

Ultraviolet dust attenuation in spiral galaxies: the role of age-dependent extinction and the initial mass function

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Accepted 2006 November 20. Received 2006 September 19; in original form 2005 December 20

ABSTRACT

We analyse the attenuation properties of a sample of ultraviolet (UV) selected galaxies, with the use of the spectrophotometric model GRASIL. In particular, we focus on the relation between dust attenuation and the reddening in the UV spectral region. We show that a realistic modelling of geometrical distribution of dust and the different population of stars can explain the UV reddening of normal spiral galaxies also with a standard Milky Way dust. Our results clearly underline that it is fundamental to take into account that younger stars suffer a higher attenuation than older stars (the age-dependent extinction) because stars are born in more-than-average dusty environments. In this work, we also find that the concentration of young stars on the galactic plane of spirals has a relevant impact on the expected UV colours, impact that has not been explored before this paper. Finally, we discuss the role of the initial mass function (IMF) in shaping the relation between UV reddening and dust attenuation, and we show that a Kroupa IMF is more consistent with observed data than the classical Salpeter IMF.

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

1 INTRODUCTION

One of the main quantities characterizing the physical and evolutionary status of galaxies is their star formation rate (SFR). Since long, many recipes to estimate the SFR, using data taken in various spectral windows, either in the continuum or in emission lines, have been considered (e.g. Kennicutt 1998; Hirashita, Buat & Inoue 2003; Panuzzo et al. 2003). One obvious possibility is to use ultraviolet (UV) radiation, since even in moderately actively star-forming systems, such as normal spirals, this radiation is expected to be dominated by short-lived massive stars, which therefore should trace the past 10^8 yr of star formation activity. The drawback of this approach is that the UV radiation is strongly affected by dust obscuration. The issue is particularly delicate because stars are formed in more-than-average dense regions, and therefore they are particularly affected by obscuration during their early evolution. Indeed it is now well established that in infrared (IR) bright galaxies, such as ultraluminous infrared galaxies or submm-selected high- z galaxies, the UV flux alone is hardly or not at all a reliable indicator of the SFR (e.g. Flores et al. 1999; Goldader et al. 2002), and even in

normal spirals it should be used with proper care (Buat & Xu 1996; Bell & Kennicutt 2001; Bell 2002; Buat et al. 2002).

In particular, when dealing with the dust obscuration in the UV domain, (i) it has to be taken into account that the relative geometry of stars and dust depends on the age of the stars (age-dependent extinction;¹ Silva et al. 1998), and (ii) it has to be understood if the dust optical properties adopted to interpret the data are well representative of the particular system. Actually, it is very difficult to disentangle from observation of external galaxies the effects of dust optical properties from those due to their complex geometry (and possibly those due to the star formation history). It is therefore advisable to clearly distinguish the attenuation law of a galaxy from the extinction law of the dust. While the latter describes just the wavelength dependence of the optical properties of the dust mixture, the former is the ratio (expressed in magnitudes) between the observed and intrinsic starlight, as a function of wavelength. This would be a direct measure of the extinction law only if the stars were obscured by a thin screen of dust between them and the observer, in general an extremely idealized situation.

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¹ Sometimes called also age-*selective* extinction.

For our own and a few nearby galaxies, the extinction law of the dust can be measured directly from observations of background stars, where indeed the dust acts as a foreground screen. The differences found between the shapes of the extinction curves of the Galaxy, the Large Magellanic Cloud and the Small Magellanic Cloud (SMC) below $\lambda \lesssim 2600 \text{ \AA}$ (Fitzpatrick 1989) are often ascribed to the different metallicities in these systems, covering the range $Z \sim 0.1-1 Z_{\odot}$. Calzetti, Kinney & Storchi-Bergmann (1994) have analysed the dust attenuation in starburst galaxies. In this case, the derivation of the intrinsic extinction is not direct, since one measures the integrated light of the whole system, where stars and dust are mixed in a complex way. From the optical and UV spectra of a sample of UV-bright starbursts, they derive an average attenuation law (Calzetti law) characterized by the absence of the 2175- \AA feature and a far-UV (FUV) slope (above the bump) shallower than that of the Milky Way extinction law.

Gordon, Calzetti & Witt (1997) argued that the observed shape of the Calzetti law can only be explained with dust that lacks the 2175- \AA feature in its extinction curve. However, they only considered clumping of dust, not of stars, and assumed a spatial distribution for stars independent of stellar age. Indeed a completely different conclusion has been reached by Granato et al. (2000), by means of the first spectral synthesis model for the entire UV-to-IR domain taking into account the effect of age-dependent extinction (GRASIL; Silva et al. 1998). Granato et al. (2000) (see also Panuzzo 2003) have shown that this more realistic geometry can explain the differences between the observed attenuation law of starburst galaxies and the galactic extinction law, even adopting the galactic cirrus optical properties. Note that this by no means demonstrates that the optical properties of dust in starbursts are well represented by the average cirrus dust in the Galaxy, but rather than any difference may be completely masked by geometrical effects. In this interpretation, the attenuation law of a specific stellar system arises, via the age-dependent extinction, from a complex blending of optical properties of dust, star formation history and relative geometry of stars and dust, including clumping of both components. The relative importance of these ingredients is a function of the evolutionary status of the galaxy. In very active systems the first ingredient is of little relevance, because much of the intrinsic optical-UV starlight is produced by stars embedded in molecular clouds, completely opaque at these wavelengths (see Section 4.2). Conversely, more gently star-forming galaxies, such as normal spirals, are expected to be better candidates to investigate variations of dust properties, provided that a sufficiently realistic geometry is used in their modelling.

Further clues on these complexities can be derived considering that different classes of galaxies lie in different regions of the plane defined by the ratio of IR and UV fluxes $F_{\text{IR}}/F_{\text{UV}}$ and the UV spectral slope β (or, equivalently, a UV colour).

Meurer, Heckman & Calzetti (1999) found that UV bright starburst galaxies follow a well-defined correlation between the $F_{\text{IR}}/F_{\text{UV}}$ and β . These authors noted that their relation implies an attenuation law with a slope around 1600 \AA very different from the Milky Way extinction law, and more similar to the Calzetti law (that was derived using some galaxies belonging to the same sample). Also Charlot & Fall (2000) explained the $F_{\text{IR}}/F_{\text{UV}}$ versus β relation in these objects using a featureless power-law extinction law.

