

The Dust Opacity of Star-Forming Galaxies

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ABSTRACT

Presence of dust in galaxies removes half or more of the stellar energy from the UV–optical budget of the Universe and has profound impact on our understanding of how galaxies evolve. Measures of opacity in local galaxies are reviewed together with widely used theoretical and empirical methods for quantifying its effects. Existing evidence shows that the dust content of nearby galaxies depends not only on their morphology, but also on their luminosity and activity level. A digression is devoted to starbursts in view of their potential relevance for measures of opacity in distant galaxies. Scarcity of coherent multiwavelength datasets hampers our ability to derive reliable obscuration estimates in intermediate and high redshift galaxies. This, in turn, limits the reliability of inferred physical quantities, such as star formation rates, stellar population ages, galaxy luminosity functions, and others.

Subject headings: ISM: dust,extinction – Galaxies: ISM – Infrared: Galaxies – Ultraviolet: Galaxies – Galaxies: Starburst

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1. Introduction

After IRAS (Soifer, Houck & Neugebauer 1987) showed that most galaxies in the nearby Universe contain at least some dust, the main question moved from “whether” to “when, where, and how much”. “When” did galaxies started to be enriched in metals and dust and how did their dust content evolve as a function of redshift? “Where” is the dust located within a galaxy and how is it distributed among Hubble types? “How much” dust there is in galaxies, how much stellar light is absorbed by dust and how is it re-emitted?

More than one third of the bolometric luminosity of local galaxies is processed by dust into the infrared. The fraction of stellar radiation reprocessed into the IRAS 8–120 μm window is $\sim 25\%$ – 30% (Soifer & Neugebauer 1991); this implies an infrared energy fraction around 35% – 40% of the total bolometric energy within the local ~ 100 Mpc, once bolometric corrections from the IRAS window to the full infrared range are included (Désert, Boulanger & Puget 1990; Xu & Buat 1995; Calzetti et al. 2000). This average value comes with a large variation between galaxies, depending on luminosity, morphological type, and activity level (see section 3).

The cosmic infrared background (CIB) observed by COBE (Puget et al. 1996; Fixsen et al. 1998; Hauser et al. 1998) sets equally stringent limits on the total amount of stellar energy re-processed by dust into the infrared at *all* redshifts. About half, and possibly more, of the background radiation between 0.1 μm and 1000 μm is emerging at wavelengths $\lambda > 40$ μm (Hauser & Dwek 2001). This implies that at some epoch(s) in the past galaxies have been infrared–luminous at least as much as, and possibly more than, today to produce the observed balance between UV/optical and infrared energy in the cosmic background. Infrared–bright sources are also found to be about two orders of magnitude more numerous in the past than today (section 5.2 and Barger, Cowie & Richards 2000). The infrared luminosity of a galaxy is related to both its dust content and nuclear/star-formation activity. The lower metal content of distant galaxies does not necessarily make them more transparent systems than galaxies today. The dust content of galaxies is, in fact, proportional to both metallicity and gas content; as stellar populations evolve in time and more gas is locked into stars, the metallicity of a galaxy increases while its gas content decreases. The two trends are opposite to each other, and the dust content reaches a peak sometimes during the evolution of the galaxy. Models predict that galaxies at $z \sim 1$ – 2 have about twice the dust opacity of local galaxies (Wang 1991; Edmunds & Phillips 1997; Calzetti & Heckman 1999; Pei, Fall & Hauser 1999). High-redshift, star-forming galaxies are indirectly observed to have large gas column densities; the average *SFR per unit galactic area* increases by more than an order of magnitude between redshift 0 and 3 (Giavalisco et al. 1996a; Meurer et al. 1997; Lanzetta et al. 1999), which is indication of a similar increase in the average gas column density via the global Schmidt law (Kennicutt 1998).

The presence of dust in galaxies limits our ability to interpret the local and distant Universe, because dust extinction dims and redden the galaxy light in the traditional UV–to–near-IR windows, where the vast majority of the data have been obtained. Dust effects hamper the interpretation of galaxies SEDs in terms of their fundamental parameters, such as age, stellar population mix, star formation rates (SFRs), and stellar Initial Mass Function (IMF). Since young stellar populations are on average more deeply embedded in dust clouds than older stars, dust opacity variations within a galaxy impact the derivation of a galaxy’s star formation history, by altering the census of the populations in the different age bins. Heavy dust extinction in nearby starburst galaxies still prevents establishing whether the stellar IMF in these systems is different from that of more quiescent environments (Rieke et al. 1980, 1993; Alonso-Herrero et al. 2001). The increase of dust content with luminosity in spirals may be responsible for the non-linear behavior of the Tully-Fisher relation, and this translates into biased distance estimates (Giovanelli et al. 1995). Determinations

of luminosity functions, mass-to-light ratios, and number counts, especially at short wavelengths, suffer from both the presence of dust and the variations of dust content from galaxy to galaxy. Light dimming by dust biases measurements of galaxies' SFRs, both locally (Bell & Kennicutt 2001; Sullivan et al. 2000) and at high redshift (Glazebrook et al. 1999; Madau et al. 1996; Steidel et al. 1999), and is the cause of uncertain cross-calibrations between different indicators. The evolution with redshift of the SFR of galaxies per unit comoving volume is still debated: unclear is whether it has a peak around $z \sim 1-3$ (Madau et al. 1996; Blain et al. 1999b) or is mostly flat between $z \sim 1$ and $z \sim 4$ (Steidel et al. 1999; Barger, Cowie & Richards 2000). Answering this question, which requires understanding the dust opacity characteristics and the nature of high redshift galaxies, can discriminate between different flavors of galaxy formation scenarios (White & Frenk 1991; Ortolani et al. 1995; Baugh et al. 1998). Finally, measuring the fraction of metals locked into dust at different epochs is a crucial ingredient for tracing the chemical evolution of galaxies.

The quantification of the dust opacity of galaxies of all types and at all redshifts as a function of wavelength has required the collective effort of many investigators over the last $\sim 10-15$ years and is still, in many aspects, an on-going process. This review attempts to capture the main results obtained so far; it concentrates on star-forming galaxies, because of their key role for interpreting the star formation history and evolution of galaxies. The topic has acquired with time large breadth and numerous publications have appeared in the field; despite the effort to include as many relevant results as possible, some important contributions may have been inadvertently overlooked.

After IRAS, the Infrared Space Observatory (ISO) continued to shed light on the dust emission properties of galaxies, and comprehensive reviews are given in Genzel & Cesarsky (2000) and in the Proceedings of the 1998 Paris conference 'The Universe as Seen by ISO' (Cox & Kessler 1999). The status of the topic before ISO is reported in the Proceedings of the 1994 Cardiff (U.K.) conference 'The Opacity of Spiral Disks' (Davies & Burstein 1995) and of the 1996 Johannesburg (South Africa) conference 'New Extragalactic Perspectives in the New South Africa' (Block & Greenberg 1996).

