Dust properties in M31.I.

Basic properties and a discussion on age-dependent dust heating

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ABSTRACT

Context.

Aims. Recent observations derived from the Spitzer Space Telescope and improvements in theoretical modeling of dust emission properties are used to discuss the distribution of dust and its characteristics in the closest neighbor spiral galaxy M31. Together with GALEX FUV, NUV, and SDSS images we studied the age dependence of the dust heating process.

Methods.

We demonstrate that cold-dust component emission dominates the infrared spectral energy distribution of M31. The mean intensity of the radiation field heating the dust is low (typically $U < 2$, where $U = 1$ is the value in the solar surrounding). Due to the lack of submillimetric measurements the dust mass ($M_{\text{dust}}$) is only weakly constrained by the infrared spectrum, but we derived a lower limit of $M_{\text{dust}} \geq 1.1 \times 10^7 M_\odot$ with a best fit value of $M_{\text{dust}} \approx 7.6 \times 10^6 M_\odot$, in good agreement with expectations from CO and HI measurements. We show that across the spiral-ring structure of M31 a fraction $>3\%$ of the total dust mass is in PAHs. UV and optical colors are correlated to total infrared to far ultraviolet (TIR/FUV) ratios in $\sim 670$ pc-sized regions across the disk of M31, although deviating from the relationship between infrared excess and ultraviolet spectral slope (referred as IRX-$\beta$ relationship) for starburst galaxies. In particular, redder regions show lower values of the TIR/FUV ratio for a fixed color. Considering the predictions of models that account for the dust-heating age dependence we derived that in 83$\%$ of the regions analyzed across the 10 kpc ring more than 50$\%$ of the energy absorbed by the dust is radiated at $A > 4000$A and that dust in M31 appears mainly heated by populations a few Gyr old even across the star-forming ring. We also found that the attenuation is varying radially peaking near 10 kpc and decreasing faster in the inner regions of M31 than in the outer regions in agreement with previous studies. We finally derived the attenuation map of M31 at 6$''$/px resolution ($\sim 100$ pc/px along the plane of M31).

Conclusions.

Key words. M31 – dust – extinction

1. Introduction

The presence of the dust affects astrophysical observations in different ways. While in the UV-optical spectral region the dust absorbs the stellar radiation field, it re-emits the absorbed energy in the IR-FIR and sub-millimetric spectral regions. It is thus essential to determine the properties of the dust in a given system as accurately as possible. While in our own galaxy we can reach very high spatial resolutions and accuracies, our particular location inside the galaxy limits our analysis.

Being the closest large spiral like the Milky Way, M31 offers a fascinating view of the dust distribution across the disk of the galaxy and an unique opportunity to study the properties of a major disc galaxy in detail. Previous studies already focused on the dust in this galaxy, but new observational results and theoretical improvements require some issues to be revisited and critically discussed and allow to shed new light onto still unresolved problems. In particular GALEX UV observations (Gil de Paz et al. 2007), SDSS optical images (York et al. 2000), and Spitzer Space Telescope observations (Barmby et al. 2006, Gordon et al. 2006) in the infrared and far infrared are now available for M31. Together with the recent CO and HI observations (Nieten et al. 2006, Braun et al. 2009) this new wealth of data allows a much more detailed exploration of the dust properties out than in previous studies. Especially Spitzer data allow to study significantly smaller scales than in the IRAS era.

Moreover, in the last years important progress has been made on the theoretical understanding of dust properties facilitating the derivation of new parameters from the data (Weingartner & Draine 2001; Draine & Li 2007; Draine et al. 2007). This work is thus devoted to an analysis of recent data available for M31 in light of the new theoretical instruments. We focus our attention on the mean radiation field heating the dust, on the dust mass determination and on the amount and distribution of Polycyclic Aromatic Hydrocarbon particles (PAHs) in M31.

M31 offers a nice example for studying a problem that has drawn a lot of attention in recent studies: what is the main source heating the dust in a galaxy? Certainly the dust tends to prefer-
antially absorb UV photons, so naively one would of course expect UV radiation especially from the young populations seen in the GALEX images of M31 to be the main source powering the observed dust emission. Indeed this idea clearly holds for starburst and very actively star forming galaxies (see e.g. Buat 1992, Meurer et al. 1995) and triggered the discovery of the IRX-β relation (Meurer et al. 1999), but in galaxies hosting older stellar populations the radiation field is clearly dominated by longer wavelengths. Recent studies have demonstrated that in systems with low relative star formation rate old stars can contribute significantly to the dust heating (Cortese et al. 2008; Kong et al. 2004, Buat et al. 2005; Gordon et al. 2000) and we will see in this paper that the latter applies for M31. This difference is crucial if one attempts to derive accurate dust attenuations and consequently star formation rates in any galactic system.

The structure of this paper is as follows: In Sect. 2 we present the examined data and the calibration procedure, in Sect. 3 we describe the dust models and their application to determine the dust mass, the mean intensity of the radiation field responsible for dust heating and of the PAHs abundances in M31. In Sec. 4 we discuss the age dependency of dust heating, deriving the $A_{FUV}$ attenuation across the spiral-ring structure of M31. Finally in Sects. 5 and 6 we discuss and summarize our results.

2. The data

2.1. IR

In this work we used the IR images of M31 described in Barmby et al. (2006) and Gordon et al. (2006), and obtained with the IRAC/MIPS instruments on board of the Spitzer Space Telescope (SST). In particular, we retrieved from the SST archive the 3.6 $µm$, 8 $µm$ IRAC, and the 24 $µm$, 70 $µm$ and 160 $µm$ MIPS Basic Calibrated Data (BCDs) which were processed by the SST’s archive pipeline (v.14). The BCDs were then stacked together using the MOPEX software (version 18.1).

For IRAC observations we applied overlap correction before mosaicing in order to match the background between adjacent images and discarded the first frame of each observing run because it is typically acquired with a lower bias level than subsequent images (first frame effect). The background was evaluated in the external regions and subtracted from the images with the IRAF $\text{imsurfit}$ task using a low order polynomial (first or second order depending on the map). We then applied the IRAC photometric corrections for infinite sources as reported in the IRAC documentation multiplying the 3.6 $µm$ image by 0.91 and the 8 $µm$ image by 0.74 in order to account for scattering of incident light in the array focal planes. We applied the correction for extended sources because in this work we focus on the diffuse dust emission, not on point-like sources.

For MIPS 70 $µm$ and 160 $µm$ data, we used our customized software for background subtraction via fitting and subtracting a first order polynomial along the scan direction excluding the M31 region. The final MIPS mosaic images have a resolution of 6$''$/px, 18$''$/px and 40$''$/px at 24 $µm$, 70 $µm$ and 160 $µm$, respectively.

Because our purpose was to directly compare the fluxes in each band on a pixel by pixel basis we had to resample the images to the same astrometric reference system. In fact we created two sets of images: in the first one the IRAC 3.6 $µm$ and 8 $µm$ images were put to the reference system of the 24 $µm$ mosaic (6$''$/px), in the second one the IRAC 3.6 $µm$ and 8 $µm$ and the MIPS 24 $µm$ and 70 $µm$ were put on the reference system of the 160 $µm$ mosaic (40$''$/px). These two sets will be considered separately in the following. To make the different instrument images comparable, we first matched the PSF of the input instrument to that one of the target instrument (MIPS 24 $µm$ or MIPS 160 $µm$). This was done with the help of the transformation kernels provided by K. Gordon (Gordon et al. 2008). These kernels give the transformation between the PSFs of each couple of IRAC-IRAC, IRAC-MIPS and MIPS-MIPS instruments dependent on the dust temperature. After the convolution we resampled the images to the same astrometric grid, in such a way that each pixel in a given band corresponded to the same physical region of the same pixel in the other bands. We estimated the uncertainty of the resampling step by means of a comparison of the integrated photometry on the whole galaxy before and after this procedure and found that in the worst case the relative variation in flux was 3%, as shown in Tab. 1. The uncertainty in the background subtraction was estimated evaluating the scatter in the background subtracted mosaics in the outermost regions and found to be negligible.

While creating the mosaics with MOPEX 2 (MOsacker and Point source EXtractor), we derived also the associated error map, which provides the error related to the whole reduction procedure performed by the pipeline. To account for the other sources of error (resampling, background subtraction, BCDs calibration) we simply added a constant term equal to 10%, with except of the 24 $µm$ map for which we would have otherwise obtained unrealistically large values of the error. In reality our approach can be considered rather conservative, because as stated in the SST documentation the standard deviation maps account for the error of the pipeline in a conservative way. This is also demonstrated by a comparison of our own measurements of the integrated fluxes of M31 in each band with those derived by Barmby et al. (2006) and Gordon et al. (2006) as shown in Tab. 2. In particular, with respect to the errors quoted by Barmby et al. (2006) and Gordon et al. (2006), our integrated flux measurements are 0.6$σ$ smaller, 0.1$σ$ smaller, 1$σ$ larger, 0.8$σ$ larger and 0.4$σ$ smaller than their own measurements at 3.6 $µm$, 8 $µm$, 24 $µm$ 70 $µm$ and 160 $µm$ respectively, and our estimated error is 9% smaller, 30%, 54%, 36% and 50% larger than their given uncertainties. We conclude that our measurements are consistent within 1$σ$ and that our errors are in general equivalent or larger with respect to the values derived by Barmby et al. (2006) and Gordon et al. (2006).

