

Red Supergiants and Extinction Law in the Large Magelanic Cloud Galaxy

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Abstract. The differential extinction technique is applied to derive the extinction law in LMC over the optical (BVR bands) and IR (IJK bands) wavelength range. For this purpose we select photometric sample consisting of 46 red supergiants with moderate and similar extinction on the RSG's branch and 19 extra reddened RSGs. The parameter space was thoroughly investigated in order to obtain the A_λ/A_V distribution most consistent with the Cardelli, Clayton & Mathis model. The most typical total-to-selective extinction ratio in LMC R_V equals 2.7 ± 0.4 and differs from the canonical Galactic value with a significance of only 1σ .

1 Introduction

The red supergiant (hereafter RSG) population over the whole LMC in the IR was revealed for the first time by [1] as a well defined branch on the 2MASS colour-magnitude diagram. RSGs were used to construct a combine initial mass function by [2] extending substantially the studied mass interval.

Recently, our knowledge concerning the extinction properties of the RSGs in the Galaxy and in the LMC vastly increased [3], [4]. Today we already know that the large surface granulation presented in these stars affects broad-band colors and that, due primarily to metallicity, there is a shift in average RSG spectral type: the LMC M-type supergiants scales being cooler than the Galactic scale by 50 K. When compared to distributions of nearby OB stars the distribution of reddening of RSGs both in LMC and Galaxy is skewed significantly toward higher values. Thus RSGs show extra extinction due to circumstellar dust. It makes them very suitable objects for the extinction law probing, especially in the optical and IR. As seen in [5], however, this wavelength span is not the range where distinct difference between the extinction laws in the Galaxy and the Clouds are expected. The substantially lower metallicities in the Clouds than in the Milky Way results in different measured extinction curves in UV toward OB-stars. The averaged total-to-selective extinction ratio for the 10 measured values in [6] is $R_V = 2.6$, indicating dominance of the finer grains in the dust size distribution. Spectral detection [7] of the dust in a damped Ly α systems at redshift $z = 0.524$ seen through the LMC is best fitted with an similar extinction law parameter $R_V = 2.5 \pm 0.2$.

2 Differential extinction technique

Usually, the extinction law in Local group galaxies [8] is studied by three methods: (1) comparing spectra of star pairs inhabiting one and the same galaxy, (2) comparing spectra of stars to those of Galactic standard stars, and (3) comparing star spectra to atmosphere models. The first method known also as differential extinction technique is applied in this work but what we compare here is integrated specific fluxes F_λ (broad-band photometry). Extra-extinction A_λ in each $BVRIJHK$ band is defined as pair magnitude difference and then normalized to A_V in order to fit the extinction curve. We minimize the residual sum Σ of squares in the form:

$$\Sigma = \sum_{i=1}^n \left[\left(\frac{A_\lambda}{A_V} \right)_{mod} - \left(\frac{A_\lambda}{A_V} \right)_{obs} \right]^2 \quad (1)$$

where index '*obs*' stands for the observational quantities, and '*mod*' - for the modeled ones according to the [9] extinction law, where R_V is the only free parameter. Although the dispersion of A_λ/A_V varies with the effective wavelength equal weights were adopted for all pass-bands.

The great advantage of the method lays in its differentiability. In practice, there is no need to know how big the real extinctions are. Among the strengths of the method is the possibility to obtain true extinction curve if an appropriate pairs are chosen. The canceling of the Galactic extinction due to the relatively small angular distances of the star pairs is a factor not to be neglected. However, the differential extinction really measures the extinction difference curves. Thus, it is sensitive to the metalloid, global and local space dust distribution differences between the individual sightlines.

3 Data and Selection criteria

Since RSGs in LMC are used as probing extinction law tool our wavelength coverage is limited to the optical and the IR where these low-temperature stars emit the bulk of their radiation. Nevertheless, for all of them U -band photometry from [10] is available and will be analyzed in a forthcoming paper. We supplemented the BVR red-stars photometry of [11] with I -band photometry of [12] and JHK from 2MASS. We started with the red supergiant branch (hereafter RSGB) identification on the colour- magnitude diagram ($J - K$) vs. K . In order to avoid rapidly evolving RSGs above 20 solar masses, introducing noise at the tip of RSGB, we put an upper limit of the luminosity $K = 7.5^m$. The second step was to construct colour-colour diagram (see, Figure 1, left panel) for all cross-identified stars redder than the blue side of RSGB. Those stars which colours were inconsistent with the colours of moderately or extra-reddened RSGs were rejected. The final step was to select (see, Figure 1, right panel) 46 moderately reddened (defined as points nearest to the fitting RSGB

