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The Physical Properties of Red Supergiants

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Abstract. Red supergiants (RSGs) are an evolved stage in the life of intermediate massive stars ($< 25M_\odot$). For many years their location in the H-R diagram was at variance with the evolutionary models. Using the MARCS stellar atmospheres, we have determined new effective temperatures and bolometric luminosities for RSGs in the Milky Way, LMC, and SMC, and our work has resulted in much better agreement with the evolutionary models. We have also found evidence of significant visual extinction due to circumstellar dust. Although in the Milky Way the RSGs contribute only a small fraction (<1%) of the dust to the interstellar medium (ISM), in starburst galaxies or galaxies at large look-back times, we expect that RSGs may be the main dust source. We are in the process of extending this work now to RSGs of higher and lower metallicities using the galaxies M31 and WLM.

1. Introduction: What Am I Doing Here?

I feel I have to explain what I'm doing at a "cool stars" conference, much less giving the opening talk. Most of my work has been concerned with the formation, physical properties, and evolution of massive stars, and for most of my career I've stayed over on the "hot" side of the H-R diagram (HRD). Still, as shown in Figure 1 *some* massive stars spend a significant fraction of their lives as red supergiants (RSGs). For these particular tracks (computed for Galactic metallicity and including the effects of rotation) stars of $20M_\odot$ and lower spend the majority of their He-burning lives as RSGs. Stars of $25M_\odot$ spend some of their He-burning phase as RSGs, but then may evolve back to the blue side of the HRD, where they end their lives as Wolf-Rayet stars (WRs). Higher mass stars never make it over to the RSG side.

The fraction of the He-burning life spent as a RSG, as well as the mass limits for becoming RSGs, should depend upon metallicity: in lower metallicity environments, such as the SMC, we expect to find lots of RSGs and few WRs, while in higher metallicity environments the opposite should be true. This was

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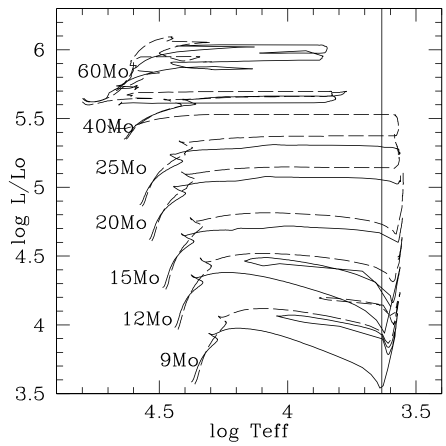

Figure 1. The evolutionary tracks of Meynet & Maeder (2003), corresponding to solar metallicity, are shown. Solid curves are for stars with no initial rotation, while dashed curves are for stars with an initial rotation velocity of 300 km s^{-1}. The solid vertical line corresponds to an effective temperature of 4300 K, cooler than which a star is spectroscopically identified as a K-M.

first pointed out by Maeder, Lequeux, & Azzopardi (1980). So, the relative number of RSGs and WRs provide a sensitive test of stellar evolutionary theory.

Still, first you have to find them. My interest in the subject of RSGs was first piqued by the comparison of blue and red stars in the nearby galaxy M33 given by Humphreys & Sandage (1980). They were nowhere near alike! The blue stars were mostly clumped together in what these authors designated OB associations, while the red stars showed a fairly uniform distribution across the face of the galaxy. (Compare their Figures 21 and 22.) They correctly interpreted this as the result of contamination by foreground Galactic K and M dwarfs. A little fiddling with the best (at the time) model atmospheres convinced me that you *could* separate out the two populations by a $B-V$, $V-R$ two color diagram (Massey 1998). Figure 2 shows such a diagram for stars seen towards NGC 6822, a Local Group irregular galaxy at fairly low Galactic latitude ($b=-18.4°$).

We eventually carried out RSG searches in selected regions of NGC 6822, M33, and M31 (Massey 1998) and the SMC and LMC (Massey & Olsen 2003). At the time we came up with an amazingly nice correlation of the RSG/WR number ratio with metallicity, which goes in the same sense as expected (Figure 3). The number ratio changes by a factor of 100 or so over just 0.9 dex in the log of the oxygen abundances.

However, one problem had become quite apparent as a result of this work: the location of RSGs in the H-R diagram did *not* agree with where the evolutionary tracks (*any* evolutionary tracks) said they should be. Massey & Olsen (2003) compared the Magellanic Cloud RSG locations to the Geneva models computed with and without "enhanced" mass loss, as well as to the Padova tracks; Massey (2003a) made a similar comparison using Galactic RSGs and appropriate metallicity tracks. In all cases it appeared that RSGs were significantly cooler and more luminous than the tracks would have it. We show this for Galactic and SMC RSGs in Figure 4.