Table 1. Percentual variation of the total integrated flux of M31 as measured before and after the resampling process of the images described in the text. The third column presents the percentual variation for the images resampled to the 24 $µm$ resolution, the third column for the images resampled to 160 $µm$. The total integrated flux was measured in the same area in all the images, correspondent to an ellipse centered on M31, with a semi-major axis of 84$,''$, a semi-minor axis of 18$,''$, and a position angle of PA = 38$°$.

| Band ($µm$) | resampled to 24 $µm$ (%) | resampled to 160 $µm$ (%) |
|------------|--------------------------|---------------------------|
| 3.6        | 2                        | 2                         |
| 7.9        | 3                        | 2                         |
| 24         | -                        | 0.8                       |
| 70         | -                        | 0.6                       |
| 160        | -                        | -                         |

1. http://dirty.as.arizona.edu/ kgordon/mips_conv_psfs/conv_psfp.html
2. http://ssc.spitzer.caltech.edu/postbcd/mopex.html
We finally subtracted from the 8 μm and the 24 μm maps the stellar continuum which was assumed to be described by the 3.6 μm map following Helou et al. (2004):

\[ F_r^{3.6}(8 \mu m) = F_r(8 \mu m) - 0.232F_r(3.6 \mu m) \]

\[ F_r^{24}(24 \mu m) = F_r(24 \mu m) - 0.032F_r(3.6 \mu m) \]

2.2. Ultraviolet

The UV maps of M31 were retrieved directly from the NASA Extragalactic Database (NED) and were obtained as part of the survey of nearby galaxies performed with the GALExy Evolution Explorer (GALEX) satellite (Gil de Paz et al. 2007). We retrieved and used both the far ultraviolet (FUV) and the near ultraviolet (NUV) images. These maps have a pixel scale of 1.5″/px, a total integration time of 800 sec and are given in units of counts per pixel per second (CPS). The background in these images can be assumed constant and was accurately measured by Gil de Paz et al. (2007) who give a mean value of \((9.29 \pm 5.24) \times 10^{-4}\) CPS and \(4.712 \pm 1.529) \times 10^{-3}\) CPS for the FUV and NUV respectively. We subtracted the background from the maps and then converted the CPS units in Jy by multiplying by the factors \(f_{0,FUV} = 108 \mu Jy/CPS\) and \(f_{0,NUV} = 36 \mu Jy/CPS\), as given by the GALEX documentation. We then accounted for the foreground galactic extinction assuming \(E(B-V) = 0.062\) in the direction of M31 as reported by Schlegel et al. (1998) with \(A_{FUV} = 7.9 \ E(B-V)\) and \(A_{NUV} = 8.0 \ E(B-V)\) as given by Gil de Paz et al. (2007). Two series of maps were finally derived in order to compare UV observations with MIPS 24 μm and MIPS 160 μm data. Both the FUV and the NUV maps were convolved to the correspondent MIPS PSFs and regridded at 60″/px and 40″/px. The global uncertainty of the final maps was estimated to be ~ 10% in flux for both maps.

2.3. Optical

We retrieved and stacked together the SDSS images of M31 obtained in the SDSS survey. In this work we made use only of the SDSS i band (hereafter SDSS) images of M31. First we subtracted the SOFTH IAS in every single frame. SOFTHIAS was originally added automatically by the SDSS pipeline to avoid negative pixel values. We aligned each single frame to a large reference image (1.5 × 4.2 square degree) using the IRAF task "wregister". Then we reconstructed each stripe. The final mosaic image contains 7 stripes \((3366-2, 3367-3, 3366-3, 3367-4, 3366-4, 3367-5, \text{and } 3366-5, \text{from left to right in the mosaic image})\). We first tested for photometric variation, but resulted in no zero-point difference between the stripes. Nevertheless we found sky variations in y-direction in different stripes when combining them into the mosaic image. Therefore, we applied an alignment in y-direction for each stripe. Using our customized written software (mupipe/skyscale) we calculated the gradient \(a \times y\) and the offset \(b\) in flux of the overlapping areas between two adjacent stripes, e.g. \(F_{3366-2} = F_{3366-3} + a_{3366-3} \times y + b_{3366-3}\) and applied the y-dependent sky correction to the whole stripe. The map was convolved with the Spitzer 160 μm PSF and rescaled at 40″/px resolution.

Then we calibrated the images using cataloged surrounding stars with SDSS photometry and masked out all the sources with \(i < 17 \text{mag}\) as most of the point-like sources in this magnitude range are foreground contaminants and excluding the brightest M31 objects (globular clusters, red supergiants, etc.) does not affect our analysis which is focused on regions dominated by the dust diffuse emission.

In order to select an uncontaminated sample of regions from the infrared and UV maps we used the two color diagram shown in Fig. 1. We corrected the 8 μm and 24 μm maps for the stellar continuum using Eq. 1 and Eq. 2 and worked at 60″/px resolution. We limited the analysis to regions with \((S/N) > 1\) by this excluding from the analysis the inner bulge region (< 3′ from the center of M31), partially the interarm regions between the inner spiral-arm and the outermost regions of the galaxy. While the bulk of the points have colors with \(1 < \nu F_{nuv}^{nuv}(8 \mu m)/\nu F_{nuv}^{nuv}(24 \mu m) < 10\) and \(0.3 < \text{FUV/NUV} < 2\), and appear after visual inspection associated with the diffuse dust emission, some deviant points are visible in Fig. 1. In our maps bright point-like sources in the 24 μm map have \(\nu F_{nuv}^{nuv}(8 \mu m)/\nu F_{nuv}^{nuv}(24 \mu m) < 1\), thus lower than the ratios found in the diffuse component of the dust. Different studies have demonstrated that the emission from point-like sources at 24 μm is associated with the emission from HII regions in the UV and Optical spectral regions (Calzetti et al. 2007; Prescott et al. 2007). Moreover, the PAHs emission at 7.7 μm is expected to be strongly reduced with respect to the diffuse dust emission in such environments (e.g. Calzetti et al. 2005; Thilker et al. 2007; Bendo et al. 2008). On the other hand regions with \(\nu F_{nuv}^{nuv}(8 \mu m)/\nu F_{nuv}^{nuv}(24 \mu m) > 10\) or FUV/NUV < 0.3 appear to be associated with bright foreground stars. We thus adopt the selection criteria for regions: \(1 < \nu F_{nuv}^{nuv}(8 \mu m)/\nu F_{nuv}^{nuv}(24 \mu m) < 10\) and FUV/NUV > 0.3. Once using also the SDSS optical map we further added the selection for excluding bright foreground stars as described above.

In Fig. 2 for each of the analyzed regions of M31 is shown the minimum signal to noise ratio \((S/N)\) when considering all the above mentioned observational maps together. The \((S/N)\) is in general larger than 3 along the 10 kpc ring and partially in the inner spiral structure. In the interarm and external regions the \((S/N)\) drops below 1.5. In the bulge region the S/N is low because of the small stellar corrected flux at 8 μm.
The emission spectrum predicted by the model can be approximated as a function of the dust-to-gas ratio abundances with 0.47%, 1.12%, 1.77%, 2.50%, 3.19%, 3.90%, and 4.58% of the total dust mass. These models assume a dust-to-gas ratio \( \frac{M_{\text{dust}}}{M_{\text{H}}} \approx 0.01 \). For further details the reader is referred to the studies mentioned above. The emission spectrum predicted by the model can be approximated as

\[
F_{\nu,\text{model}} = \Omega_{\text{star}} B_{\nu}(T_{\text{star}}) + \frac{M_{\text{dust}}}{4\pi D^2} \left[ (1 - \gamma) f_{\nu}(\text{model}, U_{\text{min}}) + \gamma j_{\nu}(\text{model}, U_{\text{min}}, U_{\text{max}}) \right]
\]

