THE Rv EXTINCTION FACTOR

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Abstract: The extinction factor Rv can be used not only to deredden stellar fluxes (in particular in the extreme and far UV), but also to determine photometric distances for distant stars and finally, as an indicator of the size of the interstellar dust. We present here preliminary results of a work aiming at obtaining Rv values for as many stars as possible, to be included in the Spanish Virtual Observatory as a tool to get the distribution of the absorption with the distance in any direction or the approximate value of Rv in any line of sight and distance. We summarize three different methods used to determine Rv and give the results for the IR method which makes use of JHK 2MASS photometry.

1 Introduction

The study of the interstellar extinction (absorption and scattering of starlight by interstellar dust grains, hereafter ISE) and its dependence on wavelength is important for two reasons. First, the extinction depends on the optical properties of the grains or dust particles in the line of sight and gives us information about the size and composition of the grains. The size and spatial distribution of the grains is also important to know the behaviour of the interstellar medium and its relation with star formation. Second, to know the true energy distribution emitted by the stars, the correction of the effects produced by the dust over the observed energy distribution is essential.

Classically, wide and intermediate band photometry was used to determine the extinction law in the optical and near infrared (NIR) spectral regions, concluding that there were no major differences among different sky directions. This law was characterized by the R parameter, Rv=Av/E(B-V), where Av is the total extinction in the V region, and E(B-V)=(B-V)-$(B\text{-}V)_o$ represents the selective extinction, in the B and V regions. The R values obtained vary from one to another sky direction ($2.2 < \mathrm{Rv} < 5.8$) with a mean value of approximately 3.1 for the general diffuse ISM [1].

The UV ISE was, on the other hand, determined from spectrophotometry, yielding different extinction curves depending on sky direction. Milestones on ISE analysis were [2, 1], giving a simple analytic formula from the IR to the UV. These two works with many others led to [3] and [4], hereafter CCM, to an ISE general formula valid for all directions on the only basis of the Rv parameter. More recently, from new JHK photometric and spectrophotometric observations [5] proposed a family of curves depending on Rv coincident in shape with the CCM law.

CCM and Fitzpatrick [5] laws have been proven to be accurate by different authors and for different directions and wavelength domains (i.e. [6, 7]).

Very shallow extinction laws (no variation with the wavelength) in the optical and UV are characterized by large Rv values. Small Rv values produce very steep curves in the UV and optical. The size of the dust grains is directly related to the value of Rv: large Rv values are produced by larger than normal grains and small grains produce Rv values smaller than normal.

In this work, firstly we present a summary of different methods used to determine Rv, and then we determine Rv for all O,B and A stars with MK spectral types and JHK photometry from 2MASS (*Two Micron All Sky Survey*, [8, 9]), using a set of intrinsic colors obtained by us from the 2MASS observations. In the visible the existent intrinsic colors are widely accepted, but in the NIR the scarcity of observations available before 2MASS produced a variety of intrinsic colors not well defined.

The majority of methods to determine Rv are strongly dependent on intrinsic colours. The potential generalization of a mean Rv to directions, depends on the size and distribution of the sample of stars used to compute it. For this reason we have centered our study in the latter method, which uses JHK colours from the catalogue of 2MASS point sources. The huge number of stars contained in 2MASS, provided us with a unique tool to compute NIR intrinsic colours and Rv values for the largest number of stars published so far,to our knowledge.

We expect to include our preliminary data on-line in the Spanish Virtual Observatory as soon as possible (*http://www.laeff.esa.es/svo/*), and make them available to the astronomy community.

2 Determination of Rv

In this work we evaluate the performance of three different methods to determine Rv. We conclude that the method based on 2MASS photometry is the most adequate except for stars with small values of E(B-V) for which the polarization method is preferred.

2.1 The method using the wavelength of maximum polarization.

When the stellar light passes through a region or cloud where there are IS grains aligned by the galactic magnetic field, the emergent light results polarized. The grains orientate their major axis perpendicular to the magnetic field. It was found that the wavelength of maximum polarization (λ_{max}) is proportional to the grain size [3, 10, 11] and then to Rv (Table 1).