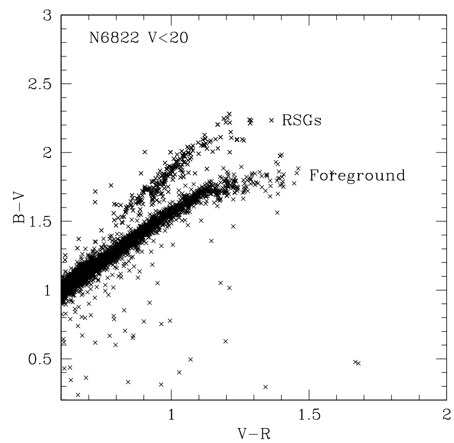

Figure 2. This two-color plot allows us to distinguish foreground dwarfs from bona fide RSGs for the nearby galaxy NGC 6822. The data are from Massey et al. (2007b).

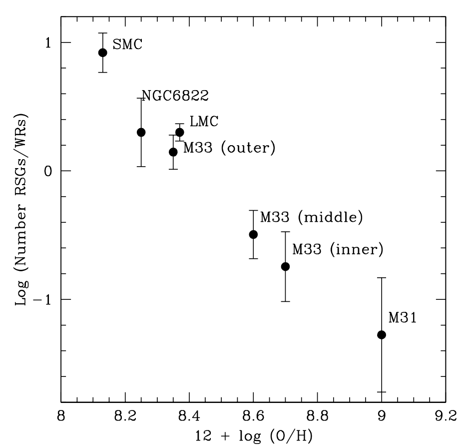

Figure 3. The ratio of the number of RSGs to WRs correlates nicely with metallicity within the local group. This figure is based upon one in Massey (2003a).

Now, usually when "observation" and theory disagree, the problem is with theory, and indeed when I showed a version of Figure 4 at the Lanzorte meeting on massive stars (Massey 2003b), Daniel Schaerer was kind enough to point out to me that the tracks could go further to the right, or not, depending upon how convection is treated; this is illustrated in Figure 9 of Maeder & Meynet (1987). Still, it seemed as if maybe this was a case that the "observations" could be wrong. We don't "observe" effective temperature and bolometric luminosity; instead, we obtain spectra and photometry and convert these to physical quantities. Indeed, it turned out that most of the basis for the effective temperature scale of RSGs was tied into lunar occultations of red *giants*—there just weren't enough RSGs located along the ecliptic. (See discussion in Massey & Olsen 2003.) *If* the effective temperature scales were actually warmer than what we (and others) had been assuming then that would also lower the luminosities,

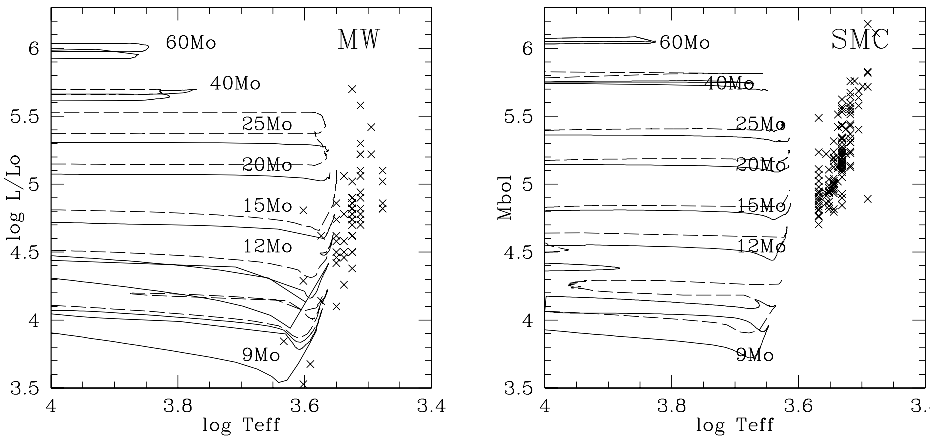

Figure 4. Massey (2003a) and Massey & Olsen (2003) found that red supergiants were considerably cooler and more luminous than the evolutionary tracks predicted. On the left we show the comparison for Milky Way RSGs, where the data are from Humphreys (1978), and the evolutionary tracks are those of Meynet & Maeder (2003) for a Galactic metallicity ($z = 0.020$). On the right we show a similar comparison for the SMC, where the data come from Massey & Olsen (2003), and the evolutionary tracks from Maeder & Meynet (2001) for a metallicity appropriate to the SMC ($z = 0.004$). Solid curves denote tracks for stars with no initial rotation, while dashed curves show an initial rotation of 300 km s^{-1}.

yielding better agreement with the tracks, as the bolometric corrections are quite significant at these cool temperatures. Of course, if the effective temperatures turned out to be even cooler than what we had been assuming, we'd be in even more trouble!