where the first term accounts for the residual infrared emission coming from the stars and is given by the product of \( \Omega_{\text{star}} \) (the solid angle subtended by the stars, and \( B_{\nu}(T_{\text{star}}) \), the blackbody emissivity with a fixed temperature \( T_{\text{star}} = 5000 \text{ K} \), which was found by Smith et al. (2007) to provide a good description of the stellar continuum for \( \lambda > 5 \mu\text{m} \). \( D \) is the distance of M31 (we assumed 778 kpc), \( f_{\nu}(\text{model}, U_{\text{min}}) \) is the dust power radiated per unit frequency per H nucleon when the dust is exposed to a single radiation field of intensity \( U_{\text{min}} \). The factor \( \gamma \) (0 \leq \gamma \leq 1) is introduced to parametrize the dust heating effects of a power-law distribution of starlight intensities, as described in Draine & Li (2007). Actually, \( j_{\nu}(\text{model}, U_{\text{min}}, U_{\text{max}}) \) gives the dust power radiated per H nucleon by dust exposed to a power law distribution of starlight intensities \( \propto U^{-2} \) comprised between \( U_{\text{min}} \leq U \leq U_{\text{max}} \). The fraction \( \gamma \) (0 \leq \gamma \leq 1) of dust emission associated with this intensity field represents dust emission close to OB associations and/or photodissociation regions, where the intensity \( U > U_{\text{min}} \), in such a way this approach allows to handle dust temperature variations, in a smooth and convenient way. Following Draine et al. (2007) we fixed in our calculation \( U_{\text{max}} = 10^6 \). Finally \( M_{\text{H}} \) is the total mass of hydrogen (providing that the models give the emission per H nucleon). The mass of the dust, \( M_{\text{dust}} \), can be obtained from \( M_{\text{dust}} = M_{\text{H}} \left( \frac{N_{\text{dust}}}{N_{\text{H}}} \right) \), assuming the dust to gas ratio of the models.

Each spectrum is thus completely characterized by 5 free parameters: the solid angle subtended by the stars \( \Omega_{\text{star}} \), the kind of emission model (amount of PAHs), the minimum intensity \( U_{\text{min}} \) of the starlight radiation field, the fraction \( \gamma \) of the total dust mass heated by the power-law distribution of starlight intensities, and the total dust (hydrogen) mass \( M_{\text{H}} \). The best fit is obtained minimizing the quantity:

\[
\chi^2 = \frac{1}{N_{\text{obs}}} \sum_{b} \frac{(F_{\text{obs},b} - \langle F_{\text{model},b} \rangle)^2}{\sigma_{\text{obs},b}^2 + \sigma_{\text{model}}^2}
\]

In Table 2 we collected all the infrared integrated flux measurements of M31 performed so far, obtained with different instruments: IRAC (Barmby et al. 2006), MIPS (Gordon et al. 2006), COBE (Odenwald et al. 1998), IRAS (Rice et al. 1988), MSX (Kraemer et al. 2002) and ISO (Haas et al. 1998). In the fourth column we show our own measurements derived from IRAC and MIPS observations. In general all these measurements
are in good agreement, and define the spectral energy distribution of M31 from ~1 µm up to ~250 µm, as shown in Fig. 3. The best fit parameters we obtained were: PAHs = 4.6%, $U_{\text{min}} = 0.4$, $\gamma = 0$ and $M_{\text{dust}} = 7.6 \times 10^8 M_\odot$, $\Omega_{\text{dust}} = 3.1 \times 10^{-16}$ sr and the $\chi^2$ of the best model was $\chi^2 = 0.55$.

In the following we discuss the uncertainties on the derived parameters and the implications of the results.

### 3.1. The uncertainty in the dust mass estimate

The mass estimate obtained in the above paragraph must be considered rather uncertain. This is due to the fact that, as shown in Fig. 3, the peak wavelength of M31’s IR spectrum is close to 160 µm. Thus, the vast majority of our analyzed observations is found at shorter wavelengths, therefore colder mass components can’t be reliably constrained by the present observations. The only measurement that gives an appreciable constraint is the COBE 248 µm observation. Otherwise, the cold-mass estimate critically depends on the temperature of the dust inferred from the infrared spectrum. For a given mean radiation field intensity from the infrared spectrum, the dust mass $M_{\text{dust}}$ derived comparing the model with the observations is $M_{\text{dust}} \propto U^{-1}$, or $dM_{\text{dust}}/M_{\text{dust}} \propto -dU/U$. This makes the dust temperature estimate relatively robust against uncertainties in $U$, i.e. a variation of 100% in $U$ (and in $M_{\text{dust}}$) produces a variation of only ~17% in dust temperature and in emission peak wavelength, to which our measurements are sensitive. Moreover, $dU/U$ can be quite large even for small changes of $U$ if $U$ is also small, as it seems to be the case for M31. In order to perform a more quantitative analysis, in Fig. 4 we show the $\chi^2$ of the best model obtained fixing the value of $U_{\text{min}}$, against the correspondent total hydrogen mass $M_H$ predicted by the model. The black points (continuous line) in that figure show the result of the fit when all measurements in Tab. 2 are considered (with the exclusion of ISO and MSX measurements which were not used here), the red dots (dotted line) when neglecting the COBE 248 µm, and the blue (dashed line) points when neglecting the MIPS 160 µm and the COBE 148 µm and 248 µm measurements. From that is clear that the cold mass can’t be accurately estimated. All the curves show a shallow minimum in $\chi^2$ but the range of mass values at which $\chi^2$ approaches the absolute minimum is large even considering the fit with all the present observations. Moreover, once FIR measurements are excluded the $\chi^2$ curves are even flatter increasing the uncertainty in the mass values. Nevertheless it has to be noted that all $\chi^2$ curves are highly asymmetric and imply that large mass values are much less constrained than low mass as explained below.

In Fig. 5, we present the difference between the observations and the values predicted by two different models: (i) the best fitting model (which has $U_{\text{min}} = 0.4$, black filled points); (ii) the best model obtained imposing $U_{\text{min}} = 2$ (red open circles). All the measurements reported in Tab. 2 are considered in the fit, thus the $\chi^2$ of these two models are shown in Fig. 4 for the correspondent values of $U_{\text{min}}$ as given by the points connected by the continuous black line. In Fig. 5, only measurements with $\lambda > 50$ µm are considered because this is the spectral region where the major differences can be noticed. A model should be considered consistent with the observations if all the observation minus model differences ($\Delta$) are consistent with zero, within the observational errors. Focusing the attention on the Far Infrared measurements (FIR) of Spitzer 160 µm and COBE 148 µm, 248 µm in Fig. 5, we obtained for the best fitting model $\Delta_{148} = 0.55 \sigma_{148}$, $\Delta_{160} = 0.24 \sigma_{160}$ and $\Delta_{248} = -0.06 \sigma_{248}$, whereas for the model with $U_{\text{min}} = 2$ we obtained $\Delta_{148} = 1.74 \sigma_{148}$, $\Delta_{160} = 1.57 \sigma_{160}$ and $\Delta_{248} = 2.45 \sigma_{248}$. Thus in this spectral range the best fitting model with $U_{\text{min}}$ appears consistent with the observations at $< 0.6 \sigma$, whereas to reconcile observations and model predictions once $U_{\text{min}} = 2$ we have to admit differences $< 2.5 \sigma$, and in any case $> 1.5 \sigma$. For smaller wavelengths the two models appear almost equivalent in reproducing the observations, although a slightly worse result is obtained for $U_{\text{min}} = 2$. An important feature of Fig. 5 is that for $\lambda > 140$ µm the flux model values for $U_{\text{min}} = 2$ are lower than the values of the best fitting model, whereas for $\lambda < 140$ µm they are systematically larger. This is what we expect as the peak emission of the model with $U_{\text{min}} = 2$ is shifted towards smaller wavelengths with respect to the best fitting model, as a consequence of the larger radiation field that is heating the dust. Because of model predictions in the FIR for the case of $U_{\text{min}} = 2$ are already at the limit of predicting an acceptable wavelength distribution, larger radiation fields can be discarded. We conclude that on the basis of the diffuse dust emission models of Draine & Li (2007) and the analysis of the FIR spectrum of M31 the mean radiation field that is heating the dust in M31 is typically $U < 2$. As the radiation field is inversely proportional to the dust mass estimate we can also conclude that the mass of the dust in M31 is $\gtrsim 1.1 \times 10^7 M_\odot$, which is the value obtained for the best model with $U_{\text{min}} = 2$, assuming a dust-to-gas ratio equal to 1%.