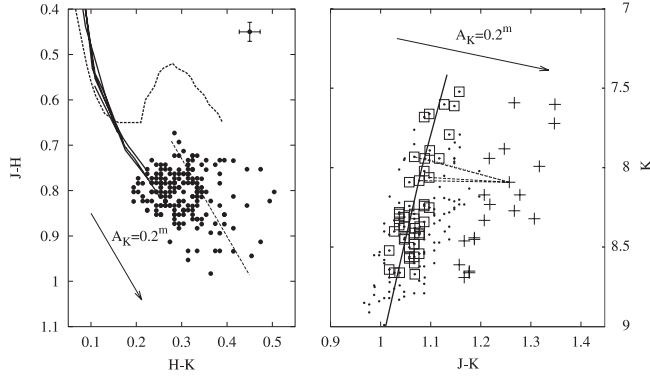


Figure 1. Preliminary selection of moderately reddened (open squares) and extra-reddened (crosses) RSGs on IR colour-colour (left) and IR colour-magnitude (right) diagrams. All stars have optical counterparts. Zero-reddening lines for the Galactic dwarfs (dashed line) and for RSG phase (solid line) are plotted on CC-diagram. The observed RSG branch in LMC is fitted by the bold line on the CM-diagram.

line) and 19 extra-reddened RSGs (defined as points redder than the RSGB) on the colour-magnitude diagram. Their positions are plotted in Figure 2. Further we continue with the selection of the appropriate star pairs. We set the following conditions: (i) $A_V > 0$, (ii) $A_\lambda > 0$, except in K & H -bands and (iii) $A_K < A_J < A_I < A_R < A_V < A_B$. 134 pairs, satisfying selection criteria were found.

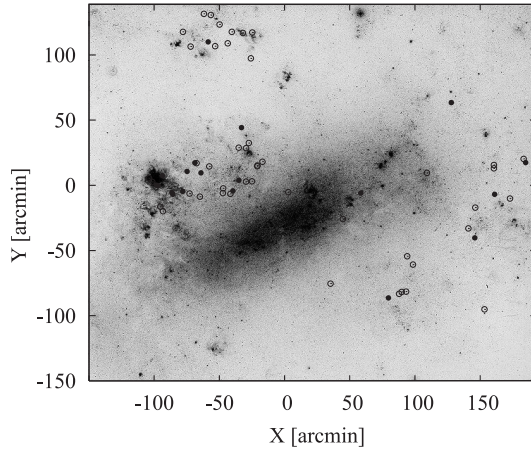


Figure 2. Positions of moderately reddened (open circles) and extra-reddened (filled circles) red supergiants plotted on an optical image of LMC. North is to the top, East is to the left.

LMC Extinction Law

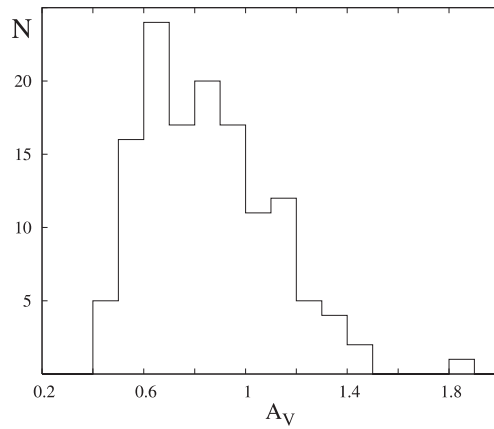


Figure 3. Histogram of the extra-extinction A_V values for all 134 pairs satisfying the selection criteria.