Relation	N. of stars	Reference
Rv= $5.5 \times \lambda_{max}$	41	[10]
Rv= $5.6 \times \lambda_{max}$	73	[11]
Rv= $6.67 \times \lambda_{max} - 0.29$	21	[3]
Rv= $5.57 \times \lambda_{max}$	78	This work (see text)

Table 1: Statistical relationship between the λ of maximum polarization and Rv.

The values of λ_{max} vary between 0.34 and 1 μm, the mean value being 0.55 μm. Polarization increases from the IR to the optical and then decreases to the UV, in contrast with the extinction law, which rises monotonically up to the UV except the hump around 2200 $\AA$. It is probable that the grains producing extinction in the UV are unable to polarize the light because they are not elongated and/or are not aligned [13].

Even though λ_{max} is proportional to Rv, the polarization law is independent of Rv. The explanation could be that the grains can be aligned only when they contain superparamagnetic particules, like magnetite. In addition to this, large grains are able to be orientated more easily than small ones, because they have a higher probability of containing a variety of chemical components supplied by the cloud where they form [14].

With λ_{max} data from catalogues in the literature [15, 17, 16, 10, 18], and the corresponding Rv values determined independently by us from NIR colours, we obtained 78 couples of values to test the relationship between λ_{max} and Rv.

As usually done in works about ISE, we exclude stars having circumstellar matter or mass loss. As shown in Table 1, our result is in between the results of [10] and [11].

An important conclusion which can be extracted from this method is that the dispersion of Rv values obtained through polarization does not depend on the value of E(B-V). On the contrary, the dispersion of Rv values obtained through NIR colours increases when E(B-V) decreases (because the dispersion of Rv is inversely proportional to the square of the extintion). Thus, the polarimetric method to obtain Rv will be the most adequate for stars with E(B-V) $<$ 0.20.

2.2 The colour difference method.

The Arizona RIJKLMNQ photometric system [19] has been used since the beginning to perform studies about the ISE [20, 21]. The usefulness of the method comes from the fact that for long wavelengths the very small size of the grains does not produce practically any absorption or scattering, and for this reason, dust clouds are almost transparent to far IR and radio wavelengths.

The colour excess for individual stars is obtained by comparing observed colours with intrinsic ones, for each spectral type. The colour excesses are normalized to E(B-V) = 1.0 and plotted against the inverse of the wavelength of each filter. An extrapolation of the curve E(V-λ)/E(B-V) = f(1/λ) to 1/λ = 0 allows for a determination of Rv because at very long wavelengths the ISE becomes zero: at this limit E(V-λ)=Av and then E(V-λ)/E(B-V) becomes Rv. In practice, the extrapolated curve gives Rv as the abscissa value for 1/λ = 0.

This method was used recently by [22], who consider 700 O and B stars observed from the UV to the IR and obtained a mean value of Rv of 3.1.

2.3 The IR excess method.

This method makes use of the NIR colours J, H and K to determine Rv. In the colour-difference method we have seen that normalizing E(V-λ) values to E(B-V)=1.0 and extrapolating to 1/λ = 0 allows us to determine Rv, which is equal to 3.05 for the Van de Hulst curve No.15 [39]. In this method, normalizing to E(V-K) and extrapolating to 1/λ = 0, we obtain Av/E(V-K)= 1.1 for the same curve. With this relationship and with the definition of Rv = Av/E(B-V) we obtain the formula used in the classical colour-excess method for the determination of Rv: Rv= 1.1 $\times$ E(V-K)/E(B-V). Similar formulae are obtained for the other two colours J and H.

Rv	Method	Stars	Considered sky zone	Reference
> 3.0	Colour diff	104	All sky	[19]
3.12	E(V-K)	40	Anticenter	[23]
3.01	E(V-K)	98	North Hemisphere	[24]
3.12	E(V-K)	129	South Hemisphere	[12]
3.1	Colour diff	700	All sky	[40]
3.08	Various	154	South Hemisphere	[7]
2.9	Vilnius	24	Galactic Eq. 135-155	[25]
3.03	E(V-K)	6,613	All sky	This work
2.94	E(V-K)	2,514	All sky E(B-V)$>$ 0.20	This work

Table 2: Previous Rv determinations.