The most recent and accurate estimate of the total mass of atomic hydrogen (H I) in M31 is that of Braun et al. (2009), and is equal to $M_{\text{HI}} = 7.33 \times 10^7 M_\odot$, Nieten et al. (2006) provided a mass of molecular hydrogen $M_{\text{H}_2}$ equal to $M_{\text{H}_2} = 3.6 \times 10^8 M_\odot$ (within a radius of 18 kpc). These recent estimates combine to a total neutral hydrogen mass of $M_{\text{HI}} + M_{\text{H}_2} = (7.69 ... 8.05) \times 10^7 M_\odot$ once considering an uncertainty range for the CO conversion factor between $X_{HY} = (2 ... 4) \times 10^{18} \text{molec} cm^{-2} (K \text{km} \text{sec}^{-1})^{-1}$. The mass estimate we obtained from the best fitting model (considering all the observations in Tab. 2, $M_{\text{HI}} = 7.6 \times 10^7 M_\odot$) is thus respectively 1% and 5% smaller with respect to the neutral hydrogen mass estimates at the extremes of the uncertainty range mentioned above. Thus despite the large uncertainty we discussed previously, the best fitting model mass estimate appears consistent with HI and CO measurements, as shown in Fig. 4. Earlier estimates of the dust mass ($M_{\text{dust}}$) in M31 provided values equal to $M_{\text{dust}} = 3.8 \times 10^7 M_\odot$ (Haas et al. 1998) and $M_{\text{dust}} = 1.3 \times 10^7 M_\odot$ (Schmidtobreick et al. 2000) which are fully consistent with our lower limit estimate but, for what have been said so far, they cannot be considered more accurate than our best model value estimate.

Draine et al. (2007) analyzing a sample of 17 galaxies from the SINGS-SCUBA sample have shown that in all these galaxies the value of the mean radiation field derived from the best fitting model was $> 2$, with a median value of 4.3. On that basis they proposed a restricted fitting procedure for the case in which submillimetric observations are not available which would im-

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In principle the value of $U_{\text{min}}$ is not coincident with the definition of the mean radiation field given by Draine & Li (2007), although these two values are essentially equivalent once $\gamma \sim 0$ as seems the case for M31.
Fig. 3. Infrared spectral energy distribution of M31. Color symbols are measurements obtained with the different instruments indicated in the legend. The continuous line denotes the best fitting model of Draine et al. (2007). Open circles represent the model predicted fluxes after convolution with the instrumental response function, and these are the points that are compared with observations.

To set $U_{\text{min}} > 0.7$ during the fit in order to avoid an overestimate of the dust mass. Nevertheless as stated by the same authors this procedure underestimates the dust mass if the radiation field heating the dust is weak. The sample of SINGS-SCUBA galaxies could be biased towards increased associated star formation as recognized by the same authors. As we have demonstrated above, for the case of M31 models with $U_{\text{min}} > 2$ are not in agreement with the FIR measurements. Moreover models with a strong UV radiation field imply gas masses far below the range given by neutral hydrogen mass measurements, whereas our best fitting model ($U_{\text{min}} = 0.4$) comes very close to the expected value. This additional constraint rules out models with high $U_{\text{min}}$ and proves that M31 is a galaxy where the mean UV radiation field heating the dust is very weak. In Sect. 4 we will provide an independent demonstration of this fact and discuss its implications.

In Fig. 6 (upper panels) we show the correlation between the logarithm of the total IR (TIR) emission and the logarithm of the $24\,\mu m$ ($160\,\mu m$) emission. The TIR was estimated from the Spitzer maps of M31 using the formula given by Draine & Li (2007):

$$I_{\text{TIR}} = 0.95\nu I\nu(8\mu m)+1.15\nu I\nu(24\mu m)+\nu I\nu(70\mu m)+\nu I\nu(160\mu m)$$

The $\log (160\mu m) - \log (\text{TIR})$ correlation is less scattered (RMS = 0.03) with respect to the $\log (24\mu m) - \log (\text{TIR})$ correlation (RMS = 0.06). We fitted these data with a simple linear model obtaining:

$$\log (\text{TIR}) = 0.89(0.02) \log (\nu F_{\nu}^{\text{IR}}[24\mu m]) - 0.1(0.2)$$

$$\log (\text{TIR}) = 1.1(0.01) \log (\nu F_{\nu}^{\text{IR}}[160\mu m]) - 1.3(0.1)$$

Although, as shown below, the correlation between the $24\mu m$ ($160\mu m$) and the TIR emission is not strictly linear, these results (in particular the calibration relation between the $\log (24\mu m)$ and the $\log (\text{TIR})$ variables) will be useful later in Sect. 5 and sufficiently accurate for our purposes.

In Fig. 6 (bottom panels) we show the $24\mu m/\text{TIR}$ ($160\mu m/\text{TIR}$) ratios against the TIR intensity. As the TIR
increases the 24 µm/TIR ratio increases, but remains confined typically between 5%-7%. Conversely, the 160 µm/TIR decreases, changing from ~ 65% to ~ 50%. This demonstrates that overall the infrared spectrum of M31 is dominated by the cold dust emission in the FIR, although the contribution of hotter dust components tends to increase at larger TIR emissions.

3.2. PAHs abundance, γ

Fig. 7, shows the ratio of the 8 µm flux (normalized to the total infrared emission) against the ratio of 71 µm flux to 160 µm flux. As proposed by Draine et al. (2007) this diagram can be used to estimate the abundance of PAHs. We used it to illustrate the uncertainty of our fit comparing the result obtained from the total integrated emission of M31 to that obtained in the single regions of our maps, regridded at the 160 µm resolution and using exclusively the regions with S/N > 3. Uncertainties were calculated as explained in Sect. 2. This selection restricted us to the study of the ring-spiral structure. Essentially PAHs are stochastically heated by single photons thus in order to derive their abundance one can compare the observations with theoretical models with γ = 0 (Draine et al. 2007, where γ is the parameter that regulates the power-law intensity radiation field in Eq. 3). In Fig. 7, we show the theoretical predictions as functions of the different amount of PAHs and of the minimum radiation field intensity U_min. The results imply that models with large abundances (> 3.19%) and rather low U_min are favored when comparing to the data. In fact the measurement associated with the integrated infrared emission (blue point) is not at the center of the distribution of points coming from the analysis of the pixel-to-pixel analysis, and in particular is biased towards smaller values of R8. As our analysis is restricted to the spiral-ring structure, this result suggests that in the inter-arm regions and/or toward the bulge the abundance of PAHs could be smaller than what we derived, but an accurate analysis of the distribution of these particles across the whole disk of M31 is beyond the purpose of this work.

In Fig. 8 we show the ratio R24 of the 24 µm flux (normalized to the total infrared emission) against the ratio R71, a similar diagram of Fig. 7, but for the 24 µm map, which is better diagnostic to the radiation field intensity (Draine et al. 2007). We considered in this case only models with PAHs abundances > 3.19% since for the analyzed regions these are the models that better agree with observations (Fig. 7). For the bulk of the points, and for the total integrated flux measurement γ can be in general considered ≤ 0.05. Using the equation:

\[ f_{PDR} = 1.05(R_{24} - 0.14R_8 - 0.035)^{0.75} \]  

(8)

taken from Draine & Li (2007), and the observed ratios R8 and R24 defined above, we determined the fraction of the total dust luminosity that is radiated by dust grains in regions with U > 10^2 f_PDR to be lower than ~ 4%.

4. Which sources are responsible for the dust heating in M31?

The analysis of the infrared spectrum presented in Sec. 3 allows to conclude that the infrared spectrum of M31 can be explained by diffuse dust emission. Nevertheless, on the basis of that, we cannot understand for which stellar populations are responsible for the dust heating process. In particular we want to know where the dust in M31 is predominantly heated by young populations (Age < 1 Gyr) or where older populations (Age > 1 Gyr) play an important role in the dust-heating process as well. As shown
below the answer to this question is of crucial impact for the
deduction of several important parameters, e.g. attenuation and
SFR, and thus has to be addressed as a central issue.

In the following we used the observational maps of M31 re-
sampled at 40′′/px as described in Sec. 2, and considered all the
regions in which the $S/N > 1$ in all the maps.

Also it should be noted that the results we obtained are based
on the theoretical models of Kong et al. (2004) and Cortese et
al. (2008). It is worth saying that alternative interpretations could
exist of the observational data we present. In particular models
considering modifications of the canonical attenuation laws have
been proposed (e.g. Inoue 2005, 2006 see later in this Section).