Throughout the following, the adopted cosmology is a flat Universe with $\Omega_\Lambda=0$ and Hubble constant $H_0=65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. 'Local Universe' refers to a sphere of 100–200 Mpc radius centered on the Milky Way.

2. The Radiative Transfer of Dust in Galaxies

The transfer of radiation through dust is governed by the well-known equation (e.g., Chandrasekhar 1960; Sobolev 1963):

$$\frac{dI_\lambda}{ds} = -\kappa_\lambda I_\lambda(s, \theta, \phi) + \epsilon_\lambda(s, \theta, \phi) + \kappa_\lambda \frac{\omega_\lambda}{4\pi} \int_\Omega I_\lambda(s, \theta', \phi') \Phi_\lambda(\cos \Theta) d\Omega', \quad (1)$$

where $I_\lambda(s, \theta, \phi)$ is the radiation intensity, ds is the element of linear distance along the direction of propagation, $d\Omega'$ is the element of solid angle as seen by the dust grain, κ_λ is the opacity (absorption

plus scattering) of the dust per unit separation s , $\epsilon_\lambda(s, \theta, \phi)$ is the emissivity of the sources along the direction of propagation, ω_λ is the albedo, i.e. the fraction of the opacity due to scattering, and $\Phi_\lambda(\cos \Theta)$ is the phase function of the dust grains expressed as a function of Θ , the angle between the directions determined by the incident radiation (θ, ϕ) and the scattered radiation (θ', ϕ') . One commonly used expression of the scattering phase function, the Henyey-Greenstein function (Henyey & Greenstein 1941), is characterized by a single parameter, the asymmetry parameter $g_\lambda = \langle \cos(\Theta) \rangle$, which is the average of the cosine of the scattering angle.

Determining the dust opacity and recovering the intrinsic physical properties of complex systems like galaxies typically requires the full treatment of the transfer of radiation through dust (equation 1). The efforts to solve the integro-differential equation 1 in the case of galactic environments have generated increasingly sophisticated radiative transfer models and codes to deal with the complexity of both the dust physical properties and the dust/emitter geometry. A representative, although non-exhaustive, list of models and their salient characteristics is given in Table 1. A detailed description and comparison between these models and codes is beyond the scope of the present review and the interested reader is referred to the papers listed in the Table. Although the simplifying assumptions implemented in many cases often appear to yield as good a solution as more complex treatments (see, for instance, Misiriotis et al. 2000), the large number of free parameters is a fundamental shortcoming of radiative transfer models. Workarounds to this shortcoming go from assembling large, coherent sets of independent observational data on just one or a small number of objects to making over-simplistic assumption on the age and metallicity mix of the galaxy stellar populations, and often both. This clearly bears deeply on the generality and applicability of any result and may account to an extent for the wide variety of conclusions on the opacity of galaxies reached by different authors.

2.1. Point Sources and the Interstellar Extinction

A point-like source (a star or an AGN) behind a screen of dust is the simplest source/dust geometry, and equation 1 has solution:

$$I_a(\lambda) = I_o(\lambda)e^{-\tau(\lambda)} = I_o(\lambda)10^{-0.4A_\lambda^o}, \quad (2)$$

where $I_a(\lambda)$ and $I_o(\lambda)$ are the attenuated (observed) and intrinsic radiation intensity, and $\tau(\lambda) = \int \kappa_\lambda ds = 0.921 A_\lambda^o$ is the optical depth of the dust screen¹. The total-to-selective extinction, i.e. the part of the optical depth which only depends on the physics of the dust grains and, therefore, only on the wavelength, is often expressed as $k(\lambda) = A_\lambda^o / E(B-V)$. The color excess $E(B-V)$ is defined as $A^o(B) - A^o(V)$, hence $k(B) - k(V) = 1$.

Although many studies traditionally employ a ‘mean Galactic extinction curve’ to correct galactic and extragalactic sources for the effects of dust obscuration, the well-studied Milky Way

¹see Appendix A for the distinction between A_λ^o and A_λ that will be used later.

interstellar extinction has been shown to be spatially variable and highly dependent on the dust grain environment along the line of sight (see reviews of Mathis (1990) and Fitzpatrick (1999)). Cardelli, Clayton & Mathis (1989) demonstrated that the variations can be effectively parametrized by the total-to-selective extinction at V, $R(V) = A_V^0 / E(B-V)$. Both the steepness of the far-UV ($\lambda \lesssim 0.3 \mu\text{m}$) rise of the extinction curve and the strength of the $0.2175 \mu\text{m}$ absorption feature decrease for increasing $R(V)$, as schematically shown in Figure 1 (Cardelli, Clayton & Mathis 1989). Most sightlines have $R(V) \approx 2-6$, with the low values corresponding to the diffuse ISM (for which $R(V) = 3.1$ is a reasonable average value, Rieke & Lebofsky (1985, e.g.,)) and the high values pertaining to dense clouds. The large values of $R(V)$ in dense clouds, usually accompanied by a gray extinction curve, are consistent with dust grains having systematically larger sizes than in the diffuse medium (Cardelli, Clayton & Mathis 1989).

The only galaxies external to the Milky Way for which some measurements of the UV extinction curves exist are the Magellanic Clouds (Figure 1; Koornneef & Code 1981; Nandy et al. 1981; Bouchet et al 1985; Fitzpatrick 1986; Gordon & Clayton 1998; Misselt, Clayton & Gordon 1999), although tentative measurements in M31 have been made (Bianchi et al. 1996). Despite the large variation of extinction properties found within each of the Magellanic Clouds (Fitzpatrick 1986; Lequeux et al. 1982; Misselt, Clayton & Gordon 1999, e.g.,), the *average* curves of the Clouds appear to have some intrinsic differences from the average Milky Way curve, including a smaller $R(V)$ ($R(V) \simeq 2.4-2.9$, Gordon & Clayton (1998); Misselt, Clayton & Gordon (1999)). This has been interpreted as an effect of the lower metallicity in the Clouds, which causes the molecular clouds to be more diffuse (Pak et al. 1998) and, possibly, to produce on average smaller dust grains (Misselt, Clayton & Gordon 1999). The weak or absent UV absorption ‘bump’ at $0.2175 \mu\text{m}$ in the extinction curves of the LMC 30 Doradus region and of the SMC bar, respectively, (Figure 1) could be related to local processes in these regions, possibly to the ongoing star formation activity (Fitzpatrick 1986; Gordon & Clayton 1998; Misselt, Clayton & Gordon 1999; Reach et al. 2000). Although the bump carriers have not been positively identified yet (e.g., Reach et al. 2000), mid- and far-infrared studies of star forming regions in the Milky Way have provided evidence that the environmental UV energy density level affects the dust properties, such as the grain size distribution, via destruction or coagulation, and/or the dust physical characteristics, via ionization state changes (Boulanger et al. 1988; Cesarsky et al. 1996). Thus, the environmental UV energy density appears to play as important a role as the metallicity in shaping the extinction curve. If confirmed by further observations, this hypothesis may explain the general absence of a $0.2175 \mu\text{m}$ absorption ‘bump’ in the extinction curve of starburst galaxies (section 4.1) and may partially account for its weakness in QSOs (e.g., Jura 1977; Sprayberry & Foltz 1992; Yamamoto & Vansevicius 1999).