In this preliminary work we have used only the colour K and the more recent formula deduced from the extinction law of [5]: Rv=1.12× E(V-K)/E(B-V) + 0.02. We determine for each star of our sample the colour excesses E(V-K) and E(B-V) from intrinsic and observed colours.

The publication of the 2MASS point-source catalogue covering 99.5 % of the sky allows us, with this method, to determine the Rv values for the largest stellar sample used so far (see Table 2).

3 Our sample selection.

Our sample was selected from the SIMBAD database at CDS, Strasbourg Observatory. We extracted all the stars with spectral types O, B and A having Johnson UBV and 2MASS JHK photometry. We have excluded all those stars showing some spectral peculiarity that could modify their colours : emission lines, shells, Bp-Ap/Am, multiple stars not resolved, etc.

The reasons to exclude these types of stars are different: shell and emission-line stars, can produce abnormal IR excesses due to circumstellar matter around them [26], therefore it is impossible to discriminate or to separate their effects from those of the ISE. We do not include Bp-Ap and Am stars because they have different absolute magnitudes and intrinsic colours from normal stars [27, 28, 29], they are brighter and bluer. An exercise we foresee for the future is to take advantage of 2MASS to obtain the intrinsic colours for Bp-Ap stars and compare them with those of normal stars.

Our final sample contains 10,466 O,B and A stars spread over all luminosity classes, and 7,753 excluding the peculiar stars mentioned. For the computation of Rv and intrinsic colour determination we used only the 6,613 stars with E(B-V) and E(V-K) greater than zero.

4 Determination of new intrinsic colours.

Several different NIR photometric systems exist with slightly different passbands. Since the two primordial NIR systems, namely, the Johnson Arizona JKLM system [20] and the Glass SAAO JHKL system [30], many other systems have appeared: ESO [31], CIT/CTIO [32], MSO [33], AAO [34]. Several attempts to homogenize these NIR systems have been made by [35, 36] and more recently by [37], incorporating the new 2MASS system [9] which is also different from the others. Although much work has been done, there are still significant uncertainties in the transformations among the different NIR systems.

For these slightly different photometric systems there are also slightly different intrinsic JHK colours in the literature (see Table 3). In order to avoid the inherent errors from system transformations, and taking advantage of a much larger number of observations, we decided to calculate a set of intrinsic colours based directly on 2MASS observations.

Colours	Stars	SpType	Reference
UBVRIJKL	104	O5-A0	[19]
JHKL	54	O8-A2	[12]
JHKLM	203	O6-M8	[41]
JHKL		B8-M6	[36]
JP11	700	O5-B9	[40]
JHK-2MASS	6,613	O5-A9	This work

Table 3: Intrinsic J,H y K colours from previous works.

Before proceeding to the intrinsic colour determination we have verified that all peculiar stars have been excluded. A (H-K)/(J-H) diagram allows as to distinguish between the reddening produced by IS and the one produced by CS matter [12].

The (H-K) and (J-H) values for reddened stars of our sample will be shifted following parallel paths to the reddening line and inside the two extreme reddening lines corresponding to our extreme spectral types O6 and A9. We have traced the two extreme reddening lines enlarged by 0.5 mag to take into account some inherent observational errors (Δ(B-V) = 0.01 mag, Δ(J-K) = 0.058 mag, [5]) as well as a possible error from a misclassification of the spectral type, which could be of the order of 0.5 mag in extreme cases. The 19 stars placed outside the zone defined by the two reddening lines are probably either misclassified and/or have probably companion stars or CS matter (IR emission), and were not considered to compute intrinsic colours.

