Anomalous dust to gas ratios in the Galaxy

Emanuele Congiu, Anna Geminale, Guido Barbaro, and Paola Mazzei

1 Department of Physics, S.P. Monserrato, 09042 Cagliari, Italy
2 Department of Astronomy, Vicolo dell’Osservatorio 3, 35122 Padova, Italy
3 INAF Astronomical Observatory, Vicolo dell’Osservatorio 5, 35122 Padova, Italy
E-mail: econgiu@ca.astro.it

Abstract. Lines of sight with \(E(B-V)/N(HI)\) considerably smaller than the average value for the solar neighbourhood have been selected from the catalogue of Diplas and Savage. In order to develop quantitative considerations, estimates of the molecular hydrogen column density were obtained using the relation of Savage et al. extended to \(E(B-V)>0.4\) with the recent data of Rachford et al. Contrary to the prevailing opinion in the literature for lines of sight with similar behaviour, we found that only 22 per cent of our sample was characterized by both an average gas density larger than 1 cm\(^{-3}\) and a value of \(R_V\) larger than that in the diffuse interstellar medium. By computing extinction models, we were able to fit the \(E(B-V)/N(HI)\) by changing the value of \(R_V\) only for some lines of sight. For the remaining ones, a \(\rho_d/\rho_H\) ratio different from the average Galactic value must be invoked. The application of the Kramers-Kronig relation to the observed extinction curves confirmed this possibility. Moreover, attempts to fit such curves with models having grain volumes corresponding to the standard \(\rho_d/\rho_H\) ratio failed.

1. Introduction

By analysing a large sample of lines of sight of which the HI and H\(_2\) column densities were measured, Bohlin et al. [1] derived an average value \(E(B-V)/N(H) = 0.17 \times 10^{-21}\) mag cm\(^2\), where \(N(H) = N(HI) + 2N(H_2)\). They also determined an analogous relation by using only the atomic hydrogen column density: \(E(B-V)/N(HI) = 0.21 \times 10^{-21}\) mag cm\(^2\). A similar result was obtained also by Diplas & Savage [2]. They found that the spread in the \(E(B-V)\) versus \(N(HI)\) diagram is larger than the errors and moreover, from a statistical analysis, they concluded that the histogram of the deviation of each star from the mean does not correspond to a normal population, the lower wing being less populated than the other one. This may suggest that there are systematic differences within the sample, as is also confirmed by theoretical considerations which will be developed further on. In fact, a non uniformity in the dust to gas ratios within the Galaxy was suggested a long time ago [3, 4].

Several papers have stressed the behaviour of some nearby stars whose lines of sight show an \(E(B-V)/N(H)\) ratio deviating greatly from the average. In particular Savage et al. [5] treated the case of \(\rho\) Oph, 67 Oph and other stars (cfr. their Fig. 7). The case of \(\rho\) Oph was considered again by Diplas & Savage [6], who determined a new value of \(N(HI)\) smaller than that derived by Savage et al., but still this sightline preserves its anomalous character with regard to the dust to gas ratio. Snow & Witt [7] analysed some lines of sight towards \(\rho\) Oph, HD 38087 and Orion, emphasizing that all are characterized by a large value of \(R_V\), which, according to the extinction
models of Mathis & Whiffen [8], outlines a deficiency of small grains with respect to large ones. Kim & Martin [9] also considered this problem by analysing the $A_V$-N(HI) and $A_V$-N(H) diagrams.

Bohlin et al. [1] discussed the reasons for these behaviours and put forward two possibilities: a) a variation of the dust to gas mass ratio and b) a reduced extinction efficiency in the photometric B and V bands as a consequence of the particular size distribution of grains typical of dense lines of sight with large $R_V$. With reference to ρ Oph, however, they favour the second interpretation which is in fact the prevailing opinion found in literature.

The aim of this work is to analyse more deeply this problem by looking at a larger number of lines of sight showing this behaviour. For this purpose we used, most of all, the large sample of Diplas & Savage [2, 6] of 393 B2 and hotter stars whose absorption lines were obtained with the IUE satellite.

2. Observational data
The selection of the lines of sight of interest, namely those with $E(B-V)/N(HI)$ strongly deviating from the average, was performed according to the following criteria: a) $E(B-V)/N(HI)<0.21\times10^{-21}$ mag cm$^2$ and b) the deviation from the average, normalized to the standard deviation, as defined in [6], $\delta$, larger than 1. The standard deviation was determined with the error propagation and with $\sigma(N(HI))$ and $\sigma(E(B-V))$ given in the same paper. In the diagram E(B-V) vs N(HI) of Figure 1 are plotted the selected 41 targets which have an anomalously lower $E(B-V)/N(HI)$ ratio even accounting for the errors in the determination of N(HI).