If the correlation found by Meurer et al. (1999) were a general property of galaxies, it would allow us to reliably estimate the SFR of galaxies from UV data alone. However, it is now established that this relationship is not a general property. In particular, luminous IR

galaxies have $F_{\text{IR}}/F_{\text{UV}}$ ratios orders of magnitude higher than UV bright starbursts with the same β (Goldader et al. 2002; Burgarella et al. 2005a). Thus for these objects the procedure would lead to severe underestimates of the actual SFR.

On the other hand, Bell (2002) and Kong et al. (2004) collected data from different UV space experiments and found that normal spirals are even redder than the $F_{\text{FIR}}/F_{\text{UV}}$ versus β relation found for UV bright starbursts. Kong et al. (2004), using the simple model by Charlot & Fall (2000), ascribed this difference to the lower ratio between the recent over average star formation activity. Note that they used the same featureless extinction law assumed for starburst galaxies.

The *Galaxy Evolution Explorer* (GALEX) (Martin et al. 2005) provides very useful data to study this problem. In particular, the UV slope can be estimated from data taken in the near-UV (NUV) and FUV GALEX bands. It is worth noting that the NUV filter, centred at 2310 \AA , is strongly affected by the presence of the 2175- \AA bump in the MW extinction law. Buat et al. (2005) and Seibert et al. (2005) (see also Cortese et al. 2006) confirmed with first GALEX observations that normal spirals do not follow the $F_{\text{FIR}}/F_{\text{UV}}$ versus β relation found for UV bright starbursts and that the position of objects in the diagram depends on the selection criteria. Finally, Calzetti et al. (2005) found that also star-forming regions within NGC 5194 do not follow the above starburst relation.

In this paper, we use the relatively sophisticated spectral synthesis model GRASIL to interpret the UV and far-IR (FIR) properties of normal spiral galaxies. We will show that these properties can be explained without invoking strongly non-standard dust, provided that a sufficiently detailed (but realistic) description of the geometry of the system is employed. Conversely, these properties would require in some sense extreme assumptions about the dust composition if a simplistic geometry were adopted. In particular, we will show the effect of taking into account that in normal spirals stars younger than $\sim 10^8$ yr are confined in a thin disc with a smaller scaleheight than older stars and diffuse medium. The different attenuations suffered by young and old stars have a relevant impact on UV colours, a fact that has not been considered in any of the above-mentioned works (see Buat & Xu 1996, for an analysis of the effect on dust attenuation estimation).

We will also discuss the role of the initial mass function (IMF) showing that an IMF with less massive stars than a Salpeter one can be more consistent with data. In particular, we will show that this makes the cirrus more efficient in attenuating young stars and reddening the final spectral energy distributions (SEDs).

This paper has the following structure. In Sections 2.1 and 2.2, we describe the data sample we consider for our analysis. In Section 3, we describe our spectrophotometric model for dusty galaxies, GRASIL. In Section 4.1, we apply our code to study different geometrical configurations of dust and stars and the relevance of an age-dependent extinction to explain the data. Furthermore, in Section 4.2 we discuss the attenuation law resulting from our models, and in section 4.3 we discuss the role of the IMF. Finally, in Section 5 we summarize and discuss the results of this work.

2 THE GALEX NUV-SELECTED SAMPLE

2.1 The data

The galaxy sample we consider in our analysis is derived from the first observations of the GALEX mission and from IRAS observations. The GALEX data are photometric measurement in two UV

bands: the FUV band (1350–1750 Å, $\lambda_{\text{mean}} = 1520$ Å) and the NUV band (1750–2750 Å, $\lambda_{\text{mean}} = 2310$ Å).

The sample was presented in Buat et al. (2005) and Iglesias-Paño et al. (2006); it consists in 59 galaxies selected on the basis of the NUV flux ($m_{\text{NUV}} \leq 16$ mag, AB system). Here, we only summarize the main information about the sample, more details on the sample can be found in Iglesias-Paño et al. (2006).

The galaxy fluxes in the sample were extracted from the *GALEX* All-Sky Imaging Survey (Martin et al. 2005) and corrected for the foreground Galactic extinction using the Schlegel, Finkbeiner & Davis (1998) dust map and the Cardelli, Clayton & Mathis (1989) extinction curve. Sources were identified using the SIMBAD, 2MASS² and PGC catalogues; the same catalogues were used to determine the morphological types of the sample galaxies. Two ellipticals, four Seyferts and one quasi-stellar object were discarded. The FIR fluxes of the remaining sources were taken from the *IRAS* Faint Source Catalogue (version 2) (Moshir et al. 1990) and the Scan Processing and Integration Facility (SCANPI) at 60 and 100 μm . We excluded from the sample multiple UV sources not resolved as single objects by *IRAS* and sources contaminated by cirrus. Complementary data in visible are taken from HyperLeda,³ while *H* magnitudes are from 2MASS.

2.2 The observed IRX– β diagram

In this paper, we will focus on the relation between $F_{\text{IR}}/F_{\text{UV}}$ and β , already called the IRX– β diagram. For this purpose, we will express the ratio $F_{\text{IR}}/F_{\text{UV}}$ with the ratio between F_{TIR} , i.e. the total dust emitted flux estimated from *IRAS* 60 and 100 μm fluxes following the prescription of Dale et al. (2001), and F_{FUV} , the observed flux in the *GALEX* FUV band. Moreover, we will express the UV spectral slope β with the NUV–FUV colour.

The IRX– β diagram as seen by *GALEX* for these NUV-selected galaxies was presented in Buat et al. (2005) and Burgarella, Buat & Iglesias-Paño (2005b). Here we would like to underline the effect of the star formation activity on the diagram.

