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Internal extinction and gas column density in spiral galaxies

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Abstract. The method for the extinction correction based on the gas column density is tested. A positive correlation is found between the total gas column density and the extinction estimated using a model based on energy conservation ('frequency-converter model'). Assuming a Solar Neighbourhood optical-depth–to–gas ratio, extinction is predicted from the gas column density using a radiative transfer model which adopts a 'Sandwich' configuration for the stellar and dust distributions, and which takes also into account the effect of scattering. This prediction agrees well with the extinction estimated from the energy conservation consideration. This indicates that (1) the method for the extinction correction based on the gas column density is a robust one; (2) in the inner part of galaxy disks where most of the extinction occurs, the dust-to-gas ratio is on average about the same as the Solar Neighbourhood value.

Our results also suggest that dust grains associated with both gas phases (HI and H_2) participate in the extinction, with a relative importance depending on the abundance of the gas phase in the inner disk. For most of the galaxies in our sample the extinction is mainly due to the dust associated with the molecular gas because they have high molecular to atomic gas column density ratios. On the other hand, for galaxies whose gas column density is dominated by the atomic gas, the extinction seems to be mainly caused by the dust associated with atomic gas.

Key words: galaxies: ISM – infrared: galaxies – ultraviolet: galaxies – ISM: dust, extinction

1. Introduction

The extinction correction is crucial for any study on galaxy emissions at UV and optical wavelengths. In particular in the UV band, substantial dust extinction occurs within the disks of spiral galaxies (Buat & Xu 1996, hereafter Paper II). At the same time there is still a controversy over the question whether galaxy disks are opaque or not in the optical band (e.g. Disney et al. 1989, Valentijn 1990, Huizinga & van Albada 1992, Boselli & Gavazzi 1994, Xu & Buat 1995, hereafter Paper I). Because it is very difficult to measure the extinction directly, it has been a common practice in the literature to estimate the extinction correction using indirect tracers such as atomic and total gas column density (e.g. Donas et al. 1987, Buat et al. 1989, Lisenfeld et al 1996), although apart from our Galaxy (Savage & Mathis 1979) the existence of a local correlation between the extinction and the gas column density has only been directly verified in the Magellanic Clouds from the observations of individual stars (LMC, Koornneef 1982; SMC, Bouchet et al. 1985), plus the evidence for such a correlation in the disk of M31 from a multi-wavelength study by Xu & Helou (1996).

It is the aim of this paper to scrutinize the validity of the widely used extinction correction method based on the gas column density. The tool we exploit is the model recently developed by two of us (Paper I and Paper II) which calculates the internal extinction for *individual* galaxies using a radiative transfer model with the far-infrared (FIR), UV and optical fluxes as input. The reliability of the model is demonstrated by the results for the internal extinction in M31 obtained by applying this radiative transfer model (Xu & Helou 1996), which agreed very well with the direct extinction measurements in that galaxy (Bajaja & Gergely 1977; Hodge & Lee 1988). In this paper we apply the model to a large sample of the galaxies with available UV, FIR, optical, HI and CO data. We will compare the resulted extinction at B-band, A_B , with the gas column density estimated from the HI and CO data.

The paper is organized in the following way: this introduction (Sect. 1) is followed by a description of the sample (Sect. 2); The model and results on A_B are presented in Sect. 3. Correlation studies on A_B and gas column densities are carried out in Sect. 4. Sect. 5 is devoted to a discussion and to the conclusion.

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2. The sample

The sample, including all spirals (Sa – Sdm) with available UV, FIR, HI and CO data contains 79 galaxies. Among them, 20 galaxies belong to the Virgo cluster including the clouds S and S' (de Vaucouleurs & Corwin (1986)), 15 galaxies to the Coma cluster and 19 to the Abell 1367 cluster. The remaining 25 galaxies are non cluster galaxies which we will refer below as field galaxies. Galaxies classified as Seyferts (Véron-Cetty & Véron 1993) have been excluded because of the possible influence of their nuclear activity on the global FIR and UV emissions. We choose not to include in our study irregular galaxies because their H_2 to CO conversion factor is highly uncertain (e.g. Maloney & Black, 1988).

The UV data ($\sim$ 200 nms) are taken from several experiments including SCAP (Donas et al. 1987), FAUST (Deharveng et al. 1994) and FOCA (Donas et al. 1988, Donas et al. 1995). Fluxes and upper limits in FIR band (40–120μm) are taken from IRAS data base, Bicay & Giovanelli (1987), Smith et al. (1987), Rice et al. (1988), Soifer et al. (1989), Thuan & Sauvage (1992), Rush et al. (1993) and from C. Lari (private communication). The CO data are taken from Young et al. (1995) and Stark et al. (1987), by order of preference, for the field and Virgo galaxies, from Boselli et al. (1996) and references therein for Abell 1367 and Coma galaxies. The data sources of HI are from de Vaucouleurs et al. (1991, RC3) for the field galaxies, Hoffman et al. (1989) and Lu et al. (1993) for Virgo galaxies, Scodeggio & Gavazzi (1993 and references therein) for Abell 1367 and Coma galaxies. All the other data necessary to the study are from the RC3 and from Gavazzi and Boselli (1996). The distance of nearby galaxies are taken from Tully (1988). A Hubble constant of H_0 = 75 km/s/Mpc is adopted.