In addition to absorbing stellar light, dust manifests itself through emission and absorption features and continuum emission at $\lambda > 1 \mu\text{m}$. Features in the near/mid-IR include, among others, the silicate absorption at 9.7 and $18 \mu\text{m}$, H_2O and CO_2 ice absorption at 3.0 and $4.3 \mu\text{m}$ (see Lutz et al. (1996) and Schutte et al. (1998) for a list of other absorption features), and the emission bands at 3.3 , 6.2 , 7.7 , 8.6 , and $11.3 \mu\text{m}$ (Sellgren 1994, 2000). The continuum emission beyond a few μm

and up to $\sim 40\text{--}70\ \mu\text{m}$ is considered to be mainly due to discrete photon heating of very small dust grains, the smallest among which are transiently heated up to $\approx 1,000\ \text{K}$ (e.g., Sellgren 1984; Draine & Anderson 1985; Li & Draine 2001); dust heated by massive stars to temperatures $> 70\ \text{K}$ also contributes to the flux in the wavelength region below $\sim 50\ \mu\text{m}$, albeit with decreasing filling factor for increasing temperature (Natta & Panagia 1976). Beyond $40\text{--}70\ \mu\text{m}$, the emission is mainly due to dust grains in nearly steady balance with the average heating by starlight; the transition wavelength between predominance of discrete photon heating versus that of nearly-steady state depends on the average color temperature of the dust and, thus, on the mean UV energy density level of the galaxy (Mezger, Mathis & Panagia 1982; Mathis, Mezger & Panagia 1983; Helou 1986; Chini, Krügel & Kreysa 1986; Lonsdale-Persson & Helou 1987; Rowan-Robinson & Crawford 1989; Désert, Boulanger & Puget 1990).

The original dust model of bare graphite and silicate grains (Mathis, Rumpl & Nordsieck 1977; Draine & Lee 1984) has evolved over time by including more complex grain compositions and extended grain size distributions, to accommodate all the details of the absorption and emission, and the variability of the environment, while at the same time accounting for the constraints imposed by the heavy elements overall abundance (Mathis 1996, e.g.,). Polycyclic aromatic hydrocarbons (Léger & Puget 1984; Désert, Boulanger & Puget 1990; Weingartner & Draine 2000; Sellgren 2000), hydrogenated amorphous carbons (Duley et al. 1989; Furton, Laiho & Witt 1999), icy and organic refractory mantles (Greenberg 1984; Tielens 1989; Greenberg 1989; Jenniskens 1993; Greenberg et al. 2000), composite and/or porous grains (Mathis & Whiffen 1989; Mathis 1996; Wolff, Clayton & Gibson 1998; Voshchinnikov & Mathis 1999), as well as grain size distributions that significantly depart from the original power law model (Kim, Martin & Hendry 1994; Weingartner & Draine 2000), have all been suggested as possible alternatives/complements to the graphite/silicate model.

2.2. Extended Emitting Sources

In the late '80s, Disney, Davies & Phillips (1989) and Valentijn (1990) revived the decade-long debate on whether galaxy disks are mainly transparent or opaque to dust. Using multi-wavelength information and surface brightness-versus-inclination tests, respectively, the two groups of authors reached the similar conclusion that the disks of galaxies are fairly opaque, with total face-on extinctions in the B band $A_{B,f} \gtrsim 1\ \text{mag}^2$. These results countered earlier findings, also based on the surface brightness-versus-inclination tests, that galaxy disks are mostly transparent with face-on extinctions at B less than 1 mag (Holmberg 1958; de Vaucouleurs 1959a).

The reason why similar approaches can produce very different results can be found in the complexity of the absolute and relative distribution of stars and dust inside galaxies. When there is a significant departure from the simplest geometry of a point source (a star) behind a homogeneous

²See Appendix A for the definition of $A_{\lambda,f}$.

screen of dust, the dust distribution, rather than the optical depth of the dust layer, becomes the dominant factor in determining the obscuration suffered by the stellar radiation (Natta & Panagia 1984; Witt, Thronson & Capuano 1992; Calzetti, Kinney & Storchi-Bergmann 1994). In particular, differential optical depth effects come into play. If, for instance, the stars are homogeneously mixed with the dust, the shorter the wavelength of the radiation the smaller the optical depth of the dust layer from which it can emerge; thus, an observer will detect blue light only from the closest outer ‘skin’ of the mixed distribution, while redder light will come from deeper layers. An extreme case is that of infinitely optically thick clumps in front of an extended light distribution: the stellar emission will come only from those lines of sight that do not intersect clumps, and the net result will be an unreddened, albeit dimmer than the original, spectral energy distribution (SED). The scattering component of the extinction curve will also modify the general characteristics of the dust obscuration, as light will be scattered *into the line of sight* as well as out of it. The net result of all these effects is a general blueing of the emerging SED relative to the foreground homogeneous dust screen case, or, in other words, an often much greyer ‘effective extinction’, even in the presence of large dust optical depths³ (Bruzual, Magris & Calvet 1988; Witt, Thronson & Capuano 1992).

For illustrative purposes, Figures 2 and 3 show how photometric and spectroscopic quantities are affected by the dust geometry for five ‘toy models’. The models represent plane-parallel geometries of dust and stars (details are given in Natta & Panagia 1984; Calzetti, Kinney & Storchi-Bergmann 1994; Wang & Heckman 1996) for: (1) the simple case of a homogeneous, non-scattering dust screen foreground to the light source; (2) a homogeneous, scattering dust screen foreground to the light source (e.g., a screen in close proximity of the source, so that scattering into the line of sight becomes an important effect); (3) a Poissonian distribution of clumps in front of the light source, with average number $\mathcal{N}=10$; (4) a homogeneous mixture of dust and emitters; (5) a homogeneous dust/emitter distribution averaged over all inclination angles, with the UV and ionized gas emission having the same scaleheight of the dust while the scaleheight of the optical light gradually increases to twice that of the dust at V and beyond. Models 2–5 include scattering in the calculations⁴. In all cases, the light source is assumed to be extended and to be represented by a 300 Myr old stellar population undergoing constant star formation, with solar metallicity and a Salpeter IMF in the mass range 0.1–100 M_{\odot} (Leitherer et al. 1999).

The ‘blueing’ effect of geometries more complex than a foreground dust screen is evident from the comparison of the five models. At fixed optical depth τ_V (fixed amount of dust), the reddening

³See Appendix A for the relation between optical depth, extinction, and effective extinction.