Compared with the total number of lines of sight in the catalogue of Diplas & Savage [2], the number of stars that have been extracted with the required properties is 10%. Nevertheless this number could be raised by the inclusion of the molecular gas in computing the column density. It must be remarked that this particular behaviour mainly concerns the dust which is associated with the atomic gas; in fact if we could detract the contribution to E(B-V) of the dust in molecular regions we still have E(B-V)/N(HI) smaller than the average.
3. Inclusion of molecular gas

As E(B-V) accounts for all the dust associated with all the types of gas met by the sightline, the analysis of the dust to gas ratio would imply the consideration of the molecular gas. It must be pointed out that objects that have E(B-V)/N(HI) smaller than the average preserve this character also as far as the E(B-V)/N(HI+H$_2$) ratio is considered. Therefore the conclusion previously reached (section 2) is not invalidated by neglecting the molecular gas. This however cannot be ignored when aiming at reaching quantitative considerations. Only for two objects of our sample the determination of N(H$_2$) is given in literature: HD 37022 (only the upper limit) and HD 147933. For three lines of sight (HD 61347, HD 152236 and HD 164740) we inferred the H$_2$ abundance directly by analysing absorption spectra obtained with the Far Ultraviolet Spectroscopic Explorer (FUSE). For the rest of the lines of sight we used the statistical relation between E(B-V) and the fraction \( f \) of molecular gas, derived from the sample of Savage et al. (1977) for \( E(B-V) < 0.5 \). Then we extended their relation up to E(B-V)=1.04 using the data of Rachford et al. [10].

Although it is known that the E(B-V)/N(H) ratio can be affected also by a change in the relative abundance of dust, the low value of E(B-V)/N(H) is often ascribed to the poor extinction efficiency of dust in the visible range, which, according to Mathis & Whiffen [8], is witnessed by large values of R$_V$. This requirement is fulfilled only by a fraction of our sample. Therefore it is interesting to inquire what range of E(B-V)/N(H) can be explained only by changing R$_V$. The suggestion is therefore that a modification of the size distribution of the grains, corresponding to changes in the R$_V$ values, partly explains the spread of the observed data but cannot solve completely the problem. A change of the \( \rho_d/\rho_H \) ratio is required, as it is necessary for explaining the E(B-V)/N(H) ratio in the Magellanic Clouds.

4. The \( \rho_d/\rho_H \) ratio

Theoretical considerations suggest that, beside changes in R$_V$ also changes in the relative abundance of dust can affect the E(B-V)/N(H) ratio, as shown in Barbaro et al. [11]. To test this possibility we have applied the Kramers-Kronig relation (e.g., Purcell, 1969 [12]) to the available observed curves of our sample in order to derive \( \rho_d/\rho_H \) (Table 1, column3)

\[
\frac{\rho_d}{\rho_H} = 1.86 \times 10^{18} \rho_s D(\epsilon_g) \int_0^{+\infty} A(x) \frac{1}{N_H} \frac{1}{x^2} dx
\]

where \( x = 1/\lambda \) is given in \( \mu m^{-1} \) and, for \( \rho_s \), the mean of the densities of the carbonaceous and silicate grains has been adopted. The quantity:

\[
D(\epsilon_g) = \frac{\epsilon_g + 2}{\epsilon_g - 1}
\]

depends on the dielectric constants of grains.

We note that the derived quantities are smaller than the average Galactic value (0.01 according to Pei [13]), thus suggesting that a reduced dust-to-gas ratio can cooperate in producing the anomalous behaviour of the selected lines of sight.

5. Analysis with extinction models

In this section we present results of our extinction models computed following the prescriptions of Weingartner & Draine [14]. This computation requires the dielectric properties of the grains and their size distribution. This last aspect depends on a total of eleven parameters, six for the carbonaceous and five for the silicate grains. The interstellar populations of “astronomical silicates”, graphite and polycyclic aromatic hydrocarbons (PAH) are considered. Li & Draine [15] assume that carbonaceous grains have graphitic properties at large sizes and PAH-like properties.
Table 1. $\rho_d/\rho_H$ for our sample derived from the Kramers-Kronig relation (column 3) and from our models (column 4).