The model of Kong et al. (2004) is based on the Bruzual &
Charlot (2003) population synthesis code, it assumes an expo-
nential star formation history (SFH) and a power-law absorp-
tion law, distinguishing between young ($< 10^7$ yr) stars embed-
ded in their birth clouds and older stars migrated into the ISM.
The model of Cortese et al. (2008) is also based on the Bruzual
& Charlot (2003) population synthesis code, but is assumes an
LMC attenuation law, and that both stars and dust were homo-
geneously distributed in a plane parallel (sandwich) geometry.
They also adopted a Star Formation History ‘a la Sandage’ in
the formalism of Gavazzi et al. (2002):

$$SFR(t, \tau) = \frac{t}{\tau} \exp \left( -\frac{t^2}{2\tau^2} \right)$$

(9)

where SFR is the Star Formation Rate per unit mass, $t$ the age (in
Gyr) of the galaxy (assuming $t=13$ Gyr at present epoch), and $\tau$
is the time (in Gyr) at which the star formation rate reaches the
highest value over the whole galaxy history (note that in this no-
tation the present age of the stellar populations born at time $t = \tau$
is given by age = 13 Gyr − τ. As stated by the same authors, τ should be considered as a proxy for the shape of the SED rather than being used to derive an exact indication of the age of the underlying stellar populations. We calculated for each value of τ, the time t* where the SFR reaches half of its maximum value (for t > τ) over the whole galaxy history. Also the age of the stellar populations correspondent to t = t* must not be considered in a strict manner but it can be considered as an indication of the age of the youngest stellar populations that are significantly contributing to the SED, given that the contribute of next generations of stars becomes increasingly less important in order to explain the observed SED. For example, for τ = 8 Gyr we obtain t* ≈ 13.5 Gyr. Assuming for the present epoch t=13 Gyr as in Cortese et al. (2008), we can expect that young populations (age < 1 Gyr) contribute significantly to the observed SED. For τ = 5 Gyr we obtain instead t* ≈ 9.6 Gyr which implies that stellar populations contributing to the SED should have an age > 3 Gyr.

It should be also remind that the predictions of these models should not be considered reliable in regions where old stars are likely to dominate the UV flux (mostly in the bulge region for M31).

At first we investigated the TIR/FUV vs. β (the UV slope) relationship for the analyzed regions as shown in Fig. 9. The solid line represents the fit obtained by Kong et al. (2004) for the 50 starburst galaxies in their sample, which represents the so called IRX − β relationship for starburst galaxies (Meurer et al. 1999). We adopted the same definition of Kong et al. (2004) to calculate β:

\[
β = \frac{\lg(T_{\text{FUV}}) - \lg(T_{\text{NUV}})}{\lg(\lambda_{\text{FUV}}) - \lg(\lambda_{\text{NUV}})}
\]

where \(\lambda_{\text{FUV}} = 1516\ \text{Å}\) and \(\lambda_{\text{NUV}} = 2267\ \text{Å}\) are the effective wavelengths of the far-ultraviolet and near-ultraviolet filters on board of GALEX and \(T_{\text{FUV}}, T_{\text{NUV}}\) are the mean flux densities (per unit wavelength) through these filters.

The small black points are the values of the TIR/FUV and β obtained in the analyzed regions of M31. A positive correlation is visible, but it does not follow the relation found in starburst galaxies. As can be expected naively, going towards negative slopes and bluer colors our observations imply similar TIR/FUV and β values with respect to the starburst galaxies relationship whereas redder regions behave differently showing typically lower TIR/FUV for equal β. This is in line with Kong et al. (2004), who showed the results coming from the analysis of their sample of normal star-forming galaxies as well and obtained that these objects typically have lower values of TIR/FUV for fixed UV-color with respect to what predicted by the (IRX−β) relation, with a large scatter of values. Other authors have recently questioned the application of the (IRX−β) relationship for normal star-forming galaxies, suggesting that such systems suffer from lower dust attenuations with respect to what could be inferred from the (IRX−β) relation (Salim et al. 2007).

Following the notation of Kong et al. (2004) we plot in Fig. 9 the lines of constant ratio of present to past-averaged star formation rate assuming an an exponentially declining star formation history (b parameter, blue short-dashed lines) and of constant attenuation (AUV, red long-dashed lines).

This comparison suggests that in the M31 regions population gradients are present but there are similar amounts of dust attenuation, being our observational points elongated along the direction indicated by the bands of equal attenuation.

As color variations seem due to a spread of ages, it is more convenient to adopt a larger color baseline like the (FUV−iSDSS)4 color. Cortese et al. (2008) provided a detailed discussion of the age dependence of the TIR/FUV ratio, colors and attenuations.

\footnote{We have decided to use here the (FUV−iSDSS) color as the 2MASS Extended Survey did not appear sufficiently deep for our purposes.}
Fig. 8. Ratio $R_{24}$ of the 24 μm flux normalized to FIR emission against 71 μm to 160 μm flux ratio $R_{71}$. The blue point is the ratio correspondent to the total integrated flux measurement of M31. Each horizontal red line shows the ratio values predicted by the models of Draine & Li (2007) for different values of the minimum radiation field intensity $U_{\text{min}}$ and of the $\gamma$ parameter (see text). The three panels show the results for models with different abundances of PAHs as indicated by the labels.

In accordance with their results, for $(\text{FUV} - i_{\text{SDSS}}) \sim 4.3$ the energy absorbed by the dust at $\lambda < 4000$ Å is approximately equal to the energy absorbed at $\lambda > 4000$ Å (as inferred from their Fig. 2 and Table 1). This corresponds to $t^* = 8.5$ Gyr as defined above, thus the stellar populations that are contributing to the SED have an age > 4.5 Gyr.

In Fig. 10 we show the TIR/FUV ratio against the $(\text{FUV} - i_{\text{SDSS}})$ color, for regions with $S/N > 1$ across the 10kpc ring ($8kpc < r < 12kpc$). The positive correlation between these variables is still clearly visible also in this diagram. Moreover the color range $3.5 < (\text{FUV} - i_{\text{SDSS}}) < 7$ demonstrates that in a large number of regions old populations dominate the dust heating process. As shown in Fig. 10 (lower left panel), the mean $A_{\text{FUV}}$ in the analyzed regions of M31 derived with this method is $A_{\text{FUV}} = 2.1 \pm 0.4$ mag where the error is the standard deviation. If the starburst scenario is considered, we obtain the result shown in the lower right panel of Fig. 10, where the mean attenuation is $A_{\text{FUV}} = 4.2 \pm 1.0$ mag. Neglecting the dust heating age dependence would imply a mean attenuation 100% larger and a scatter 150% larger, since in this case the large color changes would totally be attributed to the reddening.
In Fig. 10, we overplotted two lines of constant attenuation correspondent to $A_{\text{FUV}} = 2$ and $A_{\text{FUV}} = 3$ as indicated by the labels. The shape of these lines reflects the age dependence of the dust heating as modeled by Cortese et al. (2008). Actually for blue ($\text{FUV} - i_{\text{SDSS}} < 4$) or red colors ($\text{FUV} - i_{\text{SDSS}} > 7$) the attenuation lines tend to be parallel to the color axis, and thus independent from the color. This is due to the fact that in these color ranges the intrinsic spectral energy distribution of the populations that are heating the dust is not expected to change appreciably with age to the very young (blue) or very old (red) side. On the other hand in the range comprised between $4 < (\text{FUV} - i_{\text{SDSS}}) < 7$, which is actually where most of our observations fall, age variations contribute significantly to color changes, and older populations appear intrinsically redder thus shifting the TIR/FUV ratio towards larger values for equal amounts of attenuation with respect to bluer regions. In the following we tried to disentangle the effects of the age and of the reddening on the observed colors and TIR/FUV ratios.

At first we converted the colors to the values of $\tau$ (the time expressed in Gyr at which the star formation rate reaches the highest value over the whole galaxy history, assuming 13 Gyr at present epoch) by means of:

$$\log(\tau) = -0.073 (\text{FUV} - i_{\text{SDSS}}) + 0.96$$

(11)

taken from Table 2 of Cortese et al. (2008). The colors in Fig. 10 are codified in function of the value of $\tau$. We obtained that 83% of the analyzed regions across the spiral-ring have ($\text{FUV} - i_{\text{SDSS}} > 4.3$ and thus values of $\tau < 4.4$ Gyr. Hence according to the results of Cortese et al. (2008) in 83% of the analyzed regions the dust absorbs more than 50% of the energy at $\lambda > 4000$ Å. As stated above this implies that in these regions stellar populations responsible for the dust heating should be at least a few Gyr old. This could provide a good agreement to the low mean intensity of the radiation field we found from the analysis of the infrared spectrum of M31, although a small value of $U$ could be obtained also by young stars with a low SFR. It is important to remind that these results do not imply that younger populations are not present at all, but rather that their contribution is not dominant in these regions. If, on the contrary one tries to explain the observed colors assuming that only
Fig. 10. Upper panel: (TIR/FUV) logarithmic ratio against (FUV − iSDSS) color for regions with S/N > 1 across the 10 kpc ring (8kpc < r < 12kpc). The colors denote the different values of τ (the time expressed in Gyr at which the star formation rate reaches the highest value over the whole galaxy history, assuming 13 Gyr at present epoch) obtained for each region following the recipes of Cortese et al. (2008). The two solid lines are two lines of constant attenuation. The errorbar on the top-left corner shows the mean observational errors. Lower panels: Histograms of ultraviolet attenuations derived following the recipes of Cortese et al. (2008, left panel) and assuming the starburst scenario (right panel). Mean values and 1σ uncertainties are denoted by solid and dashed vertical lines and are A_FUV = 2.1 ± 0.4 mag and A_FUV = 4.2 ± 1.0 mag for left and right panel respectively.
young populations (age < 1 Gyr) are heating the dust, one should also admit much larger attenuations for normal galaxies, as demonstrated above and for the same distribution of star and dust as in Cortese et al. (2008). Otherwise it is clear that in order to confirm these results more accurate models are needed. Some other considerations regarding the limitation of the Cortese et al. (2008) approach are presented shortly below and in the next Section.