⁴For the models, the compilation of albedo and asymmetry parameter values of Witt & Gordon (2000) is used. In this compilation, the data are mainly from studies of reflection nebulae, and the 0.2175 μm feature is due to pure absorption (no scattering) (Calzetti et al. 1995a). These a and g values are assumed here to be representative of dust properties, although the following caveats need to be kept in mind: some values, especially for the albedo, are still unsettled (Burgh 2001); the generalization of the reflection nebulae results ($R(V)>3.1$) to the diffuse dust is not immediate (Witt, Friedmann & Sasseen 1997; Kim, Martin & Hendry 1994; Weingartner & Draine 2000); the UV a and g values could be lower in the Magellanic Clouds than in the Milky Way (Weingartner & Draine 2000).

of the V–I color of a stellar population induced by a generic geometry of stars and dust will be less, and the effective extinction A_V lower, than that induced by a foreground screen (Figure 2, panels a and b). The same will be true for colors at other wavelengths (Figure 2), where, again, the foreground non-scattering screen will provide the maximum reddening. For mixtures of dust and stars (models 4 and 5), reddening of colors and effective extinction reach asymptotic values; beyond certain values of the optical depth, an increase in τ_V corresponds to small or negligible changes in colors and A_V . This is due to the fact that the shortest wavelength emission is contributed only by the dust layers closest to the observer. One common consequence of the greyer ‘effective extinction’ caused by complex dust/emitter geometries is that a limited number of diagnostics over a small wavelength range will lead to underestimates of the true galaxy opacity, especially if the actual dust geometry is not known and is ‘a priori’ assumed to be foreground (Witt, Thronson & Capuano 1992).

To aid the comparison with data on local starbursts and high-redshift star-forming galaxies (sections 4 and 5), the models shown in Figure 3 are a function of the ratio of the attenuated-to-intrinsic Balmer line ratio:

$$R_{\alpha\beta} = \frac{(L_{H\alpha}/L_{H\beta})_a}{(L_{H\alpha}/L_{H\beta})_o}, \quad (3)$$

and of the UV spectral slope⁵ β . The luminosity ratios of nebular hydrogen lines, like H β , H α , Pa β , Br γ , etc., are rather insensitive to the details of the underlying stellar population and of the IMF, being affected at the $\sim 5\%$ – 10% level by variations of the gas physical conditions (e.g., Osterbrock 1989); they represent, therefore, accurate probes of dust reddening and geometry. Table 2 lists the commonly used hydrogen emission line ratios, and the differential extinction between each pair. When multiple line ratios widely separated in wavelength are available, they can constrain the dust geometry in the sampled wavelength range. The two drawbacks of using nebular lines are: (1) they are produced by ionizing photons, therefore an ionizing stellar population needs to be present in the galaxy; and (2) they only probe the attenuation of the *ionized gas*, and such attenuation may or may not be directly related to that of the stellar population (section 4). The explicit expression of $R_{\alpha\beta}$ depends on the dust geometry; in the simple case of a foreground, non-scattering screen:

$$R_{\alpha\beta} = 10^{0.4E(B-V)[k(H\beta)-k(H\alpha)]}, \quad (4)$$

where the values of $k(H\alpha)$ and $k(H\beta)$ are given in Table 2.

Degeneracies between the reddening induced by dust and that induced by variations in the age, metallicity, and IMF of the stellar populations play a non-negligible role in opacity determinations of galaxies. These effects are especially important when only broad band colors or low resolution spectroscopy are available, and age-sensitive or IMF-sensitive stellar features are not identifiable (e.g., discussion in Papovich, Dickinson, & Ferguson 2001). For the age-dust degeneracy, an example is given in Figure 4; here, the broad band colors and magnitudes of a dust-free, ageing stellar

⁵see Appendix B for the definition of β .

population produced by an instantaneous burst of star formation are compared with the analogous quantities of an increasingly extinguished 6 Myr old stellar population. A clumpy dust distribution with $\tau_V \sim 2$ in front of the young population reddens and attenuates it enough that its broad-band UV, optical, and near-IR colors closely resemble those of a 20 Myr old, dust-free population (corresponding to the color $V-I \sim 0.6$ in Figure 4). Thus, the dusty, young population can be mistaken for a dust-free population a factor ~ 3 older. This example is just one out of a large range of possibilities in the multi-dimensional dust/age/IMF/metallicity parameter space.

In summary, the grey effective extinction produced by dust geometry and scattering, the age-IMF-metallicity-dust degeneracy, together with uncertainties on the appropriate extinction curve to be applied to different galaxies (section 2.1) and the absence of strong emission and absorption features below $\sim 1 \mu\text{m}$ (apart from the $\sim 0.22 \text{ \AA}$ absorption bump which is not universal), all contribute to make dust obscuration measurements very difficult in galaxies.

3. Measurements of Dust Opacity in Local Galaxies

3.1. Spiral Disks

Efforts to determine the dust opacity of local galaxies have spawned the development of a number of independent techniques that have been applied to a large array of samples. The most widely used methods in the case of galaxy disks are tests of the dependence of the surface brightness on inclination, multi-wavelength comparisons, and statistical analysis of the color and number count variations induced by a foreground galaxy onto background sources. Each method has its strengths and weaknesses, as briefly detailed below.

As Burstein, Haynes & Faber (1991), Choloniewski (1991), and Davies et al. (1993) pointed out, probing galaxy dust opacity by measuring the surface brightness dependence of galaxy disks on inclination can suffer from drastic selection biases. For increasing inclination, an apparent-magnitude-limited catalog will mimick the condition for transparent galaxies, with mildly increasing surface brightnesses, increasing diameters, and constant total luminosities. Conversely, an apparent-diameter-limited catalog will mimick the conditions for opaque disks, with roughly constant surface brightnesses, increasing magnitudes and constant diameters as a function of increasing inclination (Burstein, Haynes & Faber 1991). Selection effects can, however, be controlled by combining different samples and by using galaxy redshifts/distances to discriminate among the different biases, and analysis of large samples of late-type (mainly Sbc and Sc) spirals (Huizinga & van Albada 1992; Peletier & Willner 1992; Giovanelli et al. 1994, 1995; Jones, Davies & Trewheella 1996; Moriondo, Giovanelli & Haynes 1998) has shown that the central regions of disk galaxies are opaque while the external regions beyond 2–3 scale lengths are almost completely transparent; there is also a trend for luminous galaxies to be more opaque than less luminous galaxies (Giovanelli et al. 1995). In bright, $M_I < -21$ disk galaxies, the observed magnitude correction from edge-on to face-

on, $\Delta m_I \sim 1$ mag, corresponds to a face-on central optical depth⁶ $\tau_V(0) \gtrsim 5$; this implies effective face-on extinctions $A_{B,f} \sim 0.4\text{--}0.5$ mag, $A_{I,f} \sim 0.2$ mag, and $A_{H,f} \sim 0.1$ mag (Peletier & Willner 1992), for a double exponential distribution of dust and stars, and for practically transparent external galaxy regions (Byun, Freeman & Kylafis 1994). Less luminous galaxies are progressively less opaque in their central regions, with a edge-on to face-on correction of $\Delta m_I \sim 0.5$ mag at $M_I > -18$, corresponding to effective face-on extinctions $A_{B,f} < 0.1$ mag (Giovanelli et al. 1995).