The key to this was using the new generation of MARCS stellar atmospheres (Gustafsson et al. 1975, 2003; Plez, Brett, & Nordlund 1992, Plez 2003). An early version (described by Bessell, Castelli, & Plez 1998) of these had been used by Oestricher & Schmidt-Kaler (1998, 1999) to fit the spectral energy distribution of RSGs in the Magellanic Clouds with some success. Since that time the models had been improved to include sphericity, with an order of magnitude increase in the number of opacity sampling points, and revised to incorporate improved atomic and molecular opacities.

2. Galactic RSGs

We first tackled this using a sample of 74 Galactic RSGs. The sample was selected in order to cover the full range of spectral subtypes from early K to the latest M supergiants. The sample was originally restricted to stars for which there was probable membership in OB associations and clusters with known distances (Humphreys 1978; Garmany & Stencel 1992), although we wound up including a few spectral standards from the list of Morgan & Keenan (1973) in order to help with the classifications. A full description is given by Levesque et al. (2005, hereafter Paper I). The data covered the 4000-9000 Å region, with a resolution of 4-6 Å, and were obtained with the Kitt Peak 2.1-m telescope and GoldCam spectrometer, and the Cerro Tololo Inter-American Observatory 1.5m telescope and RC spectrometer.

The fitting procedure was straightforward. We used a grid of MARCS models computed with solar metallicity at 100 K intervals for $\log g$=-1.0 to +1 at 0.5 dex increments. We interpolated the models to 25 K intermediate values. A value of $\log g$ of 0.0 is the most physically likely (given the masses and radii of these stars), and we started with those, letting the depth of the TiO bands then determine the temperature. We reddened the models using a Cardelli, Clayton, & Mathis (1989) extinction law. Once we got a good fit by just varying these two parameters (effective temperature and A_V) we then computed the star's location on the HRD, and asked whether or not a different $\log g$ would have been more appropriate. If so, we then repeated the process. An uncertainty of 0.5 dex in $\log g$ corresponded to an uncertainty in A_V of about 0.15 mag, and basically no difference in effective temperature. We felt that the latter were determined to a precision of about 50 K or better, except for the earliest K stars, which lacked TiO bands—for those, the uncertainties were considerably larger, perhaps as much as 100 K.

I want to note, for the record, that the fitting was all done by Emily [Levesque] using IDL code that she wrote herself, back when she was an undergraduate. Like all summer student projects, one never knows whether the whole thing is going to work out or not. Would the models be up to the task? Was the methodology sound? My reaction when Emily showed me the first fits was that this was FANTASTIC. The reddened MARCS models not only fit the molecular bands but also fit the continua far better (I felt) than any models had a right to do with these very difficult stars. We show some examples in Figure 5. Not everything is perfect, of course: for instance, some of the atomic lines appear to be too strong in the models, and we discuss possible reasons for this both in Paper I and Levesque et al. (2006, hereafter Paper II).

When we were done we had new physical properties (effective temperature, bolometric luminosity, surface gravities, radii) for a large sample of Galactic RSGs. We can see in Figure 6 that indeed our work resulted in the effective temperature scale getting considerably warmer, by about 250 K at spectral type M2.

What did this do the placement of stars in the H-R diagram? Exactly what we had hoped! We compare the old and new placements in Figure 7.

We can use this result to answer one other interesting question: *How large do (normal) stars get?* First, we should ask what do we mean by the "radius" of such diffuse objects? Fortunately there's a fundamental definition at hand, namely $L = 4\pi\sigma T_{\rm eff}^4 R^2$. Given that, then the radii of the largest stars are about $1500R_\odot$, or nearly 7.2 AU! We found three stars with radii near that, namely KW Sgr, V354 Cep, and KY Cyg. The star μ Cep (Herschel's "Garnet Star") comes in a close fourth, at about $1420R_\odot$.