This sample is not complete in any sense. It is biased towards galaxies with strong UV and/or FIR emissions and might be not representative of "normal" optically selected spiral galaxies. It is also very inhomogeneous given the large difference in distance between the Coma and A 1367 galaxies on one hand and the Virgo and non cluster galaxies on the other hand. Our aim in this paper has been to gather all the data available in order to have a sample as large as possible. Computer-readable copies of the data may be obtained by contacting V. Buat.

3. The model and results for optical extinction

A brief description of the model for the internal extinction in galaxy disks is given in the following. More details can be found in Paper I and Paper II. The so called 'frequency converter' model is based on the following energy conservation consideration: the extinguished stellar light (from UV to NIR) by dust absorption must be re-emitted in the FIR. Therefore, the dust radiation integrated over the entire FIR band (10 – 1000μm) tells how much stellar radiation, integrated over the entire UV to NIR range (500 – 10000 Å), has been extinguished. If the internal extinction in galaxies were gray (i.e. constant with wavelength), then the B-band extinction A_B could be easily calculated:

$$A_B = A_{gray} = -2.5 \times \log(1 - \frac{L_{IR}^{dust}}{L_{bol}}) \quad (1)$$

where L_{bol} is the bolometric luminosity, namely the sum of the stellar and dust radiations in all bands. However in reality the extinction is of course not gray. Thus, in order to determine A_B from the comparison between the stellar radiation (UV to NIR) and the dust radiation (FIR), a constraint on the frequency dependence of the extinction must be imposed in addition to the energy conservation consideration. This constraint is provided by a radiative transfer model which assumes a dust grain model (specified by the extinction curve, albedo and phase function) similar to that observed in the Solar Neighborhood (SN), and a sandwich configuration for the star and dust distribution in galaxy disks. Detailed discussions on the implications of these assumptions on the results as well as the uncertainties and limitations of this model can be found in Paper II. In particular it should be noticed that although in our radiative transfer model we assumed uniform dust and star distributions (Paper I), our results on A_B are basically constrained by the FIR to UV-plus-optical flux ratios and are therefore not sensitive to this assumption (Paper II). In fact, the most significant uncertainty for our model is related to the partition of the dust-heating sources, namely the estimate of the relative contributions from the UV radiation and from the optical radiation to the FIR emission.

Results on the B-band extinction A_B , *not corrected for face-on*, are obtained for individual galaxies in the sample including 13 upper limits due to nondetections in FIR. In order to exploit the information contained in the upper limits, the Kaplan-Meier estimator (Schmitt 1985; Feigelson & Nelson 1985) has been used in the statistical analyses in this paper.

The distribution of A_B is presented in the histogram of Fig. 1. A mean $< A_B >= 0.15 \pm 0.02$ with a dispersion of 0.20 is found for the entire sample (79 galaxies). This means that on average about 15 percent of the blue radiation is extinguished by dust within galaxy disks. The field galaxies (25) and the galaxies in Virgo, Coma and A1367 clusters (54) have similar extinction: the former have a mean of $< A_B >= 0.17 \pm 0.04$ and the later $< A_B >$ of 0.14 ± 0.03 (Fig. 1). However, it should be pointed out that our sample is very inhomogeneous. For example the sample is much deeper for the field and Virgo galaxies which are nearby, than for the Coma and A1367 cluster galaxies which are far away. Any possible intrinsic difference between field and cluster galaxies may well be missed due to this inhomogeneity.

These results are in good agreement with Paper I where we showed the face-on optical depth τ_B instead of extinction A_B . Both demonstrate that for blue radiation galaxy disks are optically thin, at least when the radiation from an entire galaxy is concerned. Some galaxies in our sample do show a rather high extinction ($A_B > 0.5$ mag), they are likely to be active star-forming galaxies (like M82) with a large part of the blue radiation coming from the heavily extinguished star-formation regions (local extinction can be as high as $A_B > 10$). On the

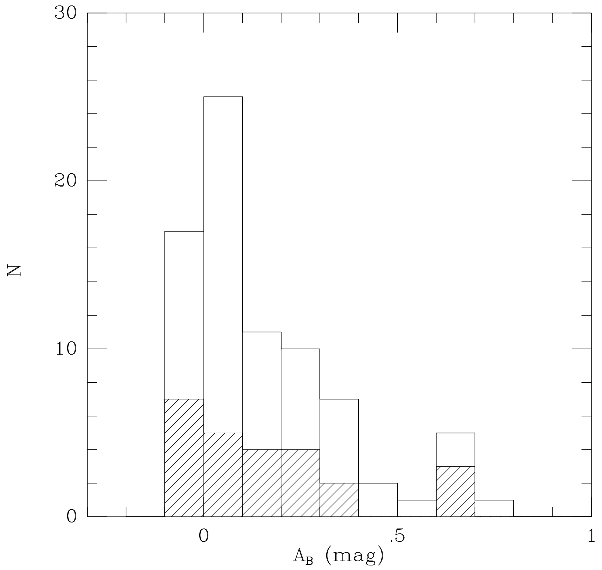

Fig. 1. Distribution of the extinction in the B band A_B (upper limits included). Field galaxies are shown by the hatched area.

other end of the A_B distribution (Fig. 1), 17 galaxies which are seen face-on have negative extinctions ('brightening') because of the effect of scattering (Bruzual et al. 1988; Witt et al. 1992). Excluding these galaxies the remaining 62 galaxies in our sample have a mean $< A_B >= 0.20 \pm 0.03$.

