Extinction law in the Magellanic Clouds

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Summary: *We have initiated a systematic study of the extinction law in the Magellanic Clouds, starting from two regions located at the centre and in the periphery of the 30 Doradus nebula. Interstellar extinction is traditionally derived through spectroscopy of massive early-type stars, which are necessarily few and short-lived and only allow one to probe the most active star forming environments. Instead, using observations at optical and near-infrared wavelengths obtained with the WFPC2, ACS and WFC3 cameras on board the HST, we have developed a new method to determine the extinction law from the much more numerous and ubiquitous stars in the red giant clump of intermediate age populations. When the levels of extinction are high and uneven, like in the regions of interest for this study, these objects are spread across the CMD. Since they share very similar physical properties and are all at the same distance, they are located on a narrow strip along the reddening vector. Thus, they allow us to derive the extinction law in the range 0.3 – 1.6 μm and the absolute extinction towards hundreds of objects in each field, or two orders of magnitude more than allowed by spectroscopy of early-type stars. At optical wavelengths, the extinction curve that we find in 30 Dor is almost parallel to that of the diffuse Galactic ISM, but the value of* $R_V \sim 5$ *that we measure indicates that there is a grey component due to a larger fraction of large grains. At wavelengths longer than ~ 1 μm, the contribution of the grey component tapers off as* $\lambda^{-1.5}$*, like in the Milky Way, suggesting that the nature of the grains is otherwise similar to those in our Galaxy. This extinction law leaves no doubts that in these regions large grains are more important than in the diffuse Galactic ISM, suggesting that in star-forming regions either grains are generally larger, or large grains are more frequent, or both.*

Studies of the properties of stellar populations hinge on the accurate knowledge of the interstellar extinction (amount and properties), since extinction affects fundamental observational quantities such as the distance and luminosity function (e.g. Gottlieb & Upson 1969). The diffuse Galactic ISM appears to have a rather uniform extinction law and the ratio of total and selective extinction $R_V = A_V / E(B - V)$ is found to be consistently about 3.1 (e.g. Savage & Mathis 1979). However, it is well known that R_V varies considerably in our Galaxy, mostly thanks to the studies conducted in the 1970's with the Orbiting Astronomical Observatory 2 (Bless & Savage 1972), with Copernicus (e.g. Seaton 1979), and later with the International Ultraviolet Explorer, which revealed a wide variety of extinction curves (see e.g. Fitzpatrick 1998, 1999).

In particular, in dense star forming regions the situation is quite different from that of the diffuse ISM and generally the value of R_V appears to increase, due to the presence of larger grains (e.g. Cardelli, Clayton & Mathis 1988), with a correspondingly rather different extinction law. Since we are interested in regions where not only the level and intensity of star formation is variable but also the chemical composition is profoundly different from that of the Galactic ISM, proper knowledge of the extinction law specific to our stellar fields is of paramount importance.

The traditional approach to deriving extinction curves is the "pair method," in which the flux distribution or colours of a reddened object are compared with those of a star of the same spectral type (e.g. Johnson 1968; Massa, Savage & Fitzpatrick 1983; Cardelli et al. 1992). This method is potentially very reliable and can detect subtle variations of the extinction law with the environment, but it requires massive stars to be present in the regions of interest and the availability of high quality spectra extending from the near ultraviolet to the near infrared. Given the difficulty of deriving high quality spectra of massive stars in crowded extragalactic star forming clusters, such as those that we are studying in the Magellanic Clouds (MC), the extinction law in those regions is based on just a handful of lines of sight (e.g. Gordon et al. 2003). Furthermore, these early-type massive stars do not necessarily sample the same environment in which low-mass stars form, and due to their short life they cannot reveal the long-term evolution of the dust grains in those regions. In other words, massive stars only allow us to probe the most active star-forming environments at the peak of the burst, but those conditions that are not characteristic of all objects in the field.