4 Results

The distribution in Figure 3 shows that the extra-extinction A_V values for the selected 134 pairs are all in practice within the range $0.4^m - 1.5^m$, as expected solely on the basis of the IR photometry. An example of optimization of the R_V value concerning individual pair “moderately – extra-reddened RSG” is presented in Figure 4. We explore the total-to-selective extinction ratio in the range between 2.0 and 5.5. The removal of one data point at certain wavelength allows to check the variance of R_V . Thus, the final total-to-selective extinction ratio is

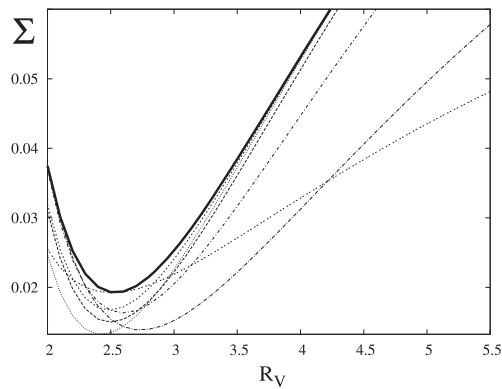


Figure 4. Optimization of the R_V value for a pair “moderately – extra-reddened RSG”, satisfying the selection criteria. The solid curve refers to the fit of the extinction law at all $BVR IJHK$ effective wavelengths and the other curves – at all except one wavelength.

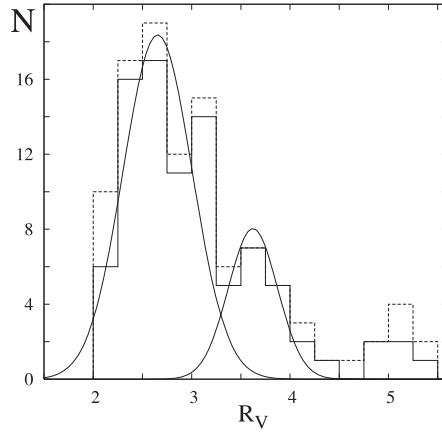


Figure 5. Histograms of the total-to-selective extinction ratio R_V values for 104 pairs with at least 1 successful minimization (dashed line) and 89 pairs with at least 3 successful minimizations (solid line). The decomposed distributions are fitted with gaussians.

simply the arithmetic mean and its error - half of R_V amplitude. There are 89 pairs with at least 3 successful minimizations. The typical relative error of R_V is less than 20%. A possible decomposition of the final R_V distribution, fitted with gaussians is shown in Figure 5. About 64 total-to-selective extinction ratios can be explained with $R_V = 2.65 \pm 0.35$, 20 ratios – with $R_V = 3.6 \pm 0.25$ and only 5 ratios – with $R_V \sim 5.1$.

An alternative approach to derive one 'mean' value of the total-to-selective extinction ratio in LMC is to consider the 89 appropriate RSGs pairs as an ensemble, i.e. to fit A_λ/A_V distribution at six wavelengths and then to use the mean ratios in order to optimize the extinction curve. It is illustrated in Figures 6 and 7.

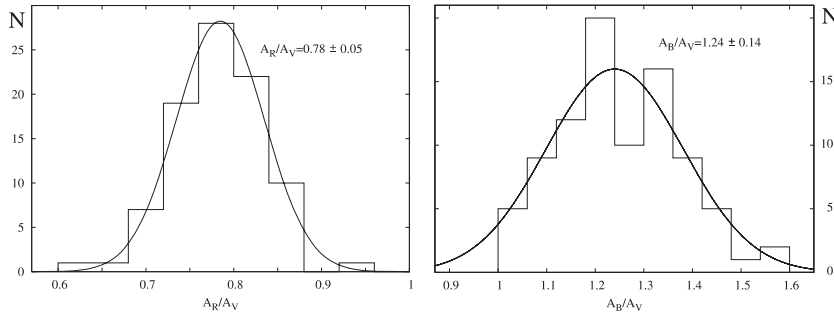


Figure 6. The distributions of A_λ/A_V at R (left) and B (right) effective wavelengths fitted with gaussians. Only 89 pairs with at least 3 successful minimizations were taken into account.

LMC Extinction Law

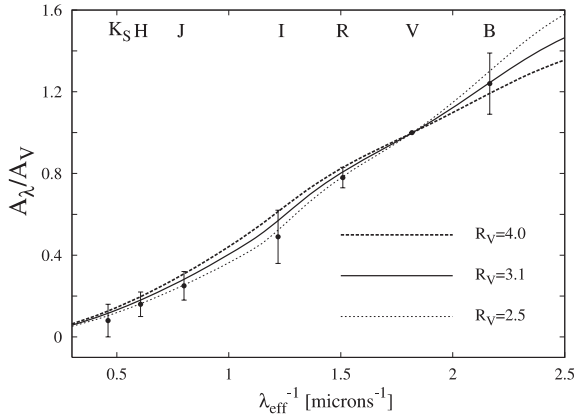


Figure 7. Mean values of A_λ/A_V at all $BVRIJHK$ effective wavelengths superimposed of the CCM extinction law for three different R_V values. Only 89 pairs with at least 3 successful minimizations were taken into account.