We perform a similar method for the optical region, plotting E(B-V) versus E(V-K) for all "normal" stars (Figure 1) and tracing two limiting reddening lines at -0.5 and +0.5mag of the lines corresponding to spectral types O6 and A9. The 56 stars outside the two reddening lines have been excluded for the computation of intrinsic colours.

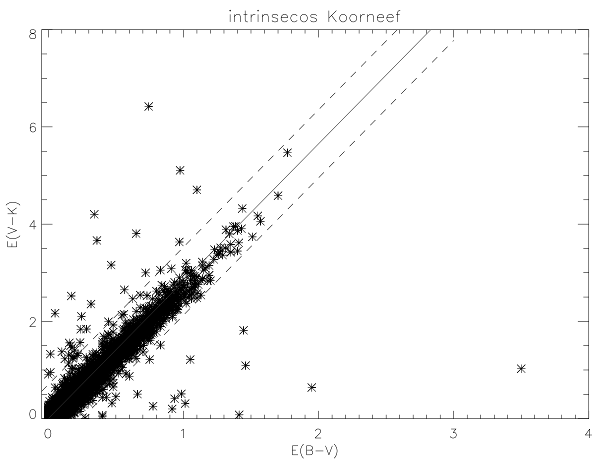

Figure 1: Diagram E(B-V)/E(V-K) for stars of our sample, and the two extreme reddening lines corresponding to spectral types O6 and A9.

To obtain intrinsic colours with this cleaner sample, we selected only stars with small E(B-V) in order to minimize the error of the dereddening process. Taking into account the differences among NIR photometric systems, we determine our own dereddening formula from 2MASS photometry alone, following the method of [40]. For doing that we plot (B-V) versus (V-K) from all the stars and fit a straight line to them, the slope of this relation is used to deredden the stars:
$(V-K)_o = (V-K) - 2.66E(B-V)$
and also to compute the intrinsic colours for each spectral type and luminosity class. The resulting intrinsic colours differ very little from the best intrinsic

colours found prior to this work [41] for luminosity classes V and IV. For luminosity classes I, II and III the difference is larger. This can be due to the small number of stars used by other authors to compute their intrinsic colours.

5 Results

Taking into account stars with E(B-V) > 0.20 (2,514 objects) we obtain a mean value of Rv of 2.94. For all the stars with E(B-V) > 0.0 we obtain Rv = 3.03 (6,613 stars), in good agreement with previous measurements but with a number of stars ten times larger than in any previous work.

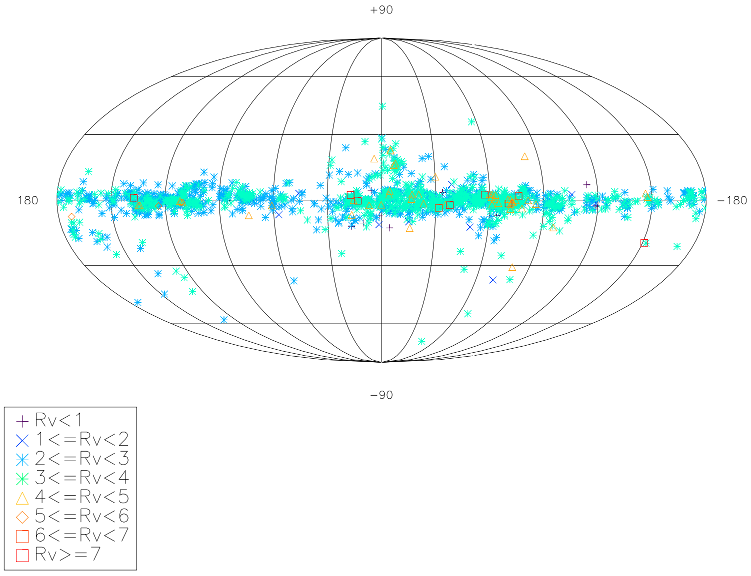

Figure 2: Rv distribution for field galactic stars

In Figure 2 we have the Aittoff projection of the values of Rv of the stars of our sample, with different symbols for different steps of Rv. Stars belonging to open clusters are not represented here.

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