3. Extension to Lower Metallicities: Fitting Magellanic Cloud RSGs

Having determined an effective temperature scale for the Milky Way RSGs, and found excellent agreement with the evolutionary tracks, we were curious

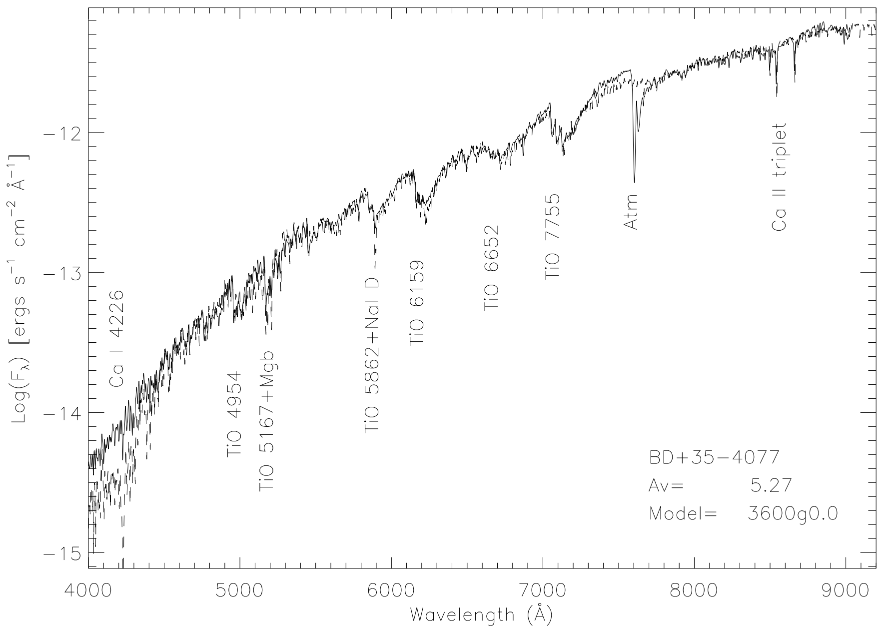

Figure 5. An example of our modeling fits. We show the spectrum of BD+35°4077, an M2.5 I star, fit with a 3600 K $\log g = 0.0$ model reddened by an $A_V = 5.27$ mag. The observed spectrophotometry is shown as a solid line, while the model is shown as a dashed line.

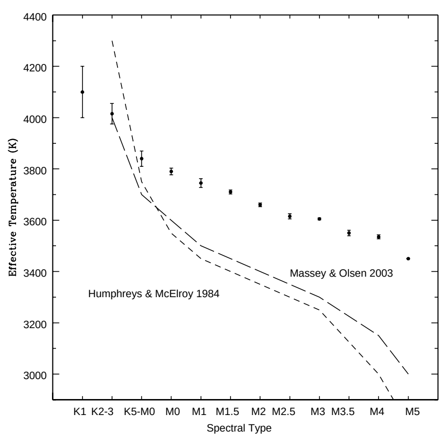

Figure 6. The new effective temperature scale for Galactic RSGs is shown by the points and error bars. The old effective temperature scales of Humphreys & McElroy (1984) and Massey & Olsen (2003) are shown for comparison.

to see what would happen at low metallicities. After all, the spectral types are determined by the absolute band strengths of TiO. So, if there is less TiO available then a star will have to be cooler to have the same band strength. At least, this is what we naively argued, and that appears to be well born out by the models, as shown in Figure 8.

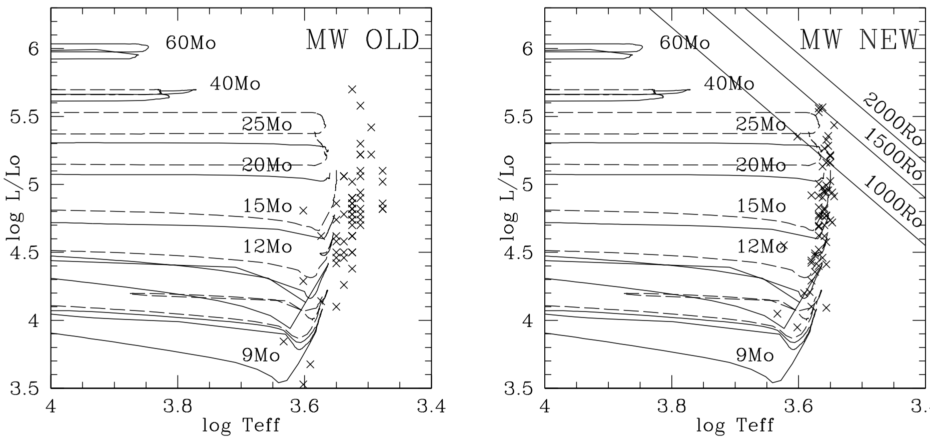

Figure 7. The new effective temperatures and bolometric luminosities of Galactic RSGs are now in excellent agreement with the models. On the left we show the distribution of RSGs in the H-R diagram based upon the old calibration; on the right, the new. The diagonal lines along the upper right denote the radii.