4. Comparison between extinction and gas column density

4.1. A_B *versus the column density of total gas (HI+H_2)*

As discussed in Paper II, a correlation between dust column density and gas column density is expected given the tight connection between heavy elements in gas phase and in grains (Spitzer 1978) provided that the metallicity does not vary a lot among galaxies. Indeed, it has been shown (see Roberts & Haynes 1994 for a review) that the variation in metallicity becomes important only for galaxies fainter than $M_b = -19$. In our sample, we have only 9 galaxies with $M_b > -18.5$ and 9 galaxies with $-19 < M_b < -18.5$.

Then, according to the relative distribution of the dust, gas and stars, a physical link between the extinction and the gas column density may or may not exist: if the dust and gas are well mixed in a slab in front of the stars the extinction is proportional to the optical depth and to the gas column density when one assumes a constant value for $E(B-V)/N_{gas}$; if the dust gas and stars are approximately uniformly mixed in galaxy disks, this also implies some link between the extinction and the gas column density but the relation between these two quantities depends on the exact distribution of each component (dust, gas and stars). On the other hand if the dust distribution is very different from the stellar distribution, for example when that the dust is concentrated in a few opaque dust lines covering only a small portion of the stellar disk, or when there is a dust hole in the inner part of a galaxy disk where most of the stellar light comes from, the extinction may not depend on the average dust column density. In this case the extinction correction based on the gas column density will be unreliable.

In the following we correlate the extinction calculated in the previous section with the gas column density for galaxies in our sample. In the literature, the gas column density is usually estimated from the HI and CO flux divided by a disk area estimated from optical diameters of galaxies (Donas et al. 1987; Buat et al. 1989). We shall take the same approach since the majority of the target galaxies in this study are unresolved in CO and HI.

Young et al. (1995) have estimated that the CO distribution can be described by an exponential disk with a scale length equal to one tenth the optical diameter at the 25th magnitude (the D_{25} in RC3). On the other hand, the ratio of the scale length of the B distribution to D_{25} is 0.15 (Peletier et al. 1994). Hence we can adopt a ratio of the B to CO radius equal to 1.5 to estimate the molecular column density. Using the H_2 to CO conversion factor of Strong et al. (1988) leads to:

$$N(H_2)(\mathrm{mol/cm^2}) = 2.3\ 10^{20} I_{CO}(\mathrm{K\ km/s})$$

and to a mean H_2 column density given by:

$$\sigma(H_2) = 0.306 \cdot f(CO)/D_{25}^2$$

where f(CO) is the total CO flux in Jy km/s and D_{25} the optical diameter in arcmin. Recent observations of the Milky Way and of nearby spirals, however, suggest a lower H_2 to CO conversion factor, of the order of $X = 10^{20}$ mol $cm^{-2}/K\ km\ s^{-1}$ (Lequeux 1995), thus $\sigma(H_2)$ would be overestimated by a factor of two. Therefore $\sigma(H_2)$ calculated using the above formula is a crude estimate of the real molecular gas column density of the target galaxies: the optical to CO disc scale length ratio of 1.5 is an average value, and in a given galaxy might be wrong up to a factor of two. Furthermore the determination of the molecular gas surface density is based on the universality of the CO to H_2 conversion factor, while it is well known that it might easily change from galaxy to galaxy (even in the bright and massive spirals) by a factor of two (Boselli et al 1996).

On the other hand, the atomic gas extends over a region much more extended than the optical disk: the isophotal HI diameter has been found to be about twice the optical one with often a rather flat distribution very different from that of the optical light (e.g. Bosma 1981, Cayatte et al. 1994). The HI column densities σ(HI) are therefore obtained by dividing the HI mass by an area with a diameter of $2 \times D_{25}$. We caution that this is only a very crude estimate, in particular for galaxies located in clusters which are known to be HI deficient. This deficiency has been shown to reduce the effective HI diameters and gas densities, a factor directly influencing any estimate of a mean HI column density based on a uniform choice for the HI diameter (Cayatte et al. 1994).

Fig. 2 is a plot of the extinction A_B v.s. the column density (i.e. the face-on surface density divided by cos(i) with i the inclination angle) of the total gas (HI+H_2). A weak but significant linear correlation, with r=0.48, is found for the 51 galaxies with CO detections. In order to exploit also the information carried

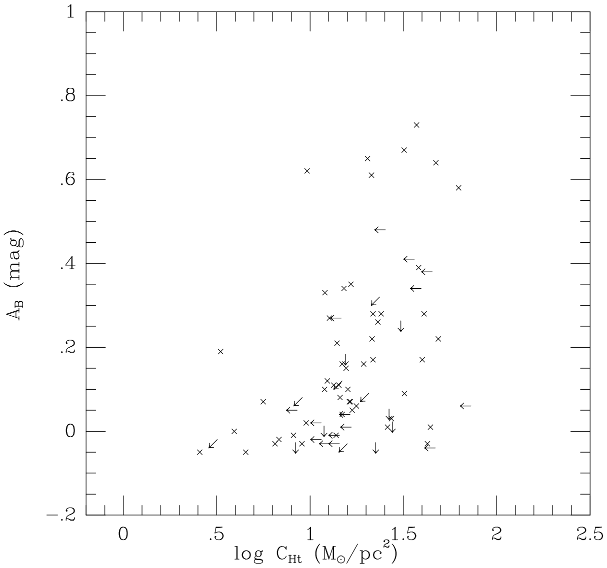

Fig. 2. Diagram of the extinction in the B band A_B versus the total gas (HI+ H_2) column density C_{Ht}. The arrows represent the upper limits.