As already mentioned, Kong et al. (2004) suggested that the displacement between normal spiral galaxies and starburst in the $F_{\text{IR}}/F_{\text{UV}}$ versus UV colour is due to the different ratio between the recent over average star formation activity. This ratio is quantified by the birthrate parameter b (Kennicutt, Tamblyn & Congdon 1994), defined as the ratio between the present SFR and the mean SFR ($\langle\text{SFR}\rangle$) in the past:

$$b \equiv \frac{\text{SFR}}{\langle\text{SFR}\rangle}. \quad (1)$$

As for the present SFR, it can be derived from the NUV luminosity, properly corrected for dust attenuation using the ratio IR/UV. From our simple stellar populations (SSP) library (see Section 3), we computed the NUV luminosity of a constant SFR lasting 100 Myr, assuming a Salpeter IMF from 0.1 to 100 M_{\odot} . The relation between SFR and L_{NUV} we got is

$$\log \frac{L_{\text{NUV}}}{1 L_{\odot}} = \log \frac{\text{SFR}}{1 M_{\odot} \text{ yr}^{-1}} + 9.356. \quad (2)$$

² The Two-Micron All-Sky Survey is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

³ HyperLeda data base is available at the URL <http://leda.univ-lyon1.fr>

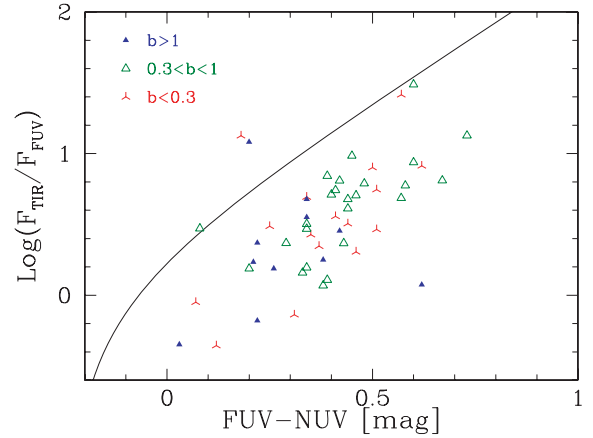


Figure 1. IRX– β diagram for the NUV-selected sample. Filled triangles are objects with a birthrate parameter b larger than 1.0; empty triangles represent objects with $0.3 < b < 1.0$, while stars represent objects with $b < 0.3$. The solid line represents the Meurer et al.’s UV bright starburst sequence converted into *GALEX* bands (see the text for more details).

As discussed by many authors (e.g. Buat & Xu 1996; Buat et al. 1999; Panuzzo et al. 2003), the ratio IR/UV is a good estimator of the UV attenuation. We used here the relation proposed by Buat et al. (2005)

$$A_{\text{NUV}} = -0.0495x^3 + 0.4718x^2 + 0.8998x + 0.2269, \quad (3)$$

where $x = \log(F_{\text{TIR}}/F_{\text{NUV}})$. Finally, the mean SFR can be derived from the *H* luminosity as shown by Boselli et al. (2001).

The resulting mean value of b for our NUV-selected sample is $b \sim 0.5$, typical of normal late-type spirals, confirmed by the morphological classification (see Iglesias-Paño et al. 2006, for discussion). Also the IR colours of our sample objects indicate a mild level star formation activity.

The position of sample galaxies in the IRX– β diagram is shown in Fig. 1, where we have used different symbols for objects having $b < 0.3$, $0.3 < b < 1.0$ and $b > 1$.

In the same diagram, we show the UV bright starburst sequence of the Meurer et al. (1999) sample, where the UV spectral index was converted into the FUV–NUV colour following Kong et al. (2004). Thus the starburst relation is given by

$$\frac{F_{\text{TIR}}}{F_{\text{FUV}}} = 10^{0.4+1.87(\text{FUV}-\text{NUV})} - 0.95. \quad (4)$$

It is worth noting that (i) most of the galaxies have a redder FUV–NUV colour than what expected by the starburst relation, regardless of their birthrate parameter value; (ii) galaxies with a small birthrate parameter are not systematically redder than more active galaxies. These two statements contrast with what predicted by Kong et al. (2004), i.e. that galaxies with birthrate $b \sim 1$ should follow the starburst relation, while galaxies with $b \geq 0.3$ should be redder. There are some explanations for this disagreement. As discussed in Burgarella et al. (2005b), the NUV flux used in the computation of the birthrate parameter is produced by all stellar populations with an age smaller than ~ 100 Myr, so the present SFR is estimated with an average over the last ~ 100 Myr. In the presence of a star formation history with significant variations in this interval of time, the SFR estimated with the NUV flux could not

be representative of the instantaneous SFR. However, the observed FUV–NUV colour is due to a complex interplay between the star formation history *and* the effect of the dust attenuation (as discussed in the following sections), so it is not clear if our birthrate parameter estimation is fully representative for the IRX– β diagram. Indeed, Cortese et al. (2006) analysed the relation between the distance from the starburst relation and the birthrate parameter computed using the H α flux (thus using an estimate of instantaneous SFR), but they found only a weak correlation for normal star-forming galaxies.

Another possible factor in this disagreement is that equation (4) for the Meurer et al. sample was obtained by translating the Meurer’s definition of β into the FUV–NUV colour, and not by observing the same sample with *GALEX*. Indeed, Calzetti et al. (2005) proposed an alternative conversion of the UV spectral index into the FUV–NUV which provides a redder colour for the UV bright starburst sequence. Thus, we think that equation (4) should be verified with *GALEX* observations.

3 SED OF GALAXIES: GRASIL

We compute the SEDs of galaxies using our code GRASIL. GRASIL⁴ is a population synthesis model to predict the time-dependent SEDs of galaxies from FUV to radio, including state-of-the-art treatment of all relevant aspects dust reprocessing (Silva et al. 1998; Granato et al. 2000; Vega et al. 2005), production of radio photons by thermal and non-thermal processes (Bressan, Silva & Granato 2002) and nebular lines emission (Panuzzo et al. 2003). We refer the reader to the original papers for details, but we summarize for convenience the main features.

The starting input for GRASIL is the history of star formation and chemical enrichment histories of the system. This is computed by an external code, which can result from a complex scenario for the formation of galaxies in a cosmological context (e.g. Granato et al. 2000, 2001, 2004), or a standard chemical evolution model for the formation of a single galaxy. Here, as in Silva et al. (1998), we follow the latter approach. Our chemical evolution model is a standard implementation of a one-zone open model including infall of primordial gas (see Silva et al. 1998, and references therein). The parameters regulating the star formation history are the baryonic mass of the galaxy (M_G), the gas infall time-scale (τ_{infall}) and the star formation efficiency (ν_{sch}) of the assumed Schmidt law.

Once the star formation and chemical enrichment histories of a galaxy are given, GRASIL computes the interaction between the stellar radiation and dust using a relatively realistic and flexible geometry for both stars and dust.