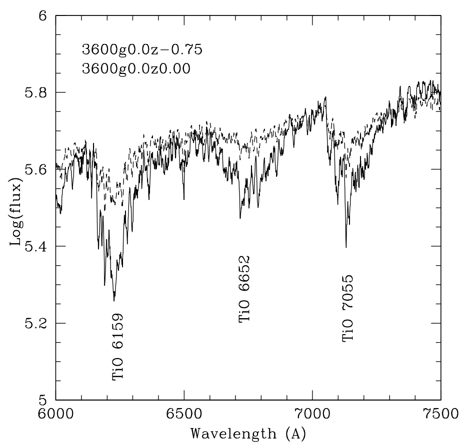

Figure 8. A small section of the MARCS models show the differences expected in TiO band strength with metallicity. The upper (dotted) model is for a 3600 K $\log g = 0.0$ model with a $\log Z/Z_{\odot} = -0.75$, similar to that of stars in the SMC. The lower model has the same effective temperature and surface gravity, but solar metallicity.

We followed the same general procedure as we had in Paper I, first choosing a sample of RSGs from Massey & Olsen (2003). For the Clouds we are faced with a similar problem recognizing RSGs as we are in M33; Massey & Olsen had used radial velocities to separate foreground disk dwarfs from Magellanic Cloud RSGs. In the end, our study included 36 RSGs in the LMC and 37 in the SMC (Paper II), all observed on the 4-m Blanco telescope at Cerro Tololo.

The effective temperature scale that we found was indeed cooler than what we found for the Milky Way for the M-type RSGs, by about 50 K for the LMC and 150 K for the SMC. The scales for the K-type RSGs were essentially the

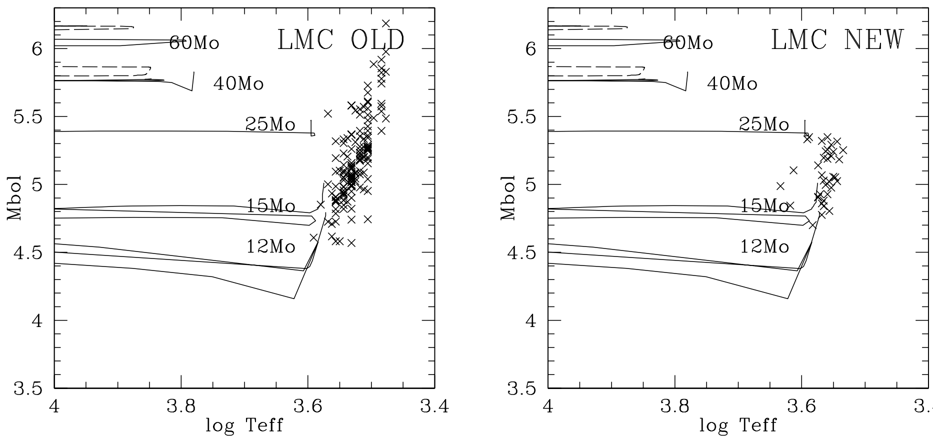

Figure 9. The H-R diagrams for RSGs in the LMC. On the left we show the very poor agreement between the old effective temperature calibration and the evolutionary tracks; on the right is the MARCS calibration of the effective temperature scale. Solid lines denote the evolutionary tracks computed for stars with no initial rotation, while dashed lines are for stars with initial rotation velocities of 300 km s^1. The tracks come from Meynet & Maeder (2005).

same, although our precision in determining temperatures is certainly worse for early K's (which lack TiO bands) than for the late K's and M's.

How did the resulting placement of stars agree with that of the evolutionary tracks? We show this in Figures 9 and 10. For the LMC the agreement is quite good. For the SMC there is a clear improvement, but there is clearly a larger spread in the effective temperatures of RSGs in the SMC, and some evidence the tracks do not go quite cool enough. This might be due to increased importance of rotational mixing in lower metallicity stars (e.g., Maeder & Meynet 2001).

4. How Self-Consistent Are the Models?

We have certainly gotten some nice results with the MARCS models: by fitting the molecular bands we obtain both effective temperatures and luminosities, with now good agreement with the evolutionary tracks. But, we can perform other self-consistency tests.

One test is to separately derive the physical properties of these stars using the broad-band colors of the stars. We chose for this test the $(V-K)_o$ and $(V-R)_o$ colors. Now, this is not completely independent, as we have to assume the color excesses $E(B-V)$ from our fitting of the spectrophotometry. Still, it provides an important check on whether the spectral flux distribution of the models are consistent with the TiO band strengths of the models. We show the comparison for $(V-K)_0$ in Figure 11. Solid points are for the Milky Way, "+" signs are for the LMC, and "x" are for the SMC. And, we do find some systematic differences. We find warmer effective temperatures (and hence smaller luminosities) using just the $(V-K)_0$ colors. The differences appear

