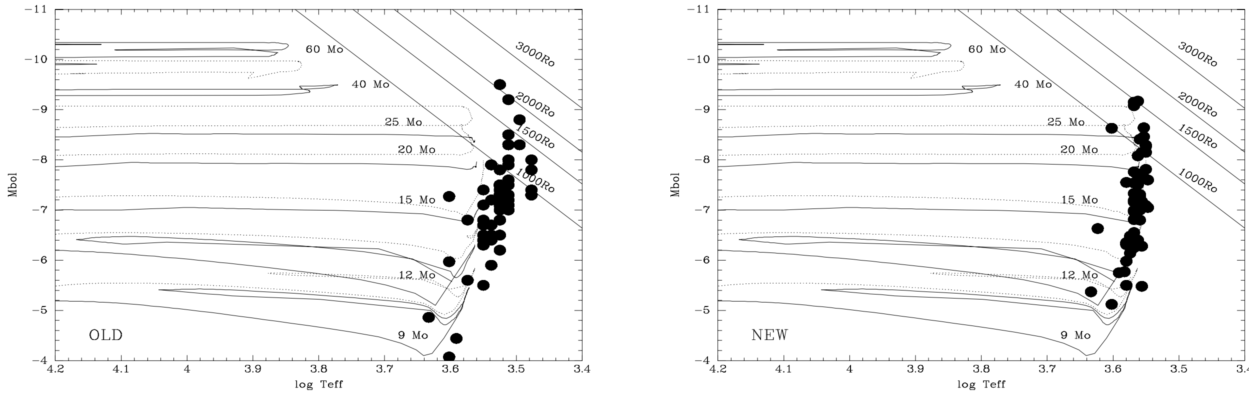

Fig. 1. Comparison of the placement of Galactic stars in the H-R diagram based on the old effective temperature scales and our new one.The evolution tracks are from Meynet & Maeder (2005) for z=0.020 (solar metallicity).

opacities. We obtained well-calibrated moderate-resolution spectrophotometry from 3500-9000Å using the KPNO 2.1 m and CTIO 1.5 m telescopes of a large sample of Galactic RSGs, chosen primarily to have well-determined distances from cluster and OB association membership in order to allow accurate luminosities to be computed. Indeed the RSG effective temperature scale proved to be warmer than previously assumed, resulting in a decrease in the calculated bolometric luminosities. The result is in excellent agreement with the evolutionary tracks, as shown on the right of Figure 1.

Since then, we have also completed similar studies for Magellanic Cloud RSGs (Levesque et al. 2006). At the lower metallicities of the Clouds, we would expect that RSGs of a given spectral subtype (M2 I, for instance) would be cooler than Galactic stars of the same spectral subtype, as there is less Ti (and hence less TiO) available, and so a cooler temperature is needed for the same equivalent width. And, indeed just what we found. We have also completed several studies of stars of particular interest (VY CMa, Massey et al. 2006; HV 11423, Massey et al. 2007), and an investigation of the circumstellar reddening of Galactic RSGs (Massey et al. 2005).

Currently, our group is studying RSGs in M31. We have one result that is already of interest: the luminosity of the most luminous RSGs in M31 are consistent with the $z = 0.040$ models of Meynet & Maeder (2005) (Figure 2). If the metallicity were really solar, as suggested from the analysis of one B supergiant by Smartt et al. (2001), then where are the higher luminosity RSGs that we see in the Milky Way (i.e., Figure 1, right)? We would expect to see RSGs with $M_{\rm bol} = -8.5$ to -9.0, while instead

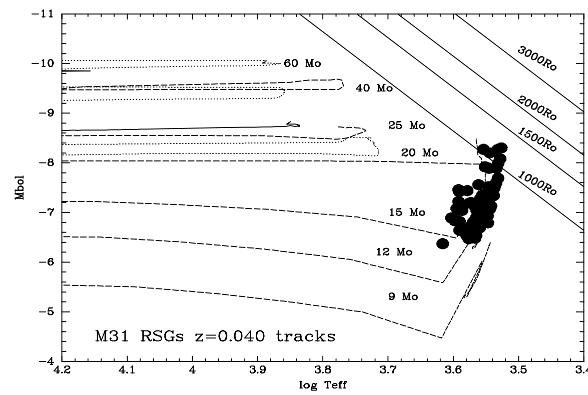

Fig. 2. Comparison of the placement of M31's RSGs with the z=0.040 tracks of Meynet & Maeder (2005).

the most luminous of M31 RSGs appear to be about −8.2.

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DISCUSSION

N. Smith - Regarding the upper luminosity limit it would be important to give close scrutiny to the most luminous RSGs like VY CMa, as well as NML Cyg, VR Sgr, μCep, S Per, etc. For VY CMa, the IR luminosity is higher than the value you derive from your atmosphere models, as is the radius measured with interferometry, but perhaps grey extinction could rectify this disagreement.

P. Massey - I agree that there's a significant problem with the luminosity we get for VY CMa. The thermal re-emission from the dust is about four times greater than what we get on the star. We are still scratching our heads on that but grey extinction is my guess too. We did include μ Cep and S Per in our Galactic study. μ Cep is right up with the most luminous ($M_{\rm bol} \sim 9.0$) with KW Sg and KY Cyg.

A. Moffat - What about the MW cluster Westerlund 1? It has many RSGs and O7 MS stars of say $\sim 40 M_\odot$. How does that fit with your scenario?

P. Massey - It would be useful to model its RSGs. However, the RSGs are not coeval with the O stars.

N. Przybilla - How well do models reproduce the photometric observations regarding the flux maximum in the near-infrared?

P. Massey - For the Milky Way, $(V-K)_0$ give the same answers for $T_{\rm eff}$ and luminosity as what we get from the spectral fittings. For low metallicity (SMC) we see a systematic offset in $T_{\rm eff}$ by about 150 K. We think this is due to the intrinsic limitations of the 1-dimensional models. Our belief is that the spectral fitting is giving the right answers because it agrees with what the models give us from $(V-R)_0$.

R. Barbá - Models for RSGs are based in single star evolution. Which is the influence of the comparison in massive close binary systems in the evolution of the RSG plane?

P. Massey - We threw away any obvious binaries in our sample (i.e. stars with Balmer absorption). You are certainly right that our analysis depends upon the stars being single (or at least much brighter in V).