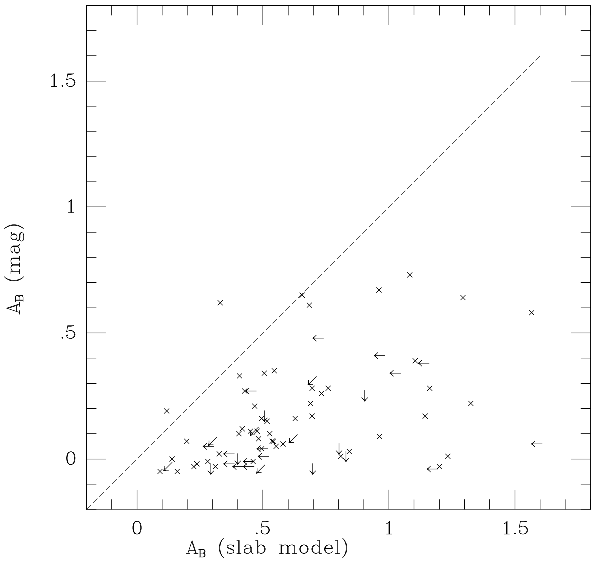

Fig. 3. Diagram of A_B versus the extinction estimated from total gas (HI+ H_2) column density using a 'slab' model.

by the upper limits of both variables, a generalized Kendall's rank correlation statistical analysis (Isobe & Feigelson 1986) is carried out for the entire sample (79 sources). Again a significant correlation, with a probability for the null-hypothesis of 4 10^{-5} , is found.

4.2. *Estimation of the extinction from the gas column density*

Now we shall compare A_B with the extinction estimated using the total gas column density. Assuming a Solar Neighbourhood blue-optical-depth–to–gas ratio of $(\tau_B/\Sigma_H)_{SN} = 5.3\ 10^{-22}$ (atom^{-1} cm^2) (Savage & Mathis 1979), the face-on optical depth can be estimated from gas surface density (face-on) as following

$$\tau_B^H = (\tau_B/\Sigma_H)_{SN} \times \Sigma_H. \tag{2}$$

The extinction can then be determined from the optical depth and the inclination angle, depending on the adopted radiative transfer model. Neglecting scattering effects, the 'plane-parallel slab' model (Mihalas 1978), with stellar and dust layers of identical thickness, gives

$$A_B^H = -2.5 \times \log \frac{1 - e^{-\tau_B^H/\cos(i)}}{\tau_B^H/\cos(i)} \tag{3}$$

where i is the inclination angle (0 for face-on). In Fig. 3 the extinction so calculated is compared with A_B . The Kendall's rank correlation between the two variables is fairly strong (probability for the null-hypothesis of 3.7 10^{-5}). Nevertheless, the slab model obviously over-estimates the extinction as compared to our "frequency converter" model.

A more realistic model is the so called 'Sandwich model' which includes different thickness of the stellar disk and the dust disk. Assuming that the stellar disk is twice as thick as the dust disk (Disney et al. 1989), one get

$$A_B^H = -2.5 \times \log \left(0.25 + 0.5 \times \frac{1 - e^{-\tau_B^H/\cos(i)}}{\tau_B^H/\cos(i)} + 0.25\, e^{-\tau_B^H/\cos(i)} \right) \tag{4}$$

A further refinement is to take into account the scattering effect within the 'Sandwich model'. To perform such calculations, we use our radiative transfer model presented in Paper I and II. Some relevant details about this model are given in the Appendix. The resulting A_B^H is compared with A_B in Fig. 4. The Kendall's rank correlation statistic gives a higher significance to the correlation in this plot (probability for the null-hypothesis of 1 10^{-7}) compared to the one in Fig. 3. The extinction calculated from gas column density using this model, A_B^H , matches the extinction estimated from the FIR, UV and optical radiations, A_B , satisfactorily well: for the galaxies with an estimated A_B from our "frequency converter" model and an available gas column density C_{Ht}, we find a mean difference between $< A_B^H >$ and $< A_B >$ of 0.04 ± 0.02, with a dispersion of 0.18 mag.

4.3. A_B *versus column density of* H_2 *and HI separately*

In this section we address the question whether the dust associated with the molecular gas or with the atomic gas dominates the extinction. In Fig. 5 and Fig. 6 plots of A_B versus the column density of the H_2 gas and of the HI gas for the 79 galaxies in our sample are presented respectively. A significant Kendall's rank correlation between A_B and C_{H2} is found for the entire sample, with a probability for null hypothesis of 7 10^{-5}, while the linear correlation coefficient for the detected data points (54 sources) is 0.43. On the other hand, A_B and HI gas are not correlated: Kendall's rank correlation statistics tells that a probability for

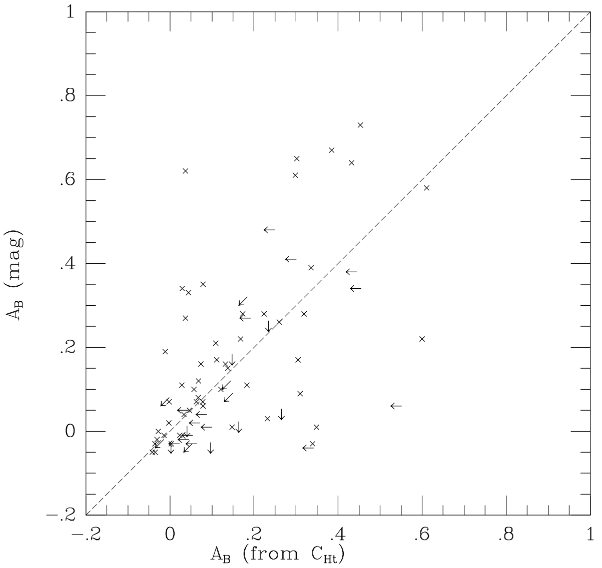

Fig. 4. Diagram of A_B versus the extinction estimated from total gas (HI+ H_2) column density using a 'Sandwich model' including scattering (Appendix).