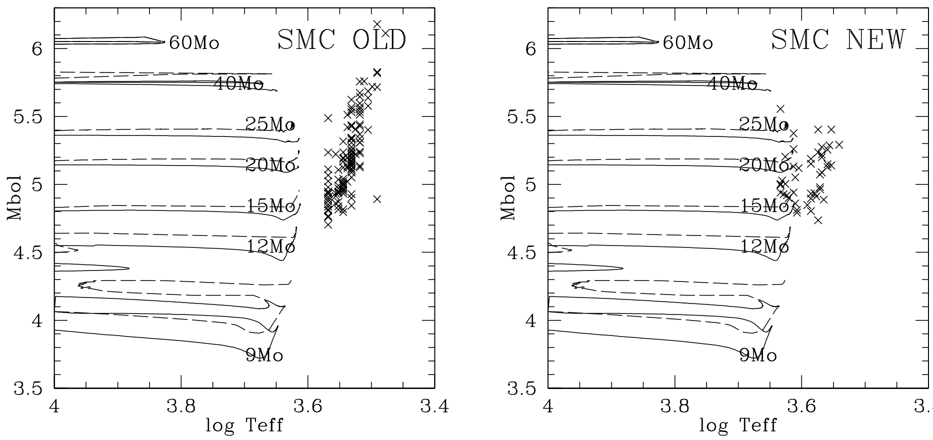

Figure 10. The H-R diagrams for RSGs in the SMC. On the left we show the very poor agreement between the old effective temperature calibration and the evolutionary tracks; on the right is the MARCS calibration of the effective temperature scale. Solid lines denote the evolutionary tracks computed for stars with no initial rotation, while dashed lines are for stars with initial rotation velocities of 300 km s[1]. The tracks come from Maeder & Meynet (2001).

to be metallicity dependent, with an median $\Delta T = -60$ K for the Milky Way, -105 K for the LMC, and -170 K for the SMC. If we make the same comparison, though, for $(V - R)_0$ the agreement is excellent.

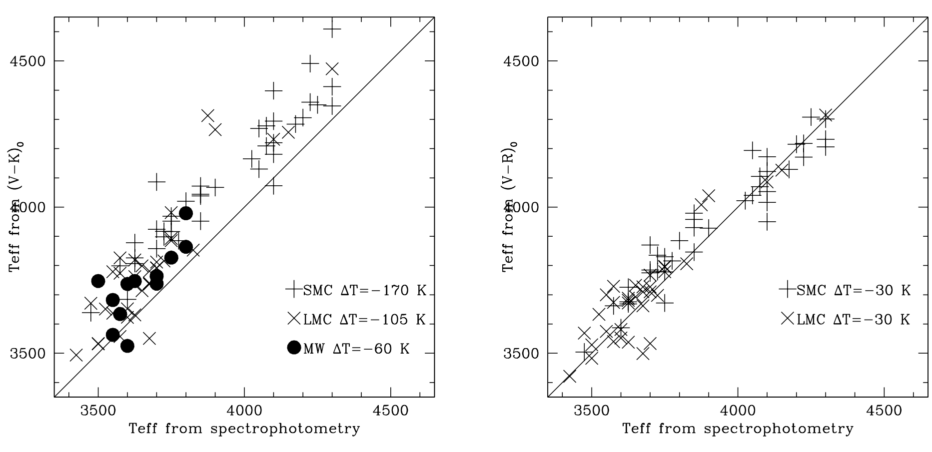

Figure 11. The effective temperatures derived from broad-band colors compared to those derived from spectral fitting. On the left we show the comparison for $(V - K)_0$; on the right, for $(V - R)_0$. Solid dots correspond to the Milky Way, "+" symbols for the LMC, and "x" symbols for the SMC.

The explanation we offered (in Paper II) is that this may just be a reflection of the intrinsic limitations of static, 1-D models. Ryde et al. (2006) found that MARCS models at the canonical 3600 K effective temperature for Betelgeuse do not reproduce the IR H_2O lines—instead, a much lower temperature, 3250 K, is needed. Radiative-hydrodynamic 3-D models (Freytag et al. 2002) show that there are likely warm and cool patches on the surfaces of these stars, which may explain such wavelength dependent effects.

5. When Smoke Gets in Your Eyes

One of the truly surprising things we found—although really we should have expected it—is that many of these RSGs have a significant amount of circumstellar reddening, presumably due to dust. We give the arguments in Massey et al. (2005), and let me repeat them here.

Our first clue that there was something funny going on was in our Galactic study: although the spectral energy distributions were generally well fit by the models, there were a number of stars that showed significant discrepancies in the wavelength region < 4000Å, always in the sense that the stars showed more flux than the models predicted. Look carefully at Figure 5. A more drastic case is shown here in Figure 12.