One of the most important distinctive features of GRASIL is that it included, for the first time, the effect of age-dependent extinction of stellar populations (younger stellar generations are more affected by dust obscuration), due to the fact that stars form in a denser-than-average environment. In particular, new stars are born inside MCs and progressively get rid of them, either because they escape or because the clouds are destroyed. This is described in GRASIL as follows. If t_{esc} is the time-scale for the process, the fraction of starlight radiated inside the clouds at time t after they formed is

given by

$$F(t) = \begin{cases} 1 & \text{for } t < t_{\text{esc}} \\ 2 - t/t_{\text{esc}} & \text{for } t_{\text{esc}} < t < 2t_{\text{esc}} \\ 0 & \text{for } t > 2t_{\text{esc}} \end{cases} \quad (5)$$

In practice, 100 per cent of the stars younger than t_{esc} are considered to radiate inside the MCs, and this percentage goes linearly to 0 per cent in $2t_{\text{esc}}$. The time-scale t_{esc} is a fundamental parameter, which was found longer in a handful of well-studied local starburst than in normal disc-like galaxies by a SED fitting procedure (Silva et al. 1998; Silva 1999).

The galaxies’ geometry in GRASIL is generally described as a superposition of an exponential disc component and a bulge component; the latter modelled by a King profile.

The stars and dust density in the exponential disc component are given by the following equation:

$$\rho = \rho_0 \exp(-R/R_d) \exp(-|z|/z_d), \quad (6)$$

with ρ_0 being the central density, R_d and z_d are the scalelength along the radial and normal directions, respectively. The code allows us to specify different values for R_d and z_d for stars and dust.

Up to now, we have only considered the contribution of molecular clouds to the age-dependent extinction, which is indeed the most prominent, at least in very active systems. In this paper, we show that to interpret the UV spectral shape of spiral galaxies, it is necessary a further step, namely to consider the fact that MCs are concentrated in the galactic plane, and therefore the same is true for young stars already free from their parent MC. As a result, though free from MCs obscuration, these stars are more extincted by the diffuse medium than older populations.

We model this geometrical configuration by dividing the star content of the galaxy into two populations, according to their age. If t_{thin} is the time-scale on which young stars stay concentrated on the galactic plane, we assume two different scalelengths sets (R_d and z_d) for stars younger or older than t_{thin} .

The total gas mass (diffuse + MCs) of the galaxy at time T_G is given by the chemical evolution model. The relative fraction of molecular gas is a free parameter of the code, f_{mc} . The total molecular mass, M_{mc} is then subdivided into spherical clouds of mass and radius, m_c and r_c . Then, the radiative transfer of starlight through the MCs and diffuse interstellar medium (ISM) is solved.

The ratio between gas mass and dust mass G/D is assumed to scale linearly with the metallicity of the residual gas and $G/D = 1/110$ for $Z = Z_{\odot}$. This ratio plus m_c/r_c^2 determine the optical depth of the clouds. Note that in GRASIL, the predicted SED depends on m_c and r_c only through the combination m_c/r_c^2 , which is the true free parameter.⁵

For the dust composition, we adopt a mixture of graphite and silicate grains and polycyclic aromatic hydrocarbons (PAHs). In general, the size distributions are adjusted to match the extinction and emissivity properties of the local diffuse ISM in the Galaxy (for more details see Silva et al. 1998; Vega et al. 2005 for the improved model of PAHs), but we have also considered other possibilities (see Section 4.1).

The SSPs included in GRASIL are based on the Padova stellar models, and cover a large range of ages and metallicities. Starlight

⁴ The code is available at the URL <http://web.oapd.inaf.it/granato> or <http://adlibitum.oat.ts.astro.it/silva/default.html>. It can be run also with an user friendly web interface, GALSYNTH, available at the URL <http://web.oapd.inaf.it/galsynth>.

⁵ In Silva et al. (1998) as well as in the present paper, we found sufficient to consider a single *population* of MCs all with the same parameters, but GRASIL treats in general many populations each with different properties. Of course, this would add more parameters.

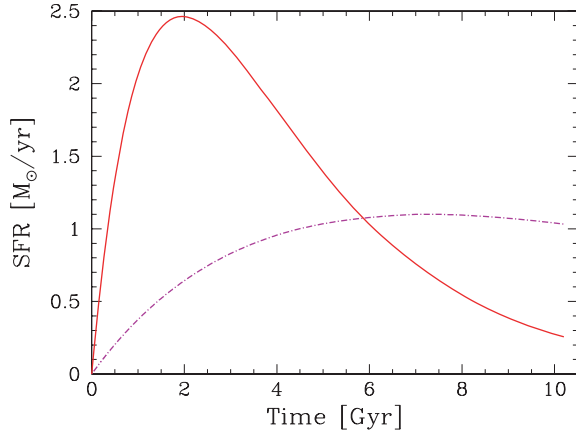


Figure 2. Star formation histories used in our models. Solid line is for a birthrate parameter $b = 0.25$, dot-dashed line is for $b = 1.25$.

Table 1. Geometrical parameters for the models. Note that set B models do not have diffuse dust, thus they do not depend on R_d or z_d .

	Set A	Sets C and D
R_d^{stars}	1 Kpc	1 Kpc (young), 2 Kpc (old)
z_d^{stars}	50 pc	50 pc (young), 400 pc (old)
R_d^{dust}	1.5 Kpc	1.5 Kpc
z_d^{dust}	50 pc	100 pc

reprocessing from dust in the envelopes of asymptotic giant branch stars is included directly into the SSPs, as described by Bressan, Granato & Silva (1998).

4 INTERPRETATION OF THE GALEX IRX- β DIAGRAM

To interpret the IRX- β diagram, we computed different sets of disc galaxy models.

For simplicity, here we consider only two star formation histories (Fig. 2) with birthrate parameters $b = 1.25$ and 0.25 . These values span most of the observed spread of the birthrate parameters in the sample. We computed the SED at a galactic age of 10 Gyr for all models.

4.1 The role of dust and stars geometry

To illustrate the effects of relative stardust geometry, and in particular the age-dependent extinction, we consider four sets of model. For all models of this section (except the last one), we assume a Salpeter IMF.