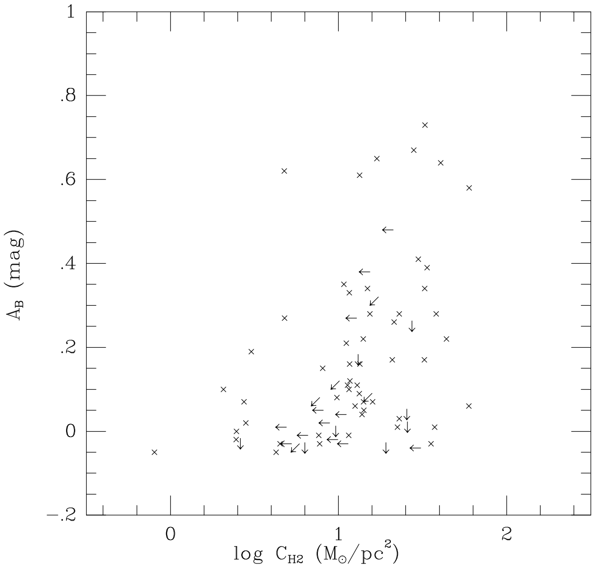

Fig. 5. Diagram of the extinction in the B band A_B versus the H_2 gas column density C_{H2}. The arrows represent the upperlimits.

null hypothesis is as high as 0.38, and the linear correlation coefficient for the detected data points (63 sources) is only 0.15. These results are in good agreement with those in Paper II, in which we found significant correlation between optical depth τ_B and the H_2 surface density, but no correlation between τ_B and the HI surface density.

Can the absence of a correlation between A_B and C_{HI} be due to the environment effects such as HI stripping, because many of galaxies in our sample are in clusters? The HI stripping mainly affects the external parts of the galaxies and therefore reduces the effective HI diameter: the normalization of the HI flux over twice the optical area induces an underestimate of the HI column density in HI deficient galaxies compared to the HI non-deficient ones. This problem is also relevant for the result in Paper II because most of galaxies studied in that paper for the dust/gas relation are in the Virgo cluster.

The effect of this bias has been investigated by estimating the HI deficiency of all the cluster galaxies of our sample using the formula of Haynes & Giovanelli (1984) for all morphological types. The UGC diameters necessary to estimate the HI mass of isolated galaxies has been obtained from D_{25} following the RC3:

$$\log(d_{UGC}) = \log(D_{25}) + 0.0038$$

We thus obtain the formula:

$$\mathrm{HIdef} = 7.19 + 1.76 \log(D_{25}) - \log(M_{HI})$$

where D_{25} is the optical radius in kpc and M_{HI} the observed HI mass in solar units.

We split our sample in three sub-samples: HIdef > 0.3 (deficient cluster galaxies), HIdef < 0.3 (non deficient cluster galaxies) and non cluster galaxies. No correlation between A_B and C_{HI} is found in any of the three sub-samples, nor in the entire sample.

A plausible interpretation for the results in Fig. 5 and Fig. 6, namely a correlation between A_B and C_{H2} and non-correlation between A_B and C_{HI}, is that the dust associated with the H_2 gas contributes dominantly to the extinction and the contribution from the dust associated with HI gas is relatively insignificant. Hence A_B is insensitive to C_{HI}. This is hinted by the fact that for most of galaxies in our sample C_{H2} is at least a factor of few times higher than C_{HI}. Indeed, the mean is $\log(C_{H2}/C_{HI}) = 0.65$ with a dispersion of 0.52 for the entire sample. Even if we consider only HI non deficient and non cluster galaxies in order to avoid the effect of the HI deficiency $\log(C_{H2}/C_{HI}) = 0.39$ with a dispersion of 0.48. This value is similar to that found for a sub-sample of 29 galaxies, mainly located in Virgo, for which radial HI distributions are available (V. Cayatte, private communication): $\log(C_{H2}/C_{HI}) = 0.29$ with a dispersion of 0.53. The relative H_2 richness of the present sample is probably due to the adopted FIR selection criterium, which favors CO rich galaxies (Boselli et al. 1996). However, in the case where the assumed X conversion factor, and thus the H_2 column density, is overestimated by a factor of two (see Sect. 4.1), the atomic and molecular gas surface densities are found similar. Nevertheless, as discussed in Paper II, the extinction deduced from our model is representative of the extinction occuring in regions with a high UV and FIR emission i.e. the inner disk. Given the exponential distribution of the molecular gas and the rather flat distribution of the atomic one, it is likely that the molecular phase dominates the atomic one in these regions. Therefore, in our sample galaxies the dust causing extinction is likely to be mainly associated to the molecular phase of the gas, therefore the extinction is found to correlate with the molecular content.