Qualitative results similar to those above have been obtained by Bosma et al. (1992) and Byun (1993) for a small number of edge-on late-type spirals using multi-wavelength kinematic information. The method, proposed by Goad & Roberts (1981), consists of comparing rotation curves of an edge-on galaxy at widely different wavelengths. If the edge-on galaxy is optically thick at a given wavelength, say, $H\alpha$, the rotation curve measured at this wavelength shows apparent solid body rotation throughout the entire disk, because the $H\alpha$ emission is coming only from the external regions of the galaxy. A comparison with a mostly unextincted rotation curve measured at a longer wavelength, such as HI, can then establish whether optical thickness at $H\alpha$ exists. This method, though fairly direct in principle, may suffer from two limitations: first, dust in galaxies tends to be patchy and the $H\alpha$ emission may be detected along the least extincted sight lines even in the presence of considerable opacity; second, the method implicitly assumes that $H\alpha$ -emitting regions are uniformly distributed across the disk.

The multi-wavelength comparison method provides an independent approach to the problem of determining the dust opacity of galaxies. In broad terms, the technique consists of using multiwavelength data to solve simultaneously for the intrinsic colors of the stellar populations and for the reddening/attenuation induced by the dust. Generally, broad band images covering as large as possible wavelength baseline, often from B to K band, are used to determine the opacity of the disks, by exploiting the differential extinction property of dust (Rix & Rieke 1993; Block et al. 1994; Peletier et al. 1995; Emsellem 1995; Beckman et al. 1996; Kuchinski et al. 1998; Xilouris et al. 1999). Indeed, in face-on quiescent galaxies K-band emission appears negligibly affected by dust obscuration, with $\lesssim 10\%$ of the light lost to dust absorption and scattering (Rix & Rieke 1993). The multiwavelength technique is the most widely adopted for measuring dust opacity in galaxies, because it employs easily accessible information on diverse galaxy types, and enables detailed modelling of optical depths as a function of galactic region. There are, however, three main weaknesses to the method: first, this technique needs as wide a wavelength coverage as possible, often difficult to obtain, to yield unambiguous results; second, if the dust optical depth exceeds unity at some wavelength, different volumes of the galaxy will be sampled at different wavelengths; third, the need for large datasets and detailed modelling makes obtaining results on large samples relatively cumbersome. Results vary from author to author, due to the different sample selections, galaxy and dust distribution models, and measurement techniques applied. Optical and near-IR image

⁶The face-on central optical depth $\tau(0)$ is the optical depth of the dust at the geometrical center of the tri-dimensional dust distribution for a face-on disk galaxy.

analysis gives typical central optical depths $\tau_V(0)$ in the range 0.3–2.5 for types Sab–Sc (Peletier et al. 1995; Kuchinski et al. 1998; Xilouris et al. 1999), although higher values have been obtained by Block et al. (1994). For exponential stellar and dust profiles, these values of $\tau_V(0)$ result in optical depths $\langle \tau_V \rangle \lesssim 1$ averaged over the inner 2–3 scale-lengths (Rix & Rieke 1993; Beckman et al. 1996; Kuchinski et al. 1998), and $A_{B,f} \sim 0.3$ –0.4 mag and $A_{I,f} \lesssim 0.15$ mag over the same area. Much lower values of the optical depth are found for late-type, low surface brightness galaxies, with face-on, central values $\tau_V(0) \sim 0.15$ (Matthews & Wood 2001). In galaxy disks, arm regions tend to be opaque, with $\tau_V \sim 1.4$ –5.5 ($A_{I,f} \sim 0.2$ –0.7 mag) and peak values at $\tau_V \sim 10$ –12, while interarm regions are generally transparent, with $\tau_V \sim 0.3$ –1.1 ($A_{I,f} \sim 0.05$ –0.15 mag, Elmegreen (1980); Rix & Rieke (1993); Beckman et al. (1996), but see the higher interarm extinction values found by Trewella (1998)).

Energy balance estimates between dust absorption and emission can also be classified as a ‘multiwavelength technique’, but it is conceptually different from the one above. This technique employs direct measurements of the dust emission in the infrared to derive an estimate of the total stellar energy absorbed by dust, and then derive opacities at shorter wavelengths; whenever possible, the wavelength baseline is extended to the UV to probe the direct light from massive stellar populations and constrain bolometric quantities (Xu & Buat 1995; Xu & Helou 1996; Buat & Xu 1996; Wang & Heckman 1996; Trewella et al. 1997; Trewella 1998). By combining UV and infrared (IRAS) data, Xu & Buat (1995), Wang & Heckman (1996), and Buat & Xu (1996) find typically lower $\langle \tau_V \rangle$ values than those derived from optical/near-IR images. This is not incompatible with those results, since Xu & Buat (1995) and Wang & Heckman (1996)’s models assume plane-parallel dust and stars, instead of exponential profiles, and thus the opaque inner regions are averaged with the nearly transparent outer regions (Peletier et al. 1995; Kuchinski et al. 1998). Still, the UV selection of the samples may bias the conclusions towards lower optical depths and the use of IRAS data leaves some uncertainty as to the bolometric correction of the dust emission. The use of ISO data, that extend the infrared wavelength coverage out to 200 μm , appear indeed to favor higher values of the effective extinction (Trewella 1998). Wang & Heckman (1996) find that opacity in disk galaxies is a function of luminosity (Figure 5), in agreement with Giovanelli et al. (1995). These authors parametrize the opacity as: $\langle \tau_V \rangle = \langle \tau_{V,*} \rangle (L_V/L_{V,*})^{0.5}$, with $\langle \tau_{V,*} \rangle = 0.6$ and $L_{V,*}$ the visible luminosity of a L^* galaxy in the local Universe. Similarly, Buat & Xu (1996) note that Sb–Scd galaxies have $\langle \tau_V \rangle \sim 0.8$ and are on average 1.5 times more opaque than Sa–Sab, and ~ 3 times more opaque than Sd–Irr galaxies, with effective face-on extinctions $A_{B,f} \sim 0.3$ mag, $A_{B,f} \sim 0.15$ mag, and $A_{B,f} < 0.1$ mag for Sb–Scd, Sa–Sab, and Sd–Irr, respectively.