In the first set (set A), we neglect any age-dependent extinction, i.e. all the dust is assumed to stay in the diffuse medium (cirrus), without molecular clouds, and the stars are smoothly distributed within this medium independently of their age. The geometrical distributions of stars and dust are exponential discs (for clarity, we do not include a bulge component), described by equation (6) with scale values reported in Table 1. The set consists of a sequence of models with increasing gas (and therefore dust) content.⁶ The parameter describing this sequence is the cirrus optical depth at

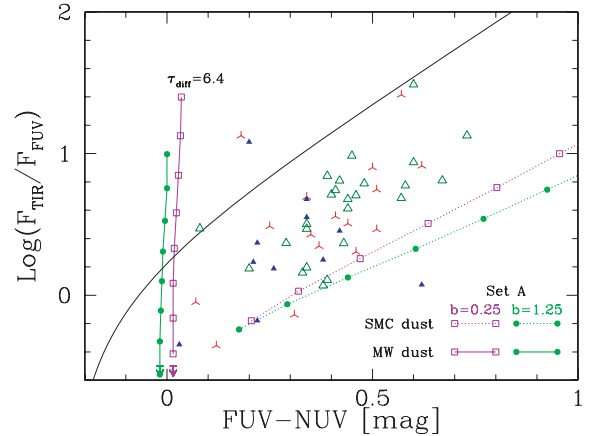


Figure 3. Comparison between the NUV-selected sample galaxies (as in Fig. 1) and set A models. Connected dots are for models with increasing optical depth of the diffuse medium.

1 μm from the centre along the polar axis, ranging from 0.05 to 6.4, and doubling between one model and the other. The models were computed for two choices of dust composition; one reproducing the MW extinction law, the other reproducing the extinction law of SMC (dust composition from Weingartner & Draine 2001). The position of models in the IRX- β diagram is shown in Fig. 3 (models connected with solid lines have a MW dust; those connected with dotted lines have a SMC dust), where NUV and FUV magnitudes have been computed taking into account the filter transmissions. All models in Fig. 3 are face-on, i.e. with the polar axis parallel to the line of sight. The two arrows show the FUV-NUV colour of dust-free models for the two star formation histories. Note that the dust-free FUV-NUV colour is redder than the zero-extinction colour for the UV bright starburst sequence due to the assumed continuous star formation.

Models with MW dust move in the diagram at nearly constant FUV-NUV colour as the dust content increases, while those with SMC dust become redder and redder. The lack of reddening for the MW dust case is due to the presence of the 2175- \AA bump in the extinction law that affects strongly the NUV band. In fact, the extinction in NUV is actually higher than in the FUV ($A_{\text{NUV}}/A_{\text{FUV}} = 1.14$) for a MW dust. From the figure, it is clear that a dust mixture somewhat intermediate between the MW and the SMC and more similar to the latter could reproduce the data points. A similar result was found by Witt & Gordon (2000), investigating the variation of the UV spectral index. They also found that this result does not depend on the relative geometry of dust and stars, which, however, was always age independent.

In the second set of models (set B), we begin to explore the role of the age-dependent extinction due to molecular clouds. In this set, we try to reproduce the observed IRX- β diagram of the UV-selected sample, assuming that all the gas is arranged in clouds obscuring young stars with no gas left in the cirrus. Here the sequence consists in models with increasing escape time, while the total amount of gas is that predicted by the chemical evolution code. The results are shown in Fig. 4: solid lines connect models (represented by circles or empty squares) with the same star formation history and gas amounts; the escape time increases from 0.5 to 64 Myr doubling

the value predicted by the chemical evolution code; in set A we specify the gas content by hand in GRASIL.

⁶ GRASIL allows us to specify at wish the gas content of the galaxy, or to use

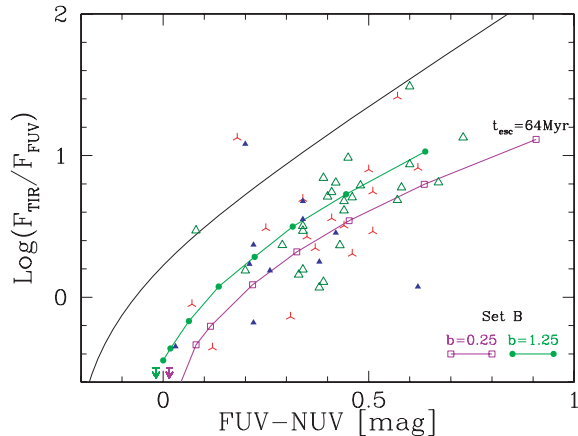


Figure 4. Comparison between NUV-selected sample galaxies (as in Fig. 1) and models with varying t_{esc} (set B). Connected dots are for models with $t_{\text{esc}} = 0.5, 1, 2, 4, 8, 16, 32$ and 64 Myr (the reddest models).

between one model and the other. The optical depth of MCs in the models is $\tau_{\text{MC}} = 20$ at $1 \mu\text{m}$; however, the position on the IRX- β diagram does not depend on the value of τ_{MC} provided that $\tau_{\text{MC}} \gtrsim 1.5$, because MCs are completely opaque at the *GALEX* wavelengths. Above this value, changes in the optical depth of MCs affect only the shape of the IR SED. It is also important to note that the position of this set on the IRX- β diagram is independent of the dust properties. In fact, FUV and NUV fluxes depend only on the escape time and the star formation history, while the F_{TIR} is nothing more than the bolometric luminosity of stars inside MCs.

To reproduce the reddest objects, very large values of the time-scale with which new stars get rid of their parent MCs are required, ($t_{\text{esc}} \geq 30$ Myr). This solution is unsatisfactory on astrophysical grounds, since stars whose lifetime is about one order of magnitude shorter than this are commonly observed in optical bands in quiescently star-forming galaxies. Moreover, the IR dust emission for these models is hotter than the observed SED: for all these models $\log(F_{60 \mu\text{m}}/F_{100 \mu\text{m}}) > -0.3$, while the observed mean value is $\log(F_{60 \mu\text{m}}/F_{100 \mu\text{m}}) \simeq -0.45$ with objects having down to $\log(F_{60 \mu\text{m}}/F_{100 \mu\text{m}}) \simeq -0.8$. This is a consequence of the assumed geometrical configuration of the dust that feels a stronger radiation field than in the diffuse medium, resulting in a higher temperature and hotter IR emission.

Our interpretation of the above results is that the assumption of age-independent extinction for all star populations outside MCs is not satisfactory. The very long escape time-scale from parent clouds tries to mimic the fact that in real spiral galaxies stars younger than $\sim 10^8$ yr are still very much concentrated in the galactic plane, and therefore they are more affected by extinction from the diffuse ISM than older ones.