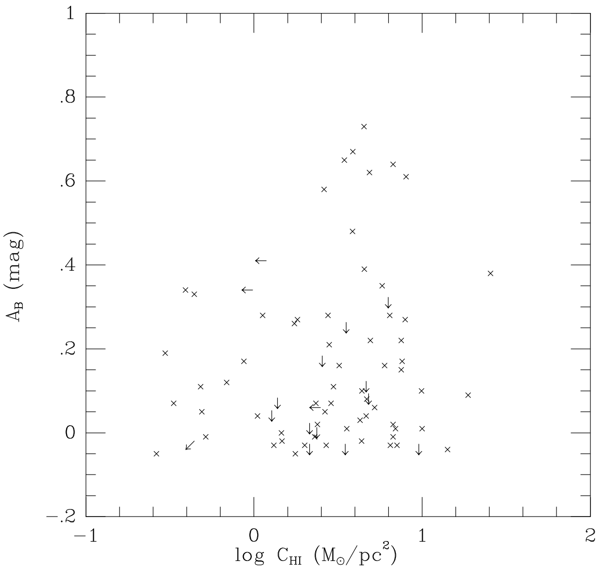

Fig. 6. Diagram of the extinction in the B band A_B versus the HI gas column density C_{HI}.

The above interpretation can be tested in the following way. If indeed the non-correlation between A_B and C_{HI} is due to the dominance of C_{H2}, then for a subsample of the galaxies with high HI-to-H2 ratios there should be a A_B v.s. C_{HI} correlation. To this aim we have first chosen non-cluster galaxies or cluster members which are non-HI-deficient (HIdef<0.3). This selection would ensure us to exclude galaxies with a truncated HI distribution. The selected galaxies must also exhibit an HI to H_2 ratio larger than 10. Given that the adopted linear sizes of the HI disks are a factor of 3 larger than that of the H2 disks (Sect. 4), this means that the HI surface density of these galaxies is more than 1.1 times of that of the H_2 gas. Once again, if the assumed X conversion factor is overestimated by a factor of two, the HI surface density of the selected galaxies is more than 2 times the molecular one. The sub-sample contains 11 galaxies and is presented in Table 1.

The diagram of A_B v.s.C_{HI} for this subsample is plotted in Fig. 7. Indeed a significant correlation is found in this plot with the linear correlation coefficient of r=0.84 for the 10 detected data and, for the entire subsample (11 sources), a probability of 0.02 for the null hypothesis is found from the generalized Kendall's rank correlation. In Fig. 8 we plot A_B^H , estimated from the HI surface density using the 'Sandwich+scattering' method (Appendix) and the optical depth to HI gas ratio of the SN, v.s. A_B for the sample. The agreement between A_B^H estimated from C_{HI} and A_B is quite good. In above two plots, the four galaxies fainter than $M_B = -18.5$ (NGC 4299, NGC 4383, NGC 3353 and NGC 5474) are marked by circled crosses. Except for NGC 3353, no significant difference in A_B were found for these galaxies compared to the rest of the subsample. NGC 3353 has a large A_B /C_{HI} ratio, resulted from its rather high FIR flux.

From the above results we conclude that for most of the galaxies in our sample the extinction is mainly due to the dust associated with the molecular gas as indicated by the good correlation between the extinction and the column density of the molecular gas, and by the high molecular to atomic gas column density ratio. On the other hand, for galaxies whose gas column density is largely dominated by the atomic gas, the extinction seems to be mainly caused by the dust associated with atomic gas. This is corroborated by recent sub-mm observation (Guélin et al. 1993, Neininger et al. 1996) where the dust emission at 1.2 mm in spiral disk is found to follow the dominant gas phase either atomic or molecular. Our results are also in agreement with those of Andreani et al. (1995) who found that the cold dust emission is probably associated to both the atomic and the molecular phases.

Table 1. Galaxies with $M(HI)/M(H_2) > 10$.

Name	M_B	$\frac{M(HI)}{M(H_2)}$	A_B	$\log C_{HI}$ $M\odot/pc^2$
	Virgo	*Cluster*		
NGC4178	-19.36	42.22	0.10	0.99
NGC4299	-18.36	13.54	-0.03	0.81
NGC4383	-18.49	12.87	0.09	1.27
NGC4519	-18.86	11.08	-0.01	0.83
	Abell 1367	*Cluster*		
Z97138	-19.44	15.49	<-0.04	0.95
Z127054	-21.26	19.95	-0.05	0.24
	Non cluster	*galaxies*		
NGC3353	-17.92	15.19	0.27	0.90
NGC4701	-18.78	21.66	0.02	0.83
NGC4713	-19.09	21.95	0.01	1.00
NGC4808	-19.27	18.13	0.38	1.41
NGC5474	-17.66	16.22	-0.02	0.59

5. Discussion and conclusion

5.1. Dust-to-gas ratio

The result presented in Sect. 3 (in particular Fig. 4) suggests that in the inner part of the galaxies disks where most of the extinction occurs (Paper II), the dust-to-gas ratio is on average about the same as the Solar Neighbourhood value. On the other hand one should be aware of the large uncertainties of this result, given the crudeness of the method with which we estimate the gas column density (in particular the constant $N(H_2/I(CO))$ conversion factor). For example changing by a factor of 1.4 the assumed disk size of the molecular gas, which dominates the gas column density for most of galaxies in our sample, the dust-to-gas ratio will be changed by about a factor of 2. Moreover, the extinction estimated from the gas column density depends