All methods described so far use the stellar radiation of the galaxy itself as light source for the dust, with the complication that intrinsic colors, age and metallicity gradients of the stellar populations and the relative distributions of dust and stars need to be disentangled from the extinction proper. A technique that overcomes these problems is the one that uses background sources as ‘light bulbs’ for the dust in foreground galaxies. In this case, the dust opacity is measured across

the full thickness of the foreground galaxy. There are basically two approaches to the technique. In the first approach the foreground galaxy is partially projected onto a nearby background galaxy (Keel 1983; White & Keel 1992; White, Keel & Conselice 2000; Keel & White 2001a,b; Berlind et al. 1997; Pizagno & Rix 1998). In general, the background galaxy needs to present a smooth light profile, thus early types and preferably ellipticals are required (see, however, Keel & White 2001b); the dimming and color changes induced by the foreground galaxy dust onto the isophotes of the background source provides a measurement of dust opacity. The drawbacks of this approach are twofold: (1) there are very few known pairs of galaxies that fulfill all the requirements and (2) the method is limited by the degree of symmetry of both galaxies (White, Keel & Conselice 2000). The second approach uses distant galaxies as background light sources. Statistical variations in number counts and colors of the background galaxies relative to control fields provide a handle on the total dust optical depth of the foreground galaxy (González et al. 1998). This method overcomes most of the limitations of the first one, but it presents some of its own: (1) high angular resolution images (e.g., from HST) are needed in order to identify background galaxies; (2) even with such images it is often difficult to discriminate background sources from extended regions within the foreground galaxy (e.g., HII regions), especially in crowded areas. Because of these limitations, the second method may also tend to avoid crowded and/or heavily extinguished areas, thus biasing the results towards less dusty galactic regions. Results from various authors indicate that the spiral arms of galaxies tend to be opaque with $A_B^o \sim 0.5\text{--}2$ mag and $A_I^o \sim 0.3\text{--}1.5$ mag at any radius, while the opacity of interarm regions decreases with increasing distance from the galaxy center, starting at $A_I^o \approx 0.7$ mag within $0.3 R_{25}$ and decreasing to practically zero at R_{25} (González et al. 1998; White, Keel & Conselice 2000; Keel & White 2001b). The dust masses inferred from these extinction measures agree within a factor ~ 2 with masses derived from the infrared/submm (ISO and SCUBA) dust emission (Domingue et al. 1999). One common trend generally found is the greyer-than-Galactic reddening in the arm regions (see, however, Keel & White 2001b). The clumpiness of the dust within each resolution bin has been suggested to be responsible for the grey reddening (Berlind et al. 1997; González et al. 1998; White, Keel & Conselice 2000; Keel & White 2001a). Less agreement exists on the shape of the reddening curve in the interarm regions, due to the larger uncertainties resulting from the lower extinction values. The measured extinctions are front-to-back, i.e. represent the optical depth of the intervening dust between the observer and the background sources. To relate these numbers to those derived from the inclination and multi-wavelength tests, one has to make assumptions as to the distribution of stars relative to the dust in the foreground galaxy; for a mixed geometry of stars and small dusty clumps, the measured optical depths correspond to effective I extinctions of $A_{I,f} \sim 0.3\text{--}0.4$ mag and $A_{I,f} \lesssim 0.2$ mag for the arms and the interarm regions, respectively.

3.2. Beyond the Optical Disks

Multi-wavelength optical and near-IR imaging of edge-on or nearly edge-on systems indicate that the scalelength of the dust is about 40% larger than the scalelength of the stars (Xilouris et

al. 1999), while the dust/stars scaleheight ratio is in the range 0.25–0.75, with a mean value of 0.5, (Kylafis & Bahcall 1987; Xilouris et al. 1997, 1999) for late-type spirals (Sb and later) and appears to have ratio ~ 1 in early-type spirals (Wainscoat, Hyland & Freeman 1990). IRAS 100 μm (Nelson, Zaritsky & Cutri 1998) and ISO long wavelength maps (Alton et al. 1998; Davies et al. 1999; Trewella et al. 2000; Radovich, Kahanpää & Lemke 2001) confirm that cold dust emission extends beyond the limits of the optical disks along the radial direction, with scales that are $\sim 40\%$ larger than those of the B-band emitting stars, but still well within the HI disks (e.g., Martin 1998). Using statistical measurements of color variations between background galaxies and control fields, Zaritsky (1994) give a $\gtrsim 2 \sigma$ detection of $A_I^o \approx 0.04$ in galaxy haloes, at a distance of about 60 kpc from the galaxy centers, along the optical major axis.

3.3. Irregular Galaxies

Spiral and irregular galaxies follow a global metallicity-luminosity (and metallicity-mass) relation, where the oxygen abundance increases by a factor ~ 100 for an increase of $\sim 10^4$ in absolute blue luminosity (Skillman, Kennicutt & Hodge 1989; Zaritsky, Kennicutt & Huchra 1994). Irregulars occupy the low metallicity locus of the relation, with ≈ 10 times on average lower oxygen abundance than spirals. Since the HI masses per unit L_B in irregulars are a factor ≈ 3 larger than in spirals (Roberts & Haynes 1994; Zaritsky, Kennicutt & Huchra 1994), the mass in interstellar metals per unit L_B is ≈ 3 times smaller. Adding the H_2 gas into the balance does not change this conclusion, since the H_2/HI mass ratio in irregulars appear to be no larger than that in spirals, even accounting for the uncertainties in the CO-to- H_2 conversion factor (Verter & Hodge 1995; Arimoto, Sofue & Tsojimoto 1996; Wilson, Walker & Thornley 1997). Measurements give the H_2 mass as 25%–50% of the HI mass in late spirals and as $\approx 20\%$ of the HI mass in irregulars (Young & Scoville 1991; Hunter & Sage 1993; Hunter & Thronson 1996; Hunter 1997; Meier et al. 2001). Smaller metal masses for the irregulars translate into smaller dust masses per unit L_B , for standard values of the metal-to-dust ratio (van den Bergh 1974; Lequeux et al. 1984), and into the expectation that irregular galaxies are at least 3 times more transparent at B than spiral galaxies, for similar dust/star geometries.

The analysis of the blue, $\text{H}\alpha$, and IRAS-detected infrared emission confirms that irregular galaxies are relatively transparent systems (Hunter et al. 1986, 1989). In a study of the Magellanic Clouds using background galaxies, Dutra et al. (2001) find that the central regions have $A_B^o \gtrsim 0.25$ in the LMC and $A_B^o \gtrsim 0.16$ in the SMC. In their UV selected samples, Wang & Heckman (1996) find that a 0.1 L^* galaxy has a mean optical depth about 1/3 of the optical depth of an L^* galaxy, and Buat & Xu (1996) reach a similar conclusion by comparing Sb-Scd galaxies with Sd-Irr. Thus, if the typical face-on effective extinction for an Sc galaxy is $A_{B,f} \sim 0.4\text{--}0.5$ mag, the analogous quantities for an irregular are $A_{B,f} \sim 0.15$ and $A_{I,f} \sim 0.05\text{--}0.10$.

3.4. Early Hubble Types

Although early Hubble type galaxies (ellipticals and S0s) do not generally fall under the category of ‘star-forming’ galaxies, they occupy a niche in terms of dust opacity properties that is at the same time opposite and complementary to that of other galaxies. Ellipticals and S0s are at the opposite end of the Hubble classification relative to Irregulars, but they appear to be no more opaque than those late systems.