Thus, in the third set of models (set C), we explored the effect of the smaller scaleheight of young star distribution in the disc. Here we assume that the dust is present only in the cirrus (no MC, like set A) and that stars younger than an age t_{thin} have a smaller scaleheight than older stars, while the dust scaleheight is in between. The scaleheights of different components are reported in Table 1. We computed SED models for different values of t_{thin} , ranging from 25 to 200 Myr. As in set A, we computed sequences of models with increasing dust content: the cirrus optical depth at $1 \mu\text{m}$ from the centre along the polar axis goes from 0.05 to 6.4, doubling between one model and the other. The models were computed for the same dust compositions of set A.

The comparison between the NUV-selected sample and set C models is shown in Fig. 5. For clarity, we showed the MW dust models and only one SMC dust model sequence. It is worth noting that, contrary to what happens in the set A models, increasing the diffuse medium optical thickness produces a reddening also in MW dust models. The results show that when the optical depth is low the UV SED is dominated by the young population, and the models move at constant FUV-NUV as the optical depth increases because the geometry is mixed. When the optical depth is high enough to attenuate considerably the young population, the contribution of stars older than t_{thin} (that have a larger scaleheight) becomes not negligible and the total SED becomes redder. However, models are still bluer than the observed sample.

It should also be noted that models with a larger value of t_{thin} have a larger $F_{\text{TIR}}/F_{\text{NUV}}$ (for the same value of FUV-NUV). In fact, if t_{thin} is larger, the young population embedded near the galactic plane is more luminous, thus a larger attenuation is needed to make the old stellar population contribution non-negligible.

In the last set of models (set D), we consider the combined effect of the smaller scaleheight of young star distribution in the disc and the age-dependent extinction due to molecular clouds. Here we assume

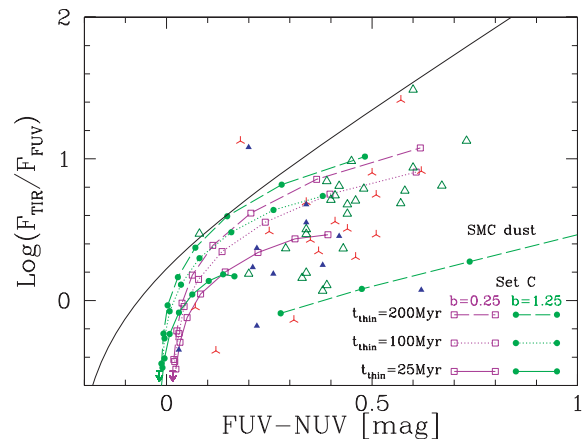


Figure 5. Comparison between NUV-selected sample galaxies and models with age-dependent scaleheight (set C). Connected dots are for models with increasing optical depth of the diffuse medium.

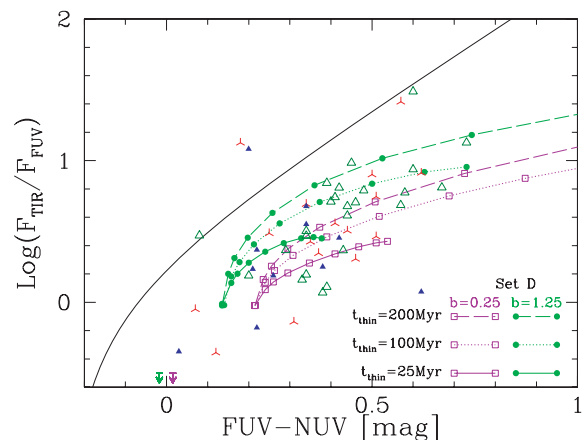


Figure 6. Comparison between NUV-selected sample galaxies and models with age-dependent scaleheights and molecular clouds with $t_{\text{esc}} = 4$ Myr (Set D). Connected dots are for models with increasing optical depth of the diffuse medium.

the same dust–star configuration used in set C, i.e. with young stars with a small scaleheight, but with the presence of molecular clouds with an escape time fixed to $t_{\text{esc}} = 4$ Myr. Again we computed sequences of models (see Fig. 6) with increasing dust content in the cirrus (dust content of MCs is fixed). The cirrus optical depth at $1 \mu\text{m}$ from the centre along the polar axis goes from 0.05 to 6.4 (except for the first models where we assume no cirrus), doubling between one model and the other.

It is worth noting that the presence of MCs increases the effect of cirrus dust and the models are more compatible with observations. In fact, the MC obscuration removes a significant fraction of UV luminosity from the young population; thus the optical thickness of cirrus needed to attenuate the young population outside MCs enough to make relevant the contribution of older stars is smaller than in set C, making the models redder.

In conclusion, in this section we have shown that inferences on the dust optical properties of galaxies derived from the analysis of the IRX– β diagram are dangerous, if the models are too schematic. In particular, the common (and unrealistic) assumption that starlight suffers the same reprocessing independently of the star age is strongly misleading.

4.2 The attenuation law

For a better understanding of the issue, we also analysed the attenuation law resulting from our models. The attenuation law A_λ in simulated galaxies is thus defined as the difference in magnitudes of the luminosity L_λ of models with and without dust.

Fig. 7 compares the attenuation curves for simulated galaxies of set C and with the attenuation law from Calzetti et al. (1994) and the MW extinction law. All curves are normalized to unity at $\lambda = 1600 \text{ \AA}$. The shadowed region shows the range of variation of the attenuation laws of the models with the variation of the parameters; the attenuation laws plotted in Fig. 7 are only for models with MW dust.

For set C models, the one with the larger bump in the attenuation law is the model with the smaller dust content. As the optical depth of dust increases, the bump strength decreases until it vanishes completely for highest optical depths. In fact, as the optical depth of dust

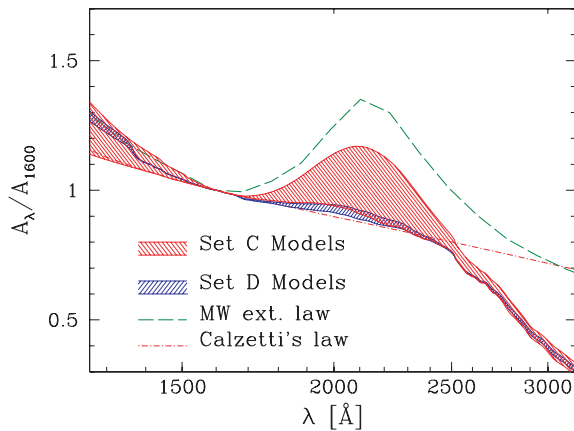


Figure 7. The attenuation curves for simulated galaxies of sets C and D with the attenuation law from Calzetti et al. (1994) (dot–dashed line) and the MW extinction law (long dashed line). All curves are normalized to unity at $\lambda = 1600 \text{ \AA}$. Our data enable us to study the attenuation curves only in the UV. Thus we can neither confirm nor disprove the deviations predicted by our models with respect to the MW extinction law and the Calzetti law above 2500 \AA .

increases, a growing fraction of the observed UV is produced by the older stellar population; this emission can fill the absorption feature in the SED of young population.