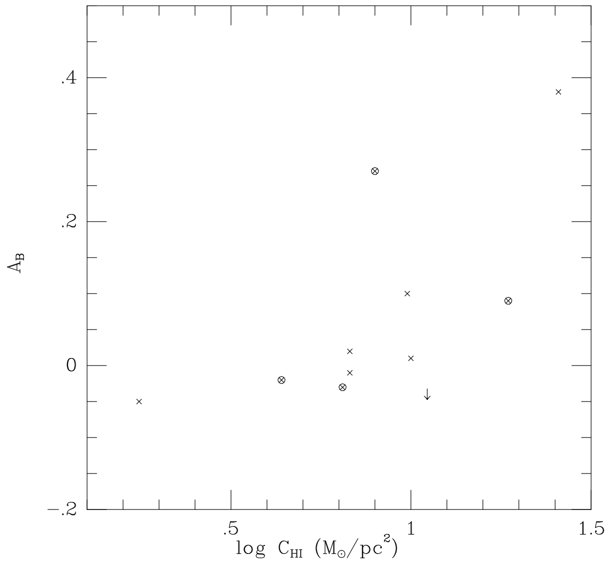

Fig. 7. A_B versus the HI column density for galaxies with M(HI) > 10M(H_2).

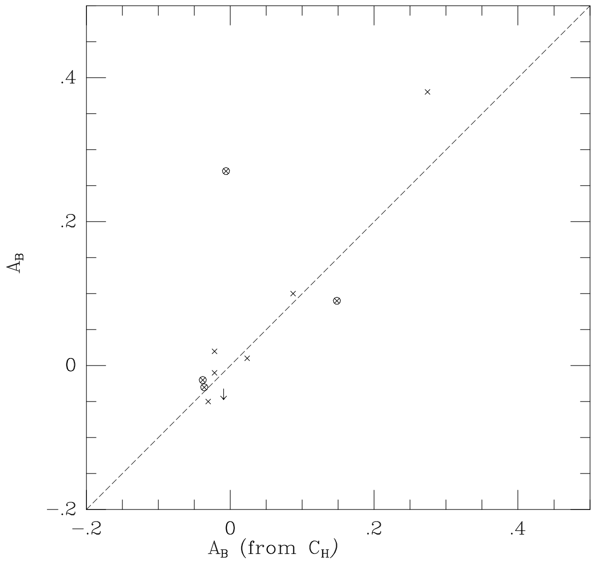

Fig. 8. A_B versus the extinction estimated from HI gas column density, for galaxies with M(HI) > 10M(H_2).

not only on the dust-to-gas ratio, but also on the radiative transfer model adopted. For example, as shown in Fig. 3, when the slab model for the radiative transfer is used, the assumption of a Solar Neighbourhood dust-to-gas ratio results in estimates for extinction from the gas column density significantly higher than the values from the frequency converter model. An average dust-to-gas ratio of a factor of 2 lower than the Solar Neighbourhood value is indicated by our data when the slab model is used.

Nevertheless, it is fair to say that galaxies in our sample do show dust-to-gas ratios similar (within a factor of few) to the Solar Neighbourhood value. This is consistent with the results for M31 (Van den Berg 1975; Bajaja & Gergely 1977), the only spiral galaxy outside the Milky Way with extinction (reddening) directly measured over the entire galaxy disk.

5.2. *The effects of the clumpiness of dust distribution*

Apparently the dust associated with the molecular gas dominates the extinction in most of galaxies in our sample (Sect. 4). This result may be general for spiral galaxies, for which the gas in the inner disk is often predominantly molecular (Young & Scoville 1991). The molecular gas at all observable scales appears to be clumpy, perhaps fractal (Falgarone, et al. 1992), hence the CO emission of unresolved external galaxies is related to molecular clouds of different dimension and gas density. If the physical conditions characterizing the interstellar medium of our sample galaxies (UV radiation field and metallicity) are similar to the one of the Solar Neighbourhood, this suggests that, as in the Milky Way, a significant contribution to the large-scale CO emission of the target galaxies is made by low optical depth diffuse molecular gas (Polk et al. 1988, Boselli et al. 1996). So the dust associated with this gas may also be diffuse and our model which assumes a uniform distribution of the dust may be valid at large scales.

The effects of clumpiness on the extinction are expected to be strong only when individual fragments are optically thick (Boissé 1990). Sofue & Yoshida (1993) have found only a moderate extinction for a dark molecular cloud in the central region of M31. Furthermore, Boissé & Thoraval (1996) find very small extinction fluctuations in front of some molecular clouds at the subparsec scale and conclude that these clouds can be considered as a uniform absorbing medium. Therefore, we argue that the total extinction on the scale of an entire galaxy is not sensitive to the opaque dust structures, although locally these structures may be very prominent (see e.g. the images by Block et al. 1994). Generally speaking, these structures occupy only a small part of the disk, i.e with a small filling factor. Therefore the contribution from them to the extinction of the total emission from a galaxy is not significant except for some special cases, for example when a galaxy is seen very edge-on so that the filling factor of the dust lanes is relatively high.

Furthermore, as far as the dust-to-gas ratio is concerned, there is another reason for the insensitiveness to the effect of very opaque clumps: the gas in these clumps, as well as the dust, may be missing, too. Allen (1996) argues that dense molecular clouds, especially when far away from UV sources, can be very cold and therefore with very high CO-to-H_2 conversion factor. Since both the CO and the FIR emissions are small from these clouds, their existence yields little effect in our results.