Early type galaxies cover a metallicity range similar to that of late type spirals (Brodie & Huchra 1991; Zaritsky, Kennicutt & Huchra 1994), but have total (HI+H₂) gas fractions per unit optical luminosity that are ~ 3 times or more smaller (Young & Scoville 1991; Roberts & Haynes 1994). Thus, for standard interstellar metal-to-dust ratios, early type galaxies are expected to be more transparent than disk galaxies.

The IRAS survey has shown that between 10% and 50% of all nearby early type systems (45% of ellipticals and 68% of S0s) contain dust (Jura et al. 1987; Knapp et al. 1989; Bregman et al. 1998), although the involved masses are generally modest, typically in the range 10^5 – $10^6 M_{\odot}$ or $M_{dust}/L_B \approx 10^{-5}$ – $10^{-4} M_{\odot} L_{\odot}^{-1}$ (Roberts et al. 1991; Goudfrooij & de Jong 1995; Wise & Silva 1996; Bregman et al. 1998). The exact fraction of dusty systems appears to depend upon the adopted detection threshold (Bregman et al. 1998), but it is likely a lower bound to the actual value, given the limits in the IRAS sensitivity. The 50% figure seems in agreement with the results of optical surveys: at least 40% of the local ellipticals and S0s show presence of disks, lanes and/or patchy distributions of dust in visual images (Ebneter & Balick 1985; Sadler & Gerhard 1985; Ebneter, Djorgovski & Davis 1988; Goudfrooij et al. 1994). About 40–50%, and possibly as many as 80%, of ellipticals also show evidence for circumnuclear dust on scales < 100 pc, as seen in HST images; the small-scale dust is mostly associated with nuclear radio activity (van Dokkum & Franx 1995; Lauer et al. 1995; Forbes, Franx, & Illingworth 1997; Carollo et al. 1997; Tran et al. 2001).

Despite the abundance of evidence for dust, optical extinction determinations of dust features in ellipticals generally account for only $\sim 1/10$ to $\sim 1/5$ of the dust mass measured from the infrared (IRAS) emission; the remaining 80%–90% of the dust mass is probably associated with a component smoothly distributed across the galaxy, and thus difficult to detect with standard techniques (Goudfrooij & de Jong 1995; Wise & Silva 1996; Bregman et al. 1998; Merluzzi 1998). Limited data from ISO in the wavelength range 120–200 μm confirm these findings (Haas 1998). Using the elliptical galaxy model of Witt, Thronson & Capuano (1992), Goudfrooij & de Jong (1995) determine that the observed infrared luminosities are compatible with central optical depths of the diffuse component $\tau_V(0) \lesssim 0.7$, with a typical value $\tau_V(0) \sim 0.2$ – 0.3 (see, however, the somewhat larger values predicted by the models of Wise & Silva (1996)). The corresponding effective extinction is $A_B \lesssim 0.05$ – 0.10 mag and $A_I \lesssim 0.02$ – 0.04 mag.

The giant ellipticals found at the centers of cooling flow clusters are often surrounded by extended, ≈ 10 – 100 kpc, filamentary, and dusty emission-line nebulae, with a higher frequency in those clusters with cooling times shorter than a Hubble time (Heckman et al. 1989; Sparks,

Macchetto & Golombek 1989; Hu 1992; Voit & Donahue 1997; Donahue et al. 2000). Dust lanes in the central galaxies have, indeed, been directly observed (Pinkney et al. 1996). Optical and UV emission line studies give extinction values in the range $A_V \sim 0.3\text{--}2$ mag for the dust associated with the nebula (Sparks, Macchetto & Golombek 1989; Hu 1992; Allen 1995; Voit & Donahue 1997; Donahue et al. 2000); infrared and sub-mm measurements give dust masses of the order of $10^7\text{--}10^8 M_\odot$, or $M_{dust}/L_B \approx 10^{-4}\text{--}10^{-3} M_\odot L_\odot^{-1}$, for these systems (Cox, Bregman & Schombert 1995; Edge et al. 1999). The existing controversy on the origin of the dust associated with the central galaxies of cooling flow clusters will be briefly reviewed in section 6. Such galaxies are, however, not a statistically significant component of ellipticals in general, thus their contribution to the dust mass budget of early type galaxies is small.

3.5. Infrared-Bright Galaxies

The galaxies discussed so far tend to be mostly ‘quiescent’, i.e. their bolometric output is *not dominated* by a single region of active star formation or by nuclear non-thermal activity, and have modest infrared outputs. Their infrared luminosities in the 3–1000 μm band are typically $\approx 10^9 L_\odot$ and less than $\sim 4\text{--}6 \times 10^{10} L_\odot$, with infrared-to-blue luminosity ratios $L_{IR}/L_B \sim 0.4\text{--}0.5$ (de Jong et al. 1984; Soifer, Houck & Neugebauer 1987; Devereux & Young 1991; Soifer & Neugebauer 1991; Hunter & Thronson 1996), and $\approx 1/2$ or less of the stellar bolometric luminosity converted into infrared emission via dust reprocessing⁷ (see Table 3).

Galaxies with $L_{IR} > 6 \times 10^{10} L_\odot$ and $L_{IR}/L_B > 1$ are progressively associated with dustier and more active systems for increasing values of the infrared luminosity (Rieke & Lebofsky 1986). The brightest infrared sources are not necessarily associated with the most massive galaxies, despite the existence of a relation between a galaxy luminosity (mass) and its dust content (Wang & Heckman 1996). Infrared luminosity is a combination of dust content and activity: brighter sources have larger amounts of star formation and/or non-thermal activity embedded in dust. Most of the luminosity from galaxies with $L_{IR} \approx L_{bol} \gtrsim 10^{11} L_\odot \sim 3\text{--}4 L^*$ appears associated with sources heavily obscured by dust (Sanders & Mirabel 1996). At the bright end of the infrared luminosity function (Soifer, Houck & Neugebauer 1987; Soifer & Neugebauer 1991; Kim & Sanders 1998) are the Ultraluminous Infrared Galaxies (ULIRGs) with luminosities from $L_{IR} \sim 10^{12} L_\odot$ up to $\sim 8 \times 10^{12} L_\odot$ (Soifer, Houck & Neugebauer 1987; Kim & Sanders 1998), infrared-to-blue ratios around 30–400 (Sanders & Mirabel 1996; Clements et al. 1996), and optical extinctions in excess of 10–40 magnitudes (Genzel et al. 1998; Murphy et al. 2001). These sources show a continuum of properties as a function of increasing luminosity, with the fraction of starburst-dominated ULIRGs

⁷The total infrared output L_{IR} of the dust emission is derived from the infrared luminosity measured in the 8–120 μm or 40–120 μm IRAS window (Helou et al. 1988; Sanders & Mirabel 1996) multiplied by ~ 1.4 or ~ 2.2 , respectively, to account for bolometric correction factors as modeled by Dale et al. (2001) from ISO data. The blue luminosity is $L_B \propto \lambda f(\lambda)(0.44 \mu\text{m})$.

going from $\sim 80\%$ – 85% at the low luminosity end to $\sim 50\%$ for $L_{IR} > 2 \times 10^{12} L_{\odot}$, and the remaining fraction being AGN-dominated (Genzel et al. 1998; Lutz et al. 1998; Veilleux, Kim & Sanders 1999). Comprehensive reviews of the properties of ULIRGs are given in Sanders & Mirabel (1996) and Genzel & Cesarsky (2000).