From another point of view we show in Fig. 11 the same diagram of Fig. 10 separating regions of low and high TIR emission as indicated by the labels and the colors. We considered 4 equal bins of TIR emission comprised between $10^{11}$ and $10^{10}$ erg cm$^{-2}$ sec$^{-1}$. From Fig. 11 it appears that moving towards redder colors along the regions of constant TIR emission, the TIR/FUV ratio increases. As the TIR emission is constant, the FUV emission must decrease. Nevertheless, if the lower FUV emission was due to larger attenuations, the TIR emission should have increased accordingly, which is not observed. Thus, the color change must be due to an intrinsic lower emission in the FUV band, that could be indicative of the presence of a population gradient. Strictly speaking this interpretation is valid for an homogeneous layer of stars embedded in an homogeneous optically thin layer of dust. In a real galaxy dust and stars (especially recently formed stars) are likely to have more clumpy and inhomogeneous distributions. Otherwise, studying two of the largest dust clouds listed in the M31 Atlas (Hodge 1980), Hodge & Kennicutt (1982) derived average extinctions of $A_B = 0.35$ mag (with a maximum value of $A_B = 0.60$ mag) and $A_R = 0.43$ mag (maximum $A_R = 0.76$ mag) for D307 and D441 respectively, indicating that the majority of all the other clouds should have smaller amounts of extinctions. Other studies confirm the idea that the interstellar medium in M31 is generally optically thin. Fan et al. (2007) derived reddening values towards 443 M31’s catalogued globular clusters obtaining that more than half of them are affected by a reddening $E(B - V) < 0.2$ mag with an average value of $E(B - V) = 0.28_{-0.14}^{+0.23}$ (see also Barmby et al. 2000). Regarding the homogeneity of the dust distribution, Inoue (2005, 2006) investigating the attenuation law resulting from clumpy spatial distributions of dust and (young) stars, proposed different explanations for the redder UV colors of normal galaxies with respect to starburst galaxies for fixed FIR to FUV ratios, which are not based on population gradients. These alternative models can be summarized as: (i) models where the attenuation law has a steeper dependence on wavelength than the canonical attenuation laws as a result of an age-selective attenuation law; (ii) models where the attenuation law has no attenuation bump at 2175Å; (iii) models with a bump at 2175Å, but with smaller albedo for shorter wavelengths (except for the bump range). While we did not try to apply these models to our data, we observe that at least the first two scenarios do not seem to fit the case of M31. Bianchi et al. (1996) derived that the M31 extinction curve is very similar to the average Galactic extinction law and a possible reduction of the 2175Å bump is significant only at the 1σ level. Similar results were reached also in previous studies (e.g. Walterbos & Kennicutt 1988). As for the third class of models further studies of the wavelength dependence of the albedo are necessary. We also observe that these considerations do not imply that clumpy structures with young stars embedded do not exist in M31, but it could be that most of the dust in M31 is not located in these structures. From counts of dark nebulae across the disk of M31 Hodge & Kennicutt (1982) obtained that the major dust lanes visible in the optical should account for ~ 15% of the total dust mass content. Recent results by Nieten et al. (2007) show a good correlation between the most prominent dust lanes and dense molecular clouds traced by strong CO emission lines but concluded that molecular gas in M31 is only ~ 7% of the total neutral gas content in M31, and that dust appears correlated also with atomic gas in M31 which is distributed in more extended regions out of the densest clouds in the spiral-ring structure. Moreover in Sec. 3.1 we derived that only a fraction < 7% of the TIR comes from the hot dust component emission at 24μm associated with young star forming regions. Finally, it is unlikely that a large fraction of the M31’s dust mass is in very cold dark clouds (T < 16 K), as the total M31 dust mass we derived in Sec. 3.1 from dust diffuse emission models was close (1%-5%) to the estimate based on neutral gas measurements. We conclude that the interpretation of Fig. 11 in terms of population gradients must be considered carefully and in need of further investigation, but it appears reasonable for regions dominated by diffuse dust emission away from large star-forming complexes (in this regard remember the criteria we applied in Sec. 2 against the selection of HII regions). In fact the attenuation along bands of equal TIR emission appears to decrease towards redder colors accordingly to the predictions of Cortese et al. (2008). This could be also in agreement with the idea of a population gradient, as older populations would tend to be intrinsically less attenuated than younger ones, because of their intrinsically redder spectral energy distribution, at least in the region where the age effect is maximal 4 < (FUV - i SDSS) < 7. We note nevertheless that the observed color could be also biased towards redder values especially in the bulge region where the geometry of the dust and star is clearly deviating from the simplified sandwich model of Cortese et al. (2008). We will discuss such potential bias effect in more details in the next Section. Another interesting consideration regarding the diagram of Fig. 11, is that moving vertically towards larger TIR/FUV ratios the TIR emission increases (whereas the FUV emission remains almost constant), which should imply larger attenuation values because of the large absorbed energy for a fixed observed FUV energy, which is what the model predicts. We have thus the following interpretation of the diagram in Fig. 11. While the large color variation of the analyzed regions seems to be due to the gradient of populations that are heating the dust, the spread of the TIR/FUV values for a fixed color seems instead due to the differential reddening of regions with similar underlying stellar populations.

We further investigated the spatial distribution of the $A_{FUV}$ across the disk of M31. We considered nine 2 kpc-wide radial bins from the center of M31 up to 18 kpc as shown in Fig. 2, and imposed a $S/N > 1$. In Fig. 12 we present the logarithmic TIR/FUV ratios against the (FUV - i SDSS) colors obtained in each radial bin. In general it appears that these observable quantities are positively correlated across all the disk of M31. Only in the innermost annulus it was not possible to verify the positive correlation of these variables because of the few regions analyzed. We fit the $\lg$/(TIR/FUV) ratios against to (FUV - i SDSS) colors in each radial bin with a linear model: $\lg$(TIR/FUV) = $a$(FUV - i SDSS) + $b$. We considered separately the uncertainties along the x and y axis and took the mean value of the derived parameters and their semi-difference as estimates of the best model parameters (a and b) and uncertainties. In Tab. 3 we reported the result of the fit along with other useful quantities.

As shown also in Fig. 13 the mean attenuation in each radial bin varies reaching a maximum near the 10kpc ring, while it seems to decrease faster towards the inner regions of M31 than in the outer regions.

These results are also shown as the color maps of Fig. 14. While as discussed above the model adopted here could be less
reliable in the inner part of the galaxy due to deviations of the dust and star distribution from the asumed geometry, the trend and the values of the mean attenuations derived with this method are in agreement with previous studies as discussed in the next Section.

The existence of a correlation between the TIR/FUV ratios and the colors that we have found needs a final remark. Actually it is important to keep in mind that the theoretical calculations of Kong et al. (2004) and Cortese et al. (2008) do not necessarily imply the existence of any correlation between these observables. Nonetheless we should remind that in this case we are studying regions inside one galaxy, and thus we can expect a more uniform and homogeneous behaviour.

5. Discussion

The models of Cortese et al. (2008) assume a simple plane parallel (sandwich) geometry for the dust and star distribution. Even if the fractional scale height between the dust and the stars is allowed to vary with wavelength no radial dependence is assumed. The method solely grounds on the relationship between two observed emission ratios and can by this be expected to be highly prone to light contamination from distant sources and a different geometry. Since, if the geometry is not plane parallel the radiation field experienced by the dust can be significantly different from what is naively measured by the outside observer, the observed color from which the age of the underlying population is estimated could be biased towards redder values in regions where older stellar populations are less embedded in the dust. This bias should be strongest in the inner regions of the galaxy as the result of the bulge light contamination. Regions with $r < 8$ kpc in Fig. 12 reach redder colors and higher TIR/FUV ratios with respect to the outer regions. For $r > 12$ kpc the color range remains almost constant although the TIR/FUV ratio decreases. In presence of the above mentioned observational bias the value of the attenuation derived from the model could have been underestimated in the inner regions. Moreover in the innermost radial bin ($r < 2$ kpc) old stars can contribute a significant
fraction of the GALEX-UV emission, and thus the model prediction should not be considered reliable in that region.