For set D models, indeed, the bump in attenuation law vanishes. In fact, in this case the attenuation is mostly due to MCs that are opaque at these wavelengths. Consider a system with two stellar populations, younger stars inside MCs and stars outside. The observed luminosity L_λ is given by

$$L_\lambda = \left[f_\lambda^y 10^{-0.4A_\lambda^y} + (1 - f_\lambda^y) 10^{-0.4A_\lambda^o} \right] L_\lambda^{\text{em}}, \quad (7)$$

where f_λ^y is the luminosity fraction of stars inside MCs, A_λ^y is the attenuation of stars inside MCs, A_λ^o is the one for stars outside and L_λ^{em} is the unextinguished luminosity. If the optical depth of MCs is very high and that towards the diffuse star population is very low, we have $L_\lambda \simeq (1 - f_\lambda^y) L_\lambda^{\text{em}}$. Thus A_λ is mostly independent of the dust properties and depends mostly on the luminosity fraction.

The prediction of a decreasing bump strength with increasing attenuation was also found in other works in the literature (e.g. Granato et al. 2000), even in the case where a uniform stellar population is assumed (Witt & Gordon 2000; Pierini et al. 2004). Note also that Burgarella et al. (2005b) found that the SEDs of NUV-selected normal spiral galaxies show an attenuation law with a reduced $2175\text{-}\text{\AA}$ bump. However, the above authors found that the bump strength seems to increase with increasing attenuation. This is probably due to the presence in their sample of a number of IR-selected galaxies with a blue FUV–NUV colour and high dust attenuation.

Finally, it could be noted that the attenuation laws from models decrease more steeply than the MW extinction law beyond 2500 \AA . This is due to the contribution (increasing with the wavelength) from older stars which suffer a much smaller attenuation than young stars thus decreasing the attenuation of the whole system. At this stage we cannot verify whether such a deviation is actually observed in our galaxies, as a comparison with data would require assumptions on the intrinsic, dust-free SEDs of normal spirals, which, at optical wavebands, strongly depend on their star formation history.

4.3 The role of IMF

We also explored the possibility of using a different IMF to interpret the observations.

Several works (see Portinari, Sommer-Larsen & Tantaló 2004, and references therein) claim that the properties of normal disc galaxies are not well reproduced using a Salpeter IMF. In particular, with a Salpeter IMF, chemical evolution models for disc galaxies produce higher mass-to-light ratios than the observed ones, and a too high efficiency in metal production. These problems can be alleviated by an IMF having a shallower slope at low masses and a steeper one at high masses. Among others, Kroupa (1998) proposed an IMF with the above characteristic, defined as (we use the formulation given by Portinari et al. 2004)

$$\frac{dn(m)}{d \log m} \propto \begin{cases} m^{-0.5} & \text{for } 0.1 < m < 0.5 M_\odot \\ m^{-1.2} & \text{for } 0.5 < m < 1 M_\odot \\ m^{-1.7} & \text{for } 1 < m < 100 M_\odot \end{cases}. \quad (8)$$

We computed a SSP spectra library using the above-formulated Kroupa IMF and compared the resulting UV SED evolution with the one obtained using a Salpeter IMF. In the *GALEX* spectral window, the UV SED of young SSPs is dominated by the more massive stars ($m \geq 30 M_\odot$), whose *GALEX* colour does not depend on the mass. As a consequence, the UV spectral slopes (or UV colours) of young SSPs with Salpeter and Kroupa IMFs are very similar, despite the

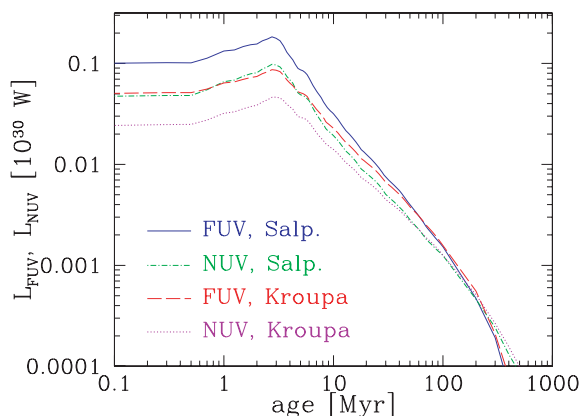


Figure 8. Time evolution of NUV and FUV luminosities of a simple stellar population of solar metallicity, with Salpeter and Kroupa IMFs. The initial total mass of the population is normalized to $1 M_{\odot}$.

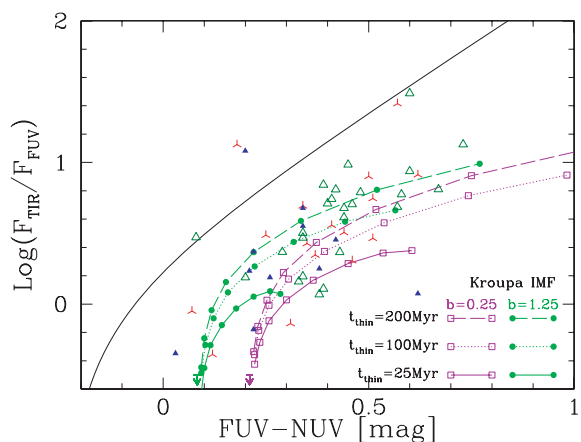


Figure 9. Comparison between NUV-selected sample galaxies and models with the age-dependent scaleheight and Kroupa IMF.

different high-mass slope. With our SSP spectra we found that the FUV–NUV colour in the two IMF cases always differs less than 0.03 mag, for all stellar ages younger than 10^8 yr.