| Name       | E(B-V)/N(H) 10^{-23} (mag cm^2) | $\rho_d/\rho_H$ (10^{-3}) Kramers-Kronig Models | $\rho_d/\rho_H$ (10^{-3}) Models |
|------------|---------------------------------|------------------------------------------------|---------------------------------|
| HD14818    | 10.82 ±3.58                    | 5.21±1.73                                      | 5.90                            |
| HD36982    | 8.13 ±2.85                     | 7.31±2.57                                      | 7.82                            |
| HD37022    | 9.81 ±3.43                     | 8.58±3.01                                      | 9.20                            |
| HD37023    | 8.48 ±2.99                     | 7.05±2.49                                      | 7.80                            |
| HD37061    | 6.08 ±2.01                     | 5.00±1.65                                      | 5.85                            |
| HD37737    | 5.67 ±3.37                     | 2.72±1.62                                      | 3.89                            |
| HD38087    | 8.52 ±3.08                     | 7.53±2.72                                      | 9.22                            |
| HD43818    | 6.05 ±3.19                     | 3.19±1.69                                      | 3.45                            |
| HD46202    | 9.85 ±4.38                     | 4.93±2.19                                      | 5.63                            |
| HD54911    | 10.43 ±3.89                    | 7.63±2.85                                      | 7.21                            |
| HD58509    | 9.54 ±3.30                     | 6.86±2.37                                      | 7.48                            |
| HD61347    | 10.90 ±3.58                    | 5.51±1.81                                      | 6.42                            |
| HD90273    | 9.60 ±4.25                     | 5.75±2.55                                      | 5.30                            |
| HD137569   | 5.67 ±2.60                     | 5.15±2.36                                      | 6.58                            |
| HD147888   | 7.38 ±2.39                     | 5.11±1.66                                      | 8.41                            |
| HD147933   | 9.38 ±2.54                     | 6.81±1.85                                      | 7.21                            |
| HD152236   | 9.81 ±3.12                     | 5.16±1.65                                      | 5.82                            |
| HD164740   | 9.69 ±2.55                     | 8.34±2.20                                      | 9.05                            |
| BD+341054 | 12.66 ±3.57                    | 8.13±2.29                                      | 9.16                            |

at very small sizes. The Levenberg-Marquardt method [16] has been adopted in order to fit the observed extinction curves by varying the size distribution parameters.

Figures 2 shows an example of an extinction curve fit together with the contribution of different dust components. The bottom panel shows the size distribution of grains from which the grain density can be derived. Thereby we evaluated the $\rho_d/\rho_H$ ratio reported in Table 2, column 4, using the following formula:

$$\frac{\rho_d}{\rho_H} = \frac{\rho_c}{m_H n_H} \frac{V_g}{3 m_H N_H} \sum_X \rho X \int_{a_{\text{min}}}^{a_{\text{max}}} a^3 N_X(a) da$$

(3)

where the integral is computed for the size distributions of the grains given by the model. It is meaningful the fact that, on the average, sightlines with E(B-V)/N(H)<0.21×10^{-21} mag cm^2 give $\rho_d/\rho_H$ values smaller than the Galactic average.

We also find out that our sample of lines of sight is well fitted by the following linear relation between the $\rho_d/\rho_H$ and E(B-V)/N(H) ratios:

$$\frac{\rho_d}{\rho_H} = 0.036 \times 10^{21} \times \frac{E(B-V)}{N(H)} + 3.34 \times 10^{-3}$$

(4)

From the $\rho_d,i/\rho_H$ ratios of each type of grains the fractions C/H and Si/H of elements trapped into grains can be estimated, even though these quantities may be affected by a large uncertainty. Nevertheless, it is remarkable that the amount of C which condenses into grains along our lines of sight is lower than the mean Galactic value. For our sample of lines of sight we find, on
average, a relative abundance of $1.24 \times 10^{-4}$ for C (37% of the solar abundance) and $3.15 \times 10^{-5}$ for Si (89% of the solar abundance). This result agrees with the hypothesis that along the sightlines of our sample the relative amount of dust in grains is reduced compared to the Galactic value.

6. Conclusions

The need for a large sample to study the dust to gas ratio has compelled us to use the catalogue of Diplas & Savage [2], even though it is affected by a relevant limitation as it lacks the data on the molecular hydrogen column density. Consequently we have been forced to analyse the quantity $E(B-V)/N(HI)$. From this analysis it turns out: a) about 10% of the stars of Diplas and Savage have $E(B-V)/N(HI)$ ratios lower than the galactic average, even accounting for the measure errors; b) this feature can be attributed to the dust associated with the atomic gas.

Quantitative evaluations however require the consideration of molecular gas to estimate $N(H)$. To this end, the relation between $f$ and $E(B-V)$, derived by Savage et al. [5], extended with the data of Rachford et al. [10] to large values of $E(B-V)$, has been used to derive $N(H)$. An analysis of the data implied in this derivation shows that a real dispersion is present beyond the errors.

By taking into account in this way the molecular gas, we find that the $E(B-V)/N(H)$ ratio displays a behaviour similar to that found for $E(B-V)/N(HI)$ regarding the relationship with the corresponding average value.

Theoretical considerations based on extinction models of Kim & Martin [9] and ours have shown that the deviations found cannot be exclusively referred to a poor efficiency in the extinction, as a consequence of large $R_V$. The range of reasonable values of $R_V$, as a matter of fact, does not cover the observed range of $E(B-V)/N(H)$. In addition there are deviating sightlines whose $R_V$ is small enough to prevent any possible interpretation of this type.

On general grounds extinction can be strongly conditioned by the $\rho_d/\rho_H$ ratio. To assess this point we performed: a) a evaluation of such a quantity by means of the Kramers-Kronig...
relation using the observed extinction curves, b) extinction models to fit the observed curves. We found that the sightlines of our sample, with only few exceptions, are characterized by a relative amount of dust smaller than the Galactic average.

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