However, it should be noted that giant molecular clouds (GMC's) associated with active star formation regions represent a different case from the dark dense clouds discussed above. A significant fraction of total extinction (and dust emission) in a galaxy occurs in these clouds (see, e.g. Boulanger & Pérault 1988; Scoville & Good 1989). The radiative transfer problem in these regions can be very complicated (Leisawitz 1991) and is obviously quite different from that in the diffuse interstel-

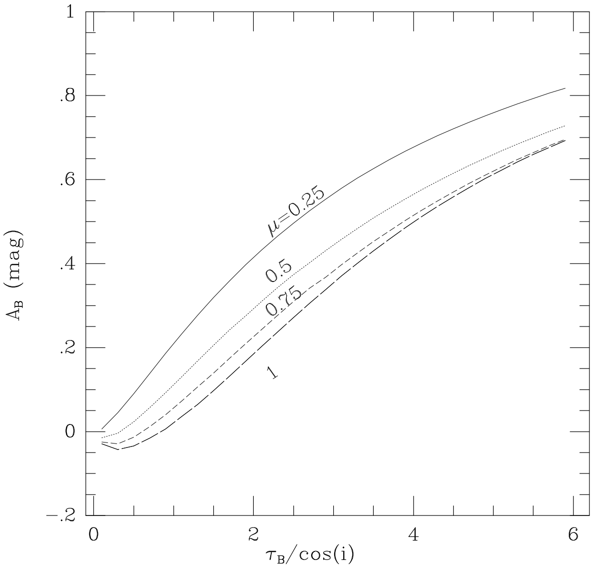

Fig. 9. Plot of A_B versus $\tau_B/\cos(i)$ for the model, where τ_B is the face-on optical depth and i the inclination angle. Different curves are model calculations with different inclination parameter $\mu = \cos(i)$, as denoted by the numbers.

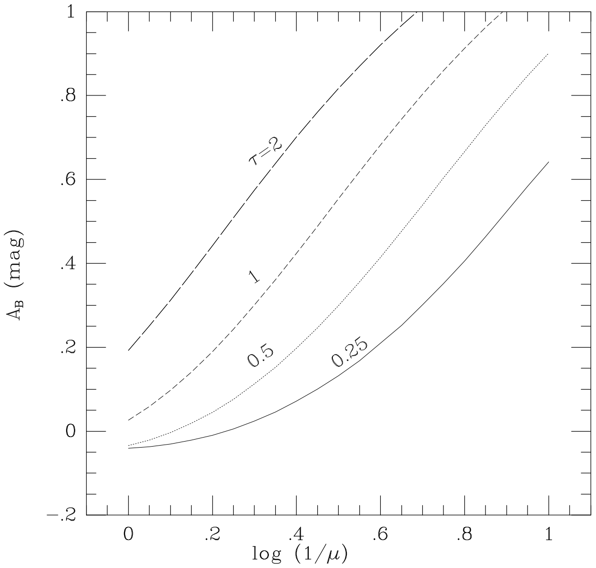

Fig. 10. Plot of A_B versus the inclination parameter $\log(\mu) = \log(\cos(i))$. Different curves are model calculations with different face-on optical depth τ, as denoted by the numbers.

lar space depicted in our model. However first, as indicated by the FIR emission, the dust in these clouds is generally not the dominant component in the absorption-reradiation process in a galaxy: Sodroski et al. (1989) concluded that less than 30% of the FIR emission of the Milky Way is from dust associated with star forming GMC's. Second, with the present data set we don't have enough contraint to separate the contribution from this component to the total extinction. Finally, as claimed in Sect. 3, our results are basically determined by the FIR/UV–optical luminosity ratio and not very sensitive to the radiative transfer model and therefore even for the dust in GMC's our result may provide a reasonable approximation to the real extinction.

5.3. Conclusion

In this paper we test the classical method for the extinction correction based on the gas column density. A positive correlation is found between total gas column density and the extinction estimated using a model based on energy conservation ('frequency-converter model'). Assuming a Solar Neighbourhood optical-depth–to–gas ratio, extinction predicted from gas surface density using a radiative transfer model which adopts a 'Sandwich' configuration for the stellar and dust distributions, and which takes also into account the effect of scattering, agrees well with the extinction estimated from the energy conservation consideration. This indicates that (1) the method for the extinction correction based on the gas column density is a reasonably robust one; (2) in the inner part of galaxy disks where most of the extinction occurs (Paper II), the dust-to-gas ratio is on average about the same as the Solar Neighbourhood value.

Our results also suggest that dust grains associated with both gas phases (HI and H_2) participate in the extinction, with a relative importance depending on the abundance of the gas phase in the inner disk. For most of galaxies in our sample the extinction is mainly due to the dust associated with the molecular gas as indicated by the good correlation between the extinction and the column density of the molecular gas, and by the high molecular to atomic gas column density ratio in the inner part of these galaxies. On the other hand, for galaxies whose gas column density is dominated by the atomic gas, the extinction is mainly caused by the dust associated with atomic gas.

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Appendix A: radiative transfer model

A 'Sandwich configuration' for the star and dust distribution in a model galaxy is adopted (Paper I). It is a plane-parallel-slab of uniformly mixed stars and dust sandwiched within two stellar slabs. The stars in the central slab contribute half of the total emission, while each of the outer stellar slab contributes a quarter of the emission. The model takes the effect of scattering fully into account in the sense that scattered light of any order has been calculated using an iteration procedure from lower order scattered light (van de Hulst & de Jong 1969). The albedo of $\omega = 0.67$ and the asymmetry factor of $g = 0.52$ are taken from the Solar Neighbourhood values (Mathis et al. 1983). Fig. 9 shows the plot of the resulted A_B versus $\tau_B/\cos(i)$, where τ_B is the face-on optical depth and i the inclination angle. Fig. 10 shows the plot of the resulted A_B versus the inclination parameter of $\log(\mu) = \log(\cos(i))$.

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