However, the difference in the IMF slope at high masses gives a different evolution of the UV luminosity between the two IMFs. Indeed, Fig. 8 shows that the UV flux for a Kroupa IMF decreases with the age of the population with a slower rate than that corresponding to a Salpeter IMF, as $t^{-1.13}$ and $t^{-1.43}$ respectively, between 3 and 100 Myr. As a consequence, the FUV–NUV dust-free colour of a galaxy with $b = 0.25$ is around 0 assuming a Salpeter IMF (Fig. 5), and 0.2 with a Kroupa IMF.

Thus we recomputed the spiral galaxies models with the age-dependent scaleheight (like set C in the previous section) but adopting a Kroupa IMF.⁷ The resulting IRX– β diagram is shown in Fig. 9, illustrating that the models well compare with observed values.

The results show that the IMF slope has an effect on the final UV colour producing redder models that agree in a better way with the observations than set C models.

The larger reddening of these models with respect to Salpeter IMF-based ones is simply due to the difference in the relative con-

⁷ We neglect here the presence of MC in order to emphasize the effect of the IMF slope.

tribution of old (and less obscured) and young (and more obscured) stars to UV luminosity. In fact, young star populations with a Kroupa IMF have less massive stars (and a lower UV luminosity) with respect to populations with a Salpeter IMF; thus, similarly to what happens in the set D models, a smaller obscuration by the cirrus is needed to make the model redder.

Finally, we computed the attenuation laws of Fig. 7 with the Kroupa IMF. However, we found that there is no visible change in the attenuation laws between models with the two different IMFs (Salpeter and Kroupa) used in this work.

5 SUMMARY AND DISCUSSION

In previous sections, we investigated the role of various physical and geometrical factors in the relation between the reddening of the UV *GALEX* colour and the attenuation. Our relatively realistic modelling allows a proper discussion of the effect of the geometrical distribution of stars and the dust and the effect of the IMF on the attenuation properties of normal spiral galaxies.

The *GALEX* data are in principle very sensitive to the dust properties because the NUV band is strongly affected by the presence of the 2175-Å bump in the extinction law; e.g. the extinction in NUV is actually slightly higher than in the FUV for a MW dust. For this reason, such data could be used to derive the dust properties.

Under the (unrealistic) assumption that stars suffer an extinction independent of their age (set A; Fig. 3), it is not possible to produce a reddening in a star population with a MW dust, regardless of the relative geometry of dust and stars. This result confirms the findings of Witt & Gordon (2000). Under this assumption, the IRX– β diagram for normal galaxies drawn by Bell (2002) and Kong et al. (2004), and confirmed by *GALEX* data (Buat et al. 2005; Seibert et al. 2005; Cortese et al. 2006), would imply a strong reduction of the 2175-Å bump in the extinction law of these galaxies (see also Calzetti et al. 2005).

Burgarella et al. (2005b) analysed the observed relation in an empirical way, using an average attenuation law rather than a radiation transport model. Fitting the UV, the optical SEDs and the IR luminosity of the UV-selected sample, they found that the mean strength of the 2175-Å bump in the attenuation law characterizing this sample is around half of the strength in the MW extinction law. However, as the authors underline, this approach cannot determine if the small bump strength is due to a dust characteristic or a geometrical effect.

Using our radiation transport model, we have shown that, indeed, the observed relation can be explained without the need of dust properties different from the MW diffuse medium. This result can be obtained taking into account the fact that young stars suffer a higher dust attenuation with respect to older stars (age-dependent extinction).

We have shown (set B; Fig. 4) that in the case with all the dust in molecular clouds obscuring stars younger than a given age, the observed *GALEX* IRX– β diagram can be fairly well reproduced. The important point of this result is that in this case the FUV–NUV colour is completely independent of the extinction law (because the MC are supposed to be optically thick), so it can be obtained with every kind of dust. It is worth stressing that such a geometrical effect could completely wash out the effect of optical properties of the dust, and undermine the idea that the IRX– β diagram could be used to derive the dust properties.

However, the above case is extreme and not very realistic. Moreover, we found that the time-scale on which young stars must be attenuated to explain redder galaxies is significantly larger (50 Myr or more) than the typical time over which young stars get rid of

their parental clouds (few Myr). Anyway, the good reproduction of the observed relation suggests that some form of age-dependent extinction has to be in place.

We interpreted this result as the effect of the different scaleheight of young and old stars in spiral galaxies. By taking into account that the stars are born near the galactic plane and therefore suffer a higher dust attenuation than older stars which are distributed in a broader way, we have shown (set C; Fig. 5) that it is possible to obtain a significant reddening also in the case of a dust with a prominent 2175-Å bump. It is worth noting that the well-known distribution of young and old stars in discs was taken into account only in few population synthesis models (e.g. Buat & Xu 1996; Tuffs et al. 2004), but its effect on the UV colour was never investigated.

The time-scale required by new stars to leave the galactic plane needed to explain the observed IRX- β relation is around 100 Myr. This is in keeping with observations in our own galaxy, according to which stars younger than ~ 150 Myr have a much smaller scaleheight than older ones (Robin et al. 2003). Moreover, our results (set D; Fig. 6) show that the combination of molecular clouds obscuration and the age-dependent scaleheight of stars can reproduce most of the observed IRX- β .

In this geometry, as the young stars become more and more obscured at increasing the dust amount, the NUV flux become dominated by the older stars, while the FUV is still mostly provided by younger ones. Therefore, the FUV-NUV colour is, in this framework, the result of the age-dependent obscuration of the different populations rather than the reddening properties of the dust. Moreover, our results show that the lack of correlation between the birthrate parameter and the distance from the starburst relation could be ascribed at least in part to the variation of t_{thin} , the time-scale required by new stars to leave the galactic plane.

We underline that our results do not rule out that the intrinsic optical properties of dust in different galaxies can be substantially different from those of the average MW dust. This is indeed in our view a likely possibility, in general. However, we have demonstrated that conclusions on this issue can be seriously affected by the use of too simple models. In particular, the effects of dust properties in data sets, such as those considered in this work, are probably overwhelmed by the age-dependent geometry.

We have also shown that the IMF can have a role in shaping the IRX- β diagram. Even if the UV colour of a simple stellar population does not depend on the IMF because it is dominated by the most massive stars, the rate at which the UV luminosities decrease with time is given by the IMF slope at higher masses. For this reason, the UV colour of the integrated SED over the star formation history depends on the IMF.

ACKNOWLEDGMENTS

PP acknowledges the warm hospitality and financial support of the LAM for this work. This work was partially funded by the European Community by means of the Marie Curie contract MRTN-CT-2004-503929 ‘MAGPOP’.

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