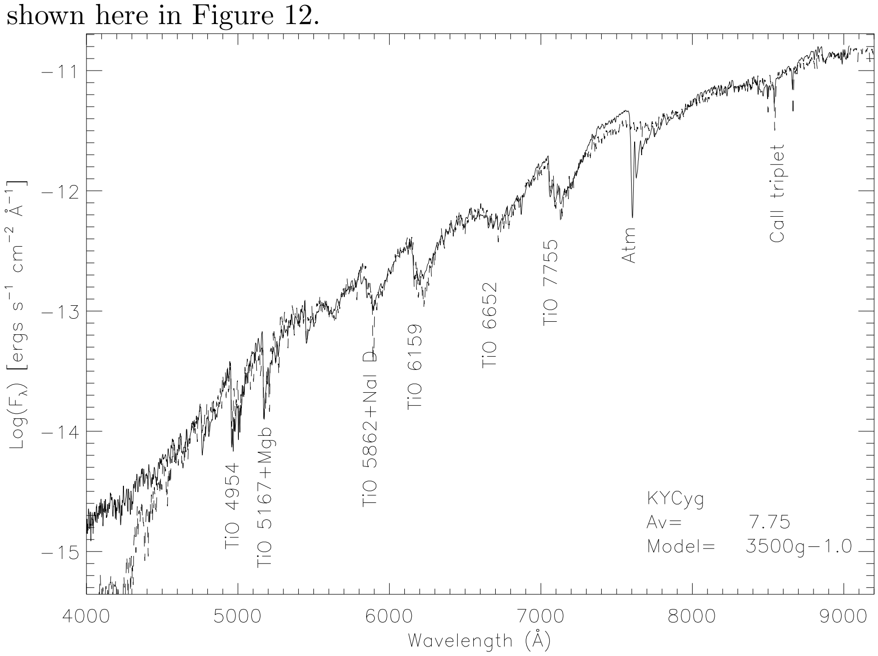

Figure 12. An example of the near-UV problem. We show the spectrum of KY Cyg, an M3-4 I star, fit with a 3500 K $\log g = -1.0$ model reddened by an $A_V = 7.75$ mag. The observed spectrophotometry is shown as a solid line, while the model is shown as a dashed line.

We considered a number of possibilities. Were these stars binaries? Well, we had found, and eliminated, a few stars from our original sample because Balmer lines were present. We convinced ourselves that the binary explanation did not work for the other stars as there were no signs that the spectra were composite. We worried a lot about instrumental effects; after all, $F_{\lambda 7000}/F_{\lambda 3500}$ is about 10,000 for our most heavily reddened RSGs, while it is roughly unity for our spectrophotometric standards. We eliminated this explanation by sticking in a $CuSO_4$ blocking filter (which should not be needed at all in first order) and obtaining the same results. We could imagine theoretical explanations for this discrepancy: as discussed above, hot spots may be present on the surfaces of these stars (Freytag et al. 2002). Additionally, chromospheric emission might play a role (Carpenter et al. 1994; Harper et al. 2001).

However, we also noticed something odd: the stars with the greatest near-UV discrepancy also seemed to be the stars with the highest reddening. We looked at this most closely. In general, these RSGs were considerably *more* reddened than the OB stars in the *same* clusters and associations. What was the deal with that? The obvious explanation seemed to be circumstellar dust. We know that RSGs are "smoky" in the sense that dust condenses out of the stellar winds at radii of 5-10$R_{\rm star}$, i.e, about $1000 R_\odot$. The presence of circumstellar dust shells was first revealed by ground-based IR photometry (Hyland et al. 1969), while *IRAS* two-color diagrams established that such shells were a nearly ubiquitous phenomenon (Stencel et al. 1988, 1989). Such dust production is thought to be episodic, with timescales of a few decades (Danchi et al. 1994)

In retrospect, it is surprising that someone had not thought of this earlier. In Massey et al. (2005) we did a simple thin-shell approximation and found that in fact one would *expect* RSGs to have of order 1 mag of visual extinction for average dust production rates over a 10-yr time span. Stars with stronger winds (more luminous) or whose dust condenses closer to the star should have more, while ones with weaker winds (less luminous) or whose dust condenses further from the star will have less. Such dust is likely to have a different grain size distribution that is standard in the ISM and thus might scatter differently in the NUV, but regardless of this we would expected to see more NUV light simply because blue light would be scattered into the beam by parts of the unresolved circumstellar dust shell off-axis to the line of sight.