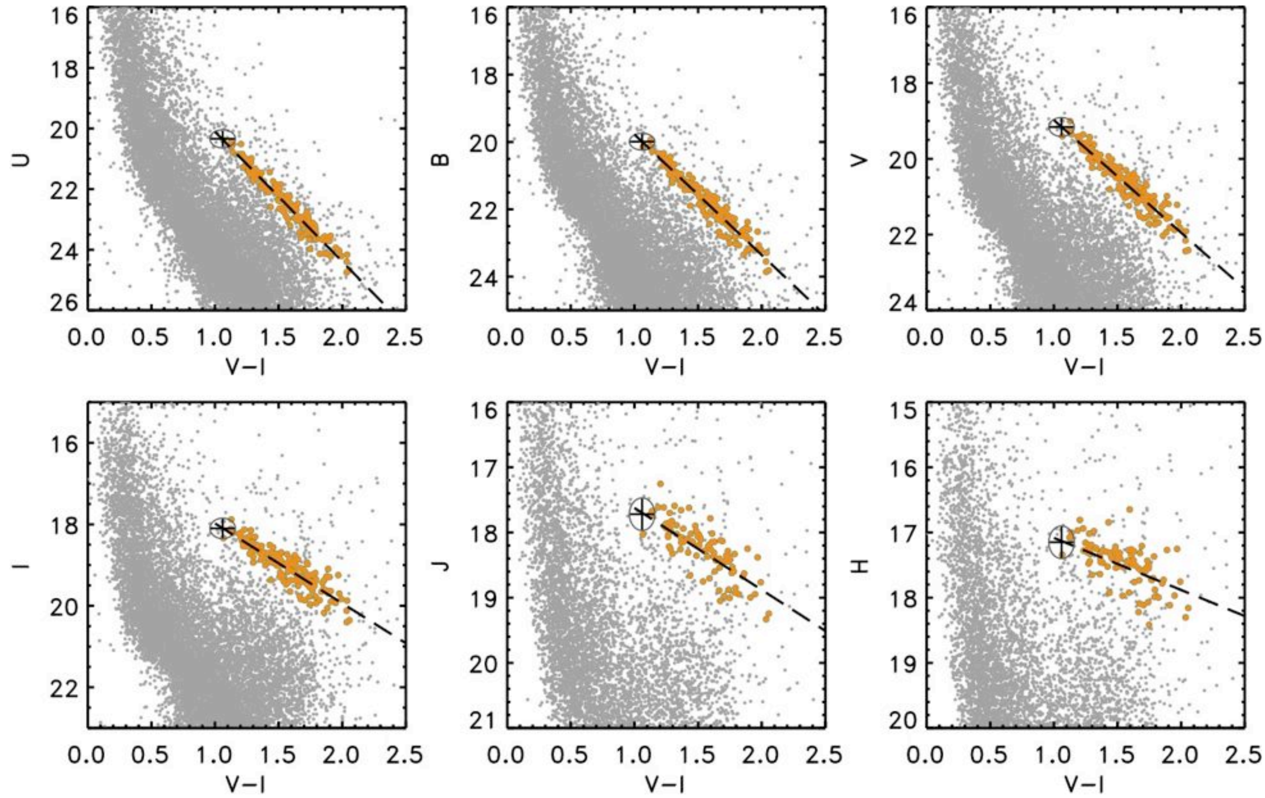

Figure 4. The CMD of 30 Dor allows us to derive the absolute extinction in all bands towards hundreds of red giants that belong to the RC (circled cross). They are located in strips that are the result of spread across the CMD by the high and variable levels of extinction in these fields. The slopes of such strips provide a direct measurement of the extinction law.

To overcome these limitations we have developed a new method to unambiguously determine the absolute value of the extinction in a uniform way across the MC in all observed bands, deriving in this way an absolute extinction law. Our method makes use of multi-band photometry of red giant stars belonging to the red clump (RC). Other authors have used RC observations in the past to study the reddening distribution and to derive reddening maps in the MC (e.g. Zaritsky 1999; Haschke et al. 2011; Tatton et al. 2013). However, all these works have assumed an extinction law and thus cannot derive it independently, while we can.

The novelty and advantage of our method consists in the facts that *(i)* all stars on which we operate are at the same distance, to better than 1%; *(ii)* they have very similar intrinsic physical properties in all bands, within 0.05 mag for similar age and metallicity; *(iii)* our statistics is very solid, with about 150 objects per field or about 20 stars per arcmin^2; and *(iv)* we derive a self-consistent absolute extinction curve over the entire optical and near-infrared range (*0.3 – 1.6 μm*) from photometry alone. Our method can be easily extended to many other nearby galaxies.

Using theoretical CMDs (Girardi & Salaris 2001; Salaris & Girardi 2002), computed for the specific HST bands of our observations, we have studied the expected behaviour of the mean RC as a function of age (from 1.4 Gyr to 3.0 Gyr) and metallicity (from 0.05 $Z_{\odot}$ to $Z_{\odot}$). We find that the magnitude of the RC is not affected considerably by the age of the stars, except at very low metallicity. This limited sensitivity of the RC to age and metallicity makes it easier to estimate the amount of reddening when there is considerable interstellar extinction ($A_V > 1$), since in this case the magnitude and colour displacement of the RC in the CMD due to extinction dominate over all uncertainties on metallicity and age.