As clearly seen in the last figure at wavelengths longer than $0.55 \mu m$ all mean A_λ/A_V ratios are well approximated with $R_V = 2.5$, but in B -band the point lays on the extinction curve, corresponding to $R_V = 3.1$. This is not surprising, since it is well known [13] that the extinction curve is not totally fixed over the entire wavelength range by a unique R_V .

5 Discussion

One possible way to obtain more precise R_V value is to reduce the scatter of A_λ/A_V . We analyze the error budget of this quantity, averaged over all wavelengths. The error propagation shows that the photometric uncertainties contribute 23% to the total error. Other significant sources are the brightness variability of RSGs (25%) and the intrinsic variations (15%) of the CCM law, doubled here because of the applied differential technique. However, the main contribution is due to the possibility of different total-to-selective extinction ratio R_V along the sightlines toward the compared pair stars. Adding one more parameter, namely, the extinction of the star on the RSGB we were able to reduce substantially (33 %) the scatter of A_λ/A_V .

It is promising to fit the CCM extinction law for the very rare (only 3!) star pairs with identical dust distribution in space along the sightlines. For this purpose we used Kolmogorov-Smirnov test to compare the extinction distributions of the hot stars [10] within a radius of $2.5'$, centered on each member of star pair. Assuming that the RSGs are more or less on the galaxy midplane one will expect to obtain an extinction curve representative for the circumstellar dust shell around the more extinguished RSG. The results are incoherent ($R_V = 2.1, 3.1$ & 3.8) indicating diverse SC conditions.

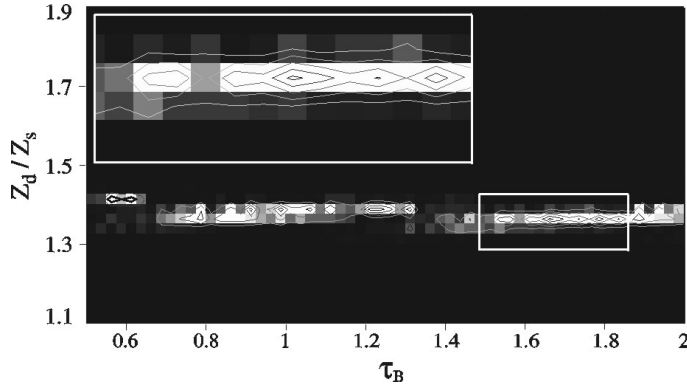


Figure 8. Monte-Carlo modeling of the global properties of the dust space distribution along the sightline toward one of the extra-reddened RSGs in LMC. The real extinction distribution used for comparison is generated with the help of Zaritsky LMC extinction tool within $2.5'$ radius, centered on the star. Contour levels of probability to reject the null hypothesis of Kolmogorov-Smirnov test are from 0 to 0.5 in steps of 0.1. The optical thickness of the LMC disk and the ratio of dust and stars Z-scale factors are free parameters. The enlarged rectangle reproduces the area of the highest probability (solution).

Further, we intent to study the extinction curve in LMC using star pairs along sightlines with equal optical depth τ and star-to-dust exponential scale factor ratio Z_S/Z_D . Such approach was implemented by [14]. Example of modeling the properties of the global space distribution of the dust is shown in Figure 8.

6 Conclusions

We draw the following conclusions:

The RSGs in LMC similarly to the Galactic RSGs exhibit extra-extinction. It could be due to circumstellar and/or interstellar dust distributed along the sightlines toward the pair members selected here for comparison.

Lower metallicity of the LMC results in lower dust mass-loss rates and leads to maximum only $1 \div 2^m$ of extra-extinction in A_V .

The most typical (72%) extinction curve in LMC is well fitted with $R_V = 2.7 \pm 0.4$, different at only 1σ level from the canonical value of $R_V = 3.1$ (ISM in MW).

The possible domination of finer grains in the dust size distribution in circumstellar shells of the RSG in LMC deserves further investigations.

Acknowledgments

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