To estimate how the integrated light along the line of sight could have affected our analysis and consequently biased the derived attenuations we compared the \((\text{FUV} - i_{\text{SDSS}})\) color along the major and minor axis as shown in Fig. 15. Each point in these figures is the average value of the colors (attenuations) inside a 200''-wide (0.75 kpc) stripe centered on the major and minor-axis in correspondence of each one of the 2kpc annular regions shown in Fig. 2. The bias effect should be more evident along the minor than the major axis because of the inclination of M31. At the same galactocentric radius of the disc the line of sight passes through more central regions of the bulge along the minor axis than along the major axis. In case the described bias affects the derived parameters it has thus to be expected that at the same galactocentric radius the adopted method will predict lower attenuations along the minor axis than on the major axis. We calculated the mean color and attenuation difference inside the 10kpc ring excluding the region around +5 kpc on the near-side of the galaxy along the minor axis because of the presence of the inner spiral arm with enhanced TIR emission and attenuation. In Fig. 15 (left panel) we see that indeed the color profile along the minor axis is systematically redder than along the major axis on average of \(\sim 0.5\) mag. This implies that the attenuations appear to be systematically lower on the minor axis of \(A_{\text{FUV}} \sim 0.2\) mag (Fig. 15 right panel).

Because also the major axis should be affected by such observational bias the effect should be in principle larger than this. Considering the radial bin at 11kpc and that one at 3kpc and considering the color shift toward redder values in the inner bin as \textit{totally} due to the bias effect we estimated the average attenuation at 3kpc to be larger of \(\sim 0.84\) mag (Fig. 16) than what derived from the observed colors. This value should be considered as an upper limit as the color shift should be in part attributed also to intrinsically redder and older populations than those in the ring where most of the star formation in M31 is taking place. Nevertheless even applying such a generous bias correction the ring would still stick out as a maximum of attenuation as shown in Fig. 16. On the other hand such an exercise points out the need...
Fig. 13. Average FUV ($\lambda_{\text{eff}} = 1516 \text{Å}$) attenuations in 2kpc radial bins from the center of M31 to $\sim 21$ kpc obtained by us (filled circles), Xu & Helou (1996, open circles). Open triangles represent the result of Hodge & Lee (1998) obtained analyzing 5 fields at different galctocentric distances.

of a more accurate model to properly account for what happens in the innermost regions.

Xu & Helou (1996) developed a dust heating/cooling model for M31 based on a radiative transfer code which assumes a sandwich geometry for stars and dust like in Cortese et al. (2008). They obtained that the mean optical depth $\tau_v$ viewed from the inclination angle of $77^\circ$ increased with radius from $\tau_v \sim 0.7$ at $r = 2$ kpc, reaching a peak of $\tau_v = 1.6$ near 10 kpc and remaining quite flat out to 14 kpc. We used Eq. 2, 3, 4 of Cortese et al. (2008) to convert the $\tau_v$ values of Xu & Helou (1996) into $A_{\text{FUV}}$ magnitudes. The resulting values are $A_{\text{FUV}} = 1.23$ mag at 2 kpc, and $A_{\text{FUV}} = 2.50$ mag near 10 kpc in good agreement with the results shown in Tab. 3 and Fig. 13. The radial trend we derived actually peaks close to 10 kpc and appears to remain quite flat in the outer regions and to decrease faster in the inner regions. While, considering the uncertainties in the $A_{\text{FUV}}$ estimate, these results are consistent with those ones of Xu & Helou (1996), some differences are visible. In the inner side of the ring our average attenuations tend to be lower (from $\sim (0.1 \ldots 0.5)$ mag) with respect to the results of those authors. Despite the fact that the same sandwich geometry is adopted, the two approaches actually differ in various aspects. At first Xu & Helou (1996) did not admit the presence of population gradients. While this assumption was motivated by the consideration that the $(V - R)$ color of M31 appeared rather constant in the disk of M31 (Walterbos & Kennicutt 1988) the results shown in the previous section, based on a much larger color baseline, indicate that indeed a population gradient is present across the disk of M31. In absence of population gradients, as discussed in the previous section, one tends to overestimate the attenuation in the region where the age effect is maximal ($4 < (\text{FUV} - i_{\text{SDSS}}) < 7$), and this independently on the observational biases discussed previously (which should affect both methods in a similar way). It is interesting to note that in the inner region at 2kpc, and thus where most of the regions have $(\text{FUV} - i_{\text{SDSS}}) > 7$ the two models appear in perfect agreement. On the other hand the model of Xu & Helou (1996) actually solves the radiative transfer problem and fully accounts for the effects of the dust scattering which are neglected by Cortese et al. (2008). If the scatter is neglected for a fixed observed color we would have a smaller TIR/FUV ratio and thus we would predict a smaller attenuation. While both these effects could have contributed to the differences we
Fig. 14. From top to bottom: (FUV−iSDSS) map, logarithmic TIR/FUV map, and $A_{\text{FUV}}$ attenuation map. Color bars indicate the range of values spanned by the quantities using a linear scale. The first two maps are derived combining the FUV, iSDSS and all the infrared maps used in this work. The regions shown here have $S/N > 1$, FUV/NUV > 0.3 and $1 < F_{\text{FUV}}^8/F_{\text{FUV}}^{24} < 10$, and avoid bright sources detected in the iSDSS band (black dots). The last map shows the attenuations $A_{\text{FUV}}$ derived using the recipes of Cortese et al. (2008) and the two above maps. The attenuation is maximum in the 10kpc ring where it reaches a mean value of $2.5 \pm 0.7$ mag, and declines more strongly towards the inner regions of the galaxy than towards the outer regions.

see in Fig. 13 the general good agreement of these results telling us that these effects are not dramatically changing our conclusions. As we have shown in the previous sections old populations are overall dominating the radiation field, so good results can be obtained if the color is fixed to the one of an old population as done in Xu & Helou (1996). The scattering should affect mostly young stars embedded in the dust, and thus mainly in the spiral-ring structure, but as the radiation field of these stars is never dominant the effect should be limited. Finally we should remind that we are comparing results obtained at different spatial resolutions (40″/px in our case and 2″/px in the case of Xu & Helou 1996) and that the accuracy of Spitzer, GALEX and SDSS maps is certainly larger than the measurements used by Xu & Helou (1996). In particular using IRAS images the cold dust emission and thus the TIR emission should be less accurately constrained than using Spitzer data as the longest wavelength measurement of IRAS is at 100µm whereas for Spitzer is at 160µm close to the FIR spectrum peak of M31 (Fig. 3). In Fig. 13 we show also the comparison of our results with those of Hodge & Lee (1998) who used two color diagrams to determine the average reddenings of 5 fields at different M31 galactocentric distances. We converted the reddening values of Hodge & Lee (1998) to the optical depths along the line of sight ($\tau_v$) by multiplying a factor of $2 \times 0.921 \times 2.8$ as in Xu & Helou (1996), then
we proceeded as before to convert the $\tau_v$ to $A_{FUV}$. Although the radial trend always peaks at 10kpc a larger scatter with respect to the results of Xu & Helou (1996) is visible. This may be anyway accounted by the fact that both us and Xu & Helou (1996) are analyzing radial averages whereas the results of Hodge & Lee (1998) are based on 5 selected regions.

The 10kpc ring is the locus where also gas density and star formation activity are maximum across the disk of M31 (e.g. Braun et al. 2009; Nieten et al. 2006; Reddish 1962; Hodge 1979; Hodge & Lee 1988) thus is not surprising to admit that also the dust density peaks at the ring as obtained also in previous studies.

Another limitation of the approach we followed consists in the assumption that each one of the cells we analyzed is independent from the others, and thus the radiation field of each region is the only responsible for the dust heating in that region. As the mean free path of photons is typically larger than the dimension of the regions here analyzed (40' / px, ~ 670 pc/px), it is possible that photons coming from nearby bright regions could contribute significantly to dust heating. Nevertheless this effect is likely to have a limited impact on our conclusions. At first because dust...
heated by stars in star forming regions is not the dominant source of emission in the FIR in M31, as given by the fact that the hot dust component emission at 24μm is overall < 7% of the TIR emission as shown in Sec. 3.1. Second of all the smooth distribution of the M31 surface brightness in the optical (λ > 4000Å from where most of the dust-heating radiation comes) suggests the hypothesis of homogeneous conditions among adjacent regions for which a local equilibrium between photon transmitted and received in closely regions can be assumed.

Finally, using the correlation between the 24μm and the TIR emission shown in Fig. 6 we derived the reddening map of M31 at 6′/px (Fig. 17). We then applied the reddening correction to the observed SDSS map (Fig. 18). The most prominent dust lanes and absorption features are clearly addressed by the reddening map, and the ring emission at 10kpc gains importance. Note that in Fig. 17, 18 we show the whole maps for clarity, but regions where optical, UV and infrared point-like sources are visible are not reliable. We discussed the issue of contaminants and how we corrected for them in Sec. 2.