Our work established that there was a pretty good correlation of dust production rates with luminosity, and so we were able to obtain an estimate for the contribution of dust from RSGs to the ISM. In the solar neighborhood this value is about $3 \times 10^{-8} M_\odot$ yr^{-1} kpc^{-2}. This is about 1% of the return rate of AGBs (Whittet 2003). However, in galaxies at large look-back times (where AGBs have not yet had time to form in large numbers), or in metal-poor starbursts, we expect that the dust produced by RSGs will dominate.

6. What's Next?

The obvious extension of our work is to extend it now to lower and high metallicities. Fortunately, that's relatively easy (and fun!) to do:

6.1. M31: Where the Metallicity Really is Higher

M31 (the Andromeda galaxy) has long been supposed to have a metallicity roughly twice solar, based upon nebular analysis of its H II regions (see, for example, Zaritzky et al. 1994). Here we would expect to find that RSGs were somewhat colder (at a given spectral type) than their Galactic or Magellanic Cloud counterparts, and that the average spectral types are even later. We used the Local Group Galaxy Survey data (Massey et al. 2006) to select a sample of

RSG candidates (using a $B-V$ vs. $V-R$ two-color diagram) and then used the WIYN 3.5-m and the Hydra fiber positioner to determine radial velocities to establish who was really an M31 RSG. The MMT 6.5-m was then used for spectroscopy.

We are still in the process of analysis, but one thing is already certain: M31 really does have (something like) two times solar metallicity. This fact had been called into question by Smartt et al. (2001), who did a chemical analysis of a single B-type supergiant in that galaxy, finding nearly solar-type abundances. In Figure 13 we show that if the abundances really were *solar* then there should be a lot more luminous RSGs than what we actually see.

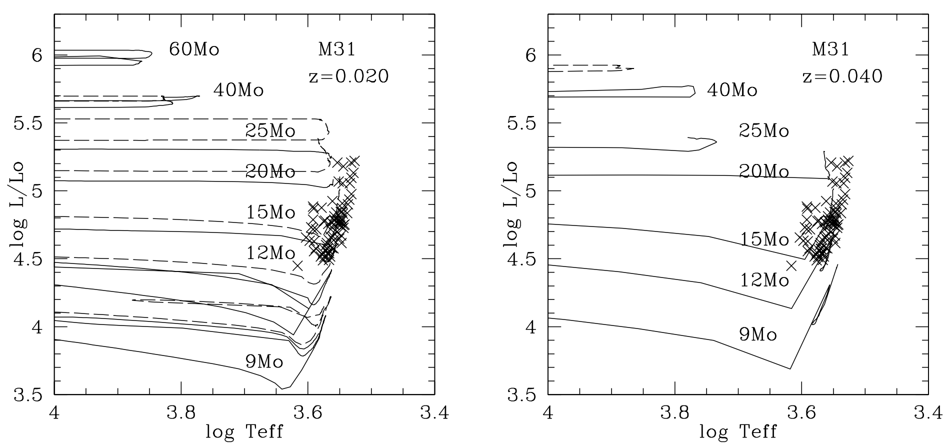

Figure 13. RSGs in M31. We show here two H-R diagrams based upon 2MASS and LGGS $V-K$. On the left we have used the MARCS atmospheres to determine effective temperatures based upon a solar metallicity calibration and compare these to the solar-metallicity ($z = 0.020$) evolutionary tracks from Meynet & Maeder (2003). On the right we have repeated the experiment for a metallicity of 2 times solar, corresponding to the metallicity determined from HII regions. If the metallicity were really solar, then there should be a lot of higher luminosity RSGs than what we actually find: in the diagram on the left, we see we would expect to see RSGs with luminosities of $\log L/L_{\odot} = 5.5$, and we don't. Instead, the highest luminosities we see are $\log L/L_{\odot} = 5.2$, which is all we expect from the higher metallicity tracks shown on the right.

6.2. WLM : Where the Metallicity is Extremely Low

As this text is being written, I am in Chile preparing to observe RSGs in WLM, a galaxy with the lowest metallicity of any galaxy in the Local Group that is forming massive stars. Will we find even worse agreement between the evolutionary tracks and the location of RSGs in the H-R diagram? Will there be peculiarly late RSGs that change their spectral types from year to year, as we found in the SMC (Massey et al. 2007a, Levesque et al. 2007, plus Levesque et al. in this volume). As our colleague Nidia Morrell said when she saw the spectrum of HV 11423, "That star is in a lot of trouble!"

Acknowledgments. Being an astronomer working on RSGs is very fun and exciting—we don't know what we're going to find next—and I've appreciated the opportunity to come to this well-organized meeting and learn a lot from cool star experts. Part of the work described today was done in collaboration with Georges Meynet, Andre Maeder, and Eric Josselin. This work is supported through the National Science Foundation AST-0604569.

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