To identify bona-fide RC stars, we have compared our observations in all bands with the theoretical CMDs for the metallicity range applicable to the LMC ($0.004 < Z/Z_{\odot} < 0.008$), taking into account the known distance modulus and intervening Milky Way reddening. This allows us to define the region of the CMDs where reddening can place RC stars, finding about 200 objects inside it in each field. With an iterative procedure, we have reduced this number by retaining

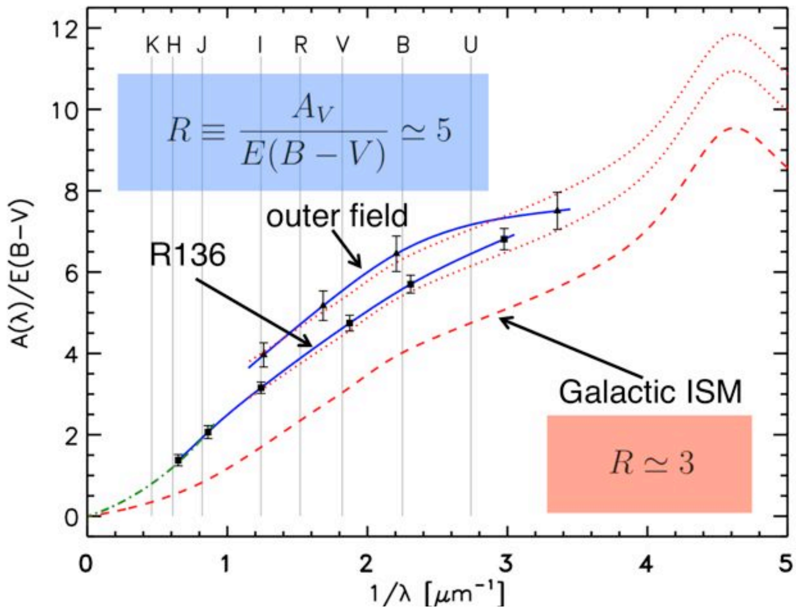

Figure 5. Extinction law in 30 Dor. The blue solid lines and data points correspond to the measurements in the cluster core (R136) and in the outer field located 6' west of it. The curves are considerably less steep than that of the diffuse Galactic ISM (dashed line). At optical wavelengths the extinction law is practically parallel to the Galactic law, being shifted to higher values of *R* by an amount of 1.4 and 2.3, respectively (dotted lines), but above ~1 μm it falls off with wavelength as $\lambda^{-1.5}$, like the Galactic law (dot-dashed line).

only those classified as bona-fide RC stars in all CMDs simultaneously (see Fig. 4). We have also very conservatively removed from this sample any bona-fide and candidate PMS stars (10 per field on average) with $H\alpha$ emission and equivalent widths in excess of 3 Å.

In each CMD, the best linear fit to the distribution of the bona-fide RC stars provides the absolute extinction and the ratio *R* between absolute and selective extinction in the specific bands of our observations, allowing us to derive the extinction law $R_\lambda = A_\lambda / E(B-V)$. Adopting the parametrization of Cardelli et al. (1989) and Fitzpatrick & Massa (1999), our extinction law (see Fig. 5) is consistent with $R_V = 4.5 \pm 0.2$ in the core of 30 Dor (De Marchi & Panagia 2014) and $R_V = 5.6 \pm 0.3$ in the field located 6' west of it (De Marchi, Panagia & Girardi 2014). As such, this extinction law (blue lines in Fig. 5) is considerably less steep than that of the diffuse Galactic ISM, i.e. it displays shallower logarithmic slopes. At optical wavelengths the extinction law is practically parallel to the Galactic law, being shifted to higher values of *R* by an amount of 1.4 and 2.3, in the two fields respectively (dotted lines), but above ~1 μm it falls off with wavelength as $\lambda^{-1.5}$, like the Galactic law (dot-dashed line).

These findings indicate that dust in these regions comprises a larger fraction of big grains, thus adding a grey component to the extinction. This law leaves no doubt that in these regions large grains are more important than in the diffuse Galactic ISM, suggesting that in star-forming regions grains are generally larger and/or large grains are more frequent.

We are currently extending this study to the entire Tarantula nebula, which was observed as part of the Hubble Tarantula Treasury Program (Sabbi et al. 2013). The wide contiguous area covered by these observations (~ 170 arcmin^2) contains ~5,000 RC stars, allowing us to detect and study in great detail local variations in the extinction law caused by the effects of massive stars on the size and distribution of the grains (e.g. through photo-ionisation or feedback). Conducting this study in the LMC will allow us to probe the conditions that were current at redshifts z~2, when most stars formed in the Universe (e.g. Madau et al. 1996; Lilly et al 1996). Therefore, our work will have important implications for cosmology as well, since a sound understanding of the extinction law and of its variations in those environments is a necessary and still missing step to properly interpret the observations of star-forming galaxies in the early Universe.

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