6. Conclusions

In this paper we have explored some properties of the dust in M31. The major results we reached are the following: (i) from the study of the infrared spectrum of M31 we have obtained that the mean intensity of the radiation field that is heating the dust is globally low (typically U < 2); (ii) the dust mass (M_dust) estimate remains uncertain due to the lack of submillimetric observations, but we have obtained that M_dust ≳ 1.1 × 10^7 M_⊙, the value given by the best fitting model being 7 × 10^7 M_⊙ in good agreement with what inferred from CO and HI observations; (iii) the abundance of Polycyclic Aromatic Hydrocarbon (PAH) particles in M31 is high (> 3% M_dust) across the spiral- ring structure of M31; (iv) we demonstrated the existence of a correlation between the observed TIR/FUV emission ratios and the color (FUV − iSDSS) overall the spiral-ring structure of M31; (vi) this correlation is not in agreement with the IRX − β relationship of starburst galaxies, thus color changes are in general not driven by dust attenuations; (v) we found that according to the prescription of models which consider the age-dependent dust heating the observed correlation could be explained as the evidence of the presence of a population gradient and of a quite homogeneous attenuation of the analyzed regions; (vi) in 83% of the regions comprised between 8kpc < r < 12kpc the dust absorbs more than 50% of the energy at λ > 4000 Å, and it appears mainly heated by populations a few Gyr old and this could provide a good interpretation to the low mean intensity of the radiation field we found from the independent analysis of the infrared spectrum; (vii) we determined that the mean attenuation on 2kpc-wide radial bins reaches the maximum value near 10kpc and decreases faster in the inner than in the outer regions of the galaxy, and that regions with larger TIR emission have also enhanced attenuations; (viii) finally we derived an attenuation map of M31 at 6′/px resolution (∼ 100 pc/px along the plane of M31).

Future contributes will investigate in more detail the dependence of the dust attenuation values from other parameters (e.g. color, metallicity), the star formation rate and the modellization of the stellar populations in M31.

The maps presented in Fig. 14 and the E(B-V) map of Fig. 17 are available via CDS.

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Fig. 17. E(B-V) map at $6''$/px resolution ($\sim 100$ pc/px along the plane of M31).

Fig. 18. Upper panel: original SDSS image in the i-band. Lower panel: SDSS i-band image deredenned with our extinction map. For clarity all regions have been shown here. Regions with bright point-like sources and/or with occasional negative fluxes in some (UV/Optical/IR) maps (black regions) are not reliable. The colorbar shows intensity levels in Jansky in logarithmic units. Images have $6''$/px resolution.
Table 2. Measurements of M31 infrared integrated fluxes obtained using IRAC (Barmby et al. 2006), MIPS (Gordon et al. 2006), COBE (Odenwald et al. 1998), IRAS (Rice et al. 1988), MSX (Kraemer et al. 2002) and ISO (Haas et al. 1998) instruments. The last column shows our own measurements derived from IRAC and MIPS observations. We measured the integrated flux in an ellipse of semi-major axis 84′ and semi-minor axis 18′ centered on M31 with a position angle of PA = 38°.

| λa (µm) | λa,min (µm) | λa,max (µm) | This work (Jy) | IRAC (Jy) | MIPS (Jy) | COBE (Jy) | IRAS (Jy) | MSX (Jy) | ISO (Jy) |
|---------|-------------|-------------|----------------|-----------|-----------|-----------|-----------|---------|---------|
| 1.27    | 1.1         | 1.5         | 534 ± 107      | 461 ± 92  | 245 ± 49  |           |           |         |         |
| 2.22    | 2.0         | 2.4         |                |           |           |           |           |         |         |
| 3.53    | 3.0         | 4.1         |                |           |           |           |           |         |         |
| 3.55    | 3.2         | 3.9         | 239±29         | 259±32    |           |           |           |         |         |
| 4.88    | 4.5         | 5.3         |                |           |           |           |           |         |         |
| 4.49    | 4.0         | 5.0         | 144±20         |           |           |           |           |         |         |
| 5.73    | 5.0         | 6.5         | 190±35         |           |           |           |           |         |         |
| 7.87    | 6.4         | 9.5         | 149±27         | 151±21    |           |           |           |         |         |
| 8.5     | 6.0         | 10.9        |                |           |           |           |           |         |         |
| 12.0    | 7.6         | 15.4        | 163±24         |           |           |           |           |         |         |
| 23.7    | 20.5        | 28.5        | 118±17         | 107 ± 11  | 108±16    |           |           |         |         |
| 56.0    | 38.6        | 76.5        |                | 700 ± 140 |           |           |           |         |         |
| 60.0    | 37.0        | 82.8        |                | 536 ± 80  |           |           |           |         |         |
| 71.4    | 55.1        | 91.6        | 1086 ± 256     | 940 ± 188 |           |           |           |         |         |
| 97.7    | 68.6        | 121.8       |                | 3706 ± 741|           |           |           |         |         |
| 100.0   | 74.4        | 130.6       |                | 2928 ± 439|           |           |           |         |         |
| 155.9   | 128.9       | 184.0       | 7315 ± 1632    | 7900 ± 1580|           |           |           |         |         |
| 147.9   | 108.2       | 181.7       | 7545 ± 1509    |           |           |           |           |         |         |
| 175.0   | 140.0       | 220.0       |                | 7900 ± 800 |           |           |           |         |         |
| 247.9   | 174.7       | 335.9       |                |           |           |           |           |         |         |

* The wavelengths reported in the first column are the nominal wavelengths of each instrument waveband. The minimum and maximum wavelengths reported in the second and third columns correspond to a system response (filter+detector) equal to 10% the maximum. In particular the system response functions were taken for Spitzer/IRAC from http://ssc.spitzer.caltech.edu/irac/spectral_response.html, for Spitzer/MIPS from http://ssc.spitzer.caltech.edu/mips/MIPSfiltsumm.txt, for COBE/DIRBE from http://lambda.gsfc.nasa.gov/data/cobe/dirbe/ancil/spec_resp/DIRBE_SYSTEM_SPECTRAL_RESPONSE_TABLE.ASC, for IRAS from http://irsa.ipac.caltech.edu/IRASdocs/exp.sup/ch2/tabC5.html, for MSX/SpiritIII from http://irsa.ipac.caltech.edu/data/MSX/docs/MSX_psc_es.pdf (Appendix A, Table A-3), for ISO/ISOPHOT from http://www.mpia.de/ISO/welcome.html.

* Uncertainties in this table have been directly taken from the literature when available. For COBE measurements we assumed an error equal to 20% of the measured flux in each band as suggested by Odenwald et al. (1998) and for IRAS measurements equal to 15% as suggested by Rice et al. (1988). For our own measurements the uncertainties have been derived as detailed in the text.

Table 3. Average values and standard deviation (in parenthesis) of lg(TIR/FUV), (FUV − iSDSS) and A_{FUV} in each annular region shown in Fig. 12 (upper panel). The fifth and sixth columns show the linear regression parameters obtained fitting the data in Fig. 12 (bottom panel) with the relation lg(TIR/FUV) = a(FUV − iSDSS) + b. The last column shows the number of regions used in each annulus.

| R(kpc) | lg(TIR/FUV) | (FUV − iSDSS) | A_{FUV} | a   | b   | N.Reg. |
|--------|-------------|---------------|---------|-----|-----|--------|
| 1.0    | 2.13 (0.11) | 7.51 (0.07)   | 1.20 (0.14) | -   | -   | 9     |
| 3.0    | 2.15 (0.16) | 7.18 (0.45)   | 1.31 (0.16) | 0.38 (0.13) | -0.55 (0.93) | 115 |
| 5.0    | 2.12 (0.28) | 6.68 (0.70)   | 1.50 (0.30) | 0.41 (0.11) | -0.62 (0.74) | 381 |
| 7.0    | 2.05 (0.23) | 6.18 (0.75)   | 1.71 (0.40) | 0.32 (0.10) | 0.10 (0.64) | 590 |
| 9.0    | 2.03 (0.26) | 5.66 (0.71)   | 2.06 (0.44) | 0.37 (0.15) | -0.05 (0.88) | 879 |
| 11.0   | 1.91 (0.24) | 4.96 (0.68)   | 2.45 (0.47) | 0.42 (0.24) | -0.19 (1.21) | 1200 |
| 13.0   | 1.81 (0.26) | 4.84 (0.69)   | 2.37 (0.47) | 0.47 (0.27) | -0.45 (1.35) | 1228 |
| 15.0   | 1.61 (0.22) | 4.63 (0.64)   | 2.17 (0.28) | 0.35 (0.10) | 0.03 (0.47) | 1380 |
| 17.0   | 1.59 (0.21) | 4.66 (0.80)   | 2.06 (0.33) | 0.28 (0.09) | 0.29 (0.42) | 615 |