Despite their large luminosities, bright infrared sources do not represent a major contributor to the energy budget of galaxies in the present-day Universe. Such objects are relatively rare within the local 100–200 Mpc: galaxies with $L_{IR} \geq 10^{11} L_{\odot}$ and with $L_{IR} \geq 10^{12} L_{\odot}$ represent $\sim 6\%$ and $< 1\%$, respectively, of the total infrared emission in the local Universe (Soifer, Houck & Neugebauer 1987; Sanders & Mirabel 1996; Kim & Sanders 1998; Yun, Reddy & Condon 2001). However, the contribution of infrared–bright sources to the galaxy energy budget increases with redshift (see section 5.2), as does their relevance in the framework of galaxy evolution.

3.6. Summary

Although the issue of dust opacity of galaxies is far from settled, an overall picture is apparent: galaxies in the local Universe are only moderately opaque, and extreme values of the opacity are only found in the statistically non-dominant, more active systems.

Table 3 summarizes the main conclusions of this section, by listing the effective extinction values for local galaxies according to morphological type. For disk and irregular galaxies, both the face-on and the inclination-averaged extinctions are given. For instance, in Sb–Scd galaxies, the typical inclination-averaged extinctions are 0.6–0.65 mag larger than face-on at 0.15 μm , ~ 0.4 mag at B, ~ 0.25 mag at I, and 0.1 mag at K, for a stellar to dust scaleheight ratio that varies between 1 in the UV and 2 in the I and K bands (model 5 of section 2.2).

Among the non-active galaxies, luminous Sb–Scd galaxies contain the largest amounts of dust, which absorb $\approx 1/2$ of their bolometric light. For comparison, dust emission represents between 35% and 40% of the bolometric luminosity of our Milky Way galaxy (Cox, Krügel & Mezger 1986; Sodroski et al. 1994). The dust content generally decreases in less luminous galaxies and for earlier and later type galaxies; dust absorbs less than $\sim 15\%$ of the bolometric light in E/S0 galaxies, and the fraction rises to $\approx 30\%$ in irregulars (Table 3).

Interpolating from Table 3, the inclination-averaged effective extinction of the stellar emission in late spiral galaxies at the restframe wavelength of $H\alpha$ is $A_{0.6563} \lesssim 0.60$ mag. This value should be compared with the effective extinction measured for the $H\alpha$ line emission, $A_{H\alpha} \sim 0.8$ – 1.1 mag, from the ratio of the line to the reddening-free thermal radio emission (Kennicutt 1983; Niklas, Klein & Wielebinski 1997; Kennicutt 1998; Bell & Kennicutt 2001). Although there are relatively large uncertainties associated with both numbers, the two extinction values suggest that the nebular emission is more reddened than the stellar continuum, with $A_{H\alpha} \approx 1.5 A_{0.6563}$. Studies of controlled samples indicate a value of 2 as more typical for the ratio between the dust attenuation of the ionized gas and that of the stellar continuum, both in the case of spirals and irregulars (Bell 2001) and in

the case of moderate-intensity starbursts (section 4).

4. A Case Study in the Local Universe: Starburst Galaxies

Among local galaxies, starbursts occupy a special niche. The average UV and infrared luminosities (both proxies for SFR) per unit comoving volume increase with redshift by roughly an order of magnitude up to $z \sim 1-2$ (Lilly et al 1996; Cowie, Songaila & Barger 1999). Active star formation played a larger role in the past than today, and may have been a fundamental ingredient in the shaping of galaxy populations.

Nuclear and circumnuclear starbursts occur in galaxies spanning a wide range of properties, from almost dust-free, infrared-faint, low-mass irregulars (e.g., Tol1924–416 and NGC1569) to dust-rich, massive spirals (e.g, NGC5236), to infrared-bright interacting galaxies (e.g., NGC7714 and NGC6090), to mergers and ULIRGs (e.g., NGC4194 and NGC1614; Arp220, Scoville et al. 1998). Nuclear and circumnuclear bursts of star formation can be triggered by a variety of mechanisms, including secular evolution of bars (Friedli & Benz 1995; Norman, Sellwood & Hasan 1996) and galaxy interactions and mergers (Larson & Tinsley 1978; Keel et al. 1985; Sanders et al. 1988; Mihos & Hernquist 1996; Hibbard 1997). The latter produce the most luminous starbursts (ULIRGs), which rapidly deplete the molecular gas content of the galaxy as merging progresses (Yu & Solomon 1999). Less extreme starbursts, hosted in galaxies with $L_{bol} \lesssim 5 \times 10^{11} L_{\odot}$, obey a positive correlation between the luminosity of the starburst and the luminosity and mass of the host galaxy (Heckman et al. 1998):

$$L_{B,host}(L_{\odot}) \sim 10^{9.9} SFR_{starb}^{0.94}, \tag{5}$$

where SFR_{starb} is in $M_{\odot} \text{ yr}^{-1}$ for a Salpeter IMF in the mass range 0.1–100 M_{\odot} (from the formulae of Kennicutt 1998). Equation 5 is probably a consequence of the fact that large SFRs are sustained by the massive gas inflows that only a deep potential well can support (Heckman et al. 1998). Indeed, from causality arguments, the maximum luminosity of a starburst scales as $\approx \sigma v^2$, with σ the dispersion velocity of the gas and v the rotation velocity of the host galaxy (Heckman 1994; Lehnert & Heckman 1996; Meurer et al. 1997). There are notable exceptions to this average trend: M82 is an example of a dwarf, $M \sim 10^{10} M_{\odot}$ (Sofue et al. 1992) and $L_{B,host} \sim 5 \times 10^9 L_{\odot}$, galaxy hosting a relatively powerful starburst, with $SFR \sim 6 M_{\odot} \text{ yr}^{-1}$ and $L_{IR} \sim 3 \times 10^{10} L_{\odot}$. A secondary effect of both the SFR_{starb} –host galaxy mass correlation and the mass-metallicity correlation is that the more powerful starbursts are hosted in the more metal-rich and dustier host galaxies (Heckman et al. 1998, also Figure 7, panel c):

$$10^{A_{0.15}} \sim 250 SFR_{starb}^{2.2} \tag{6}$$

(see, also, Hopkins et al. 2001). Although equation 6 is not applicable to ULIRGs, still in the local Universe there are no examples of ‘naked’ Arp220-like galaxies, emitting most of the luminosity produced by their $SFR \sim 100-200 M_{\odot} \text{ yr}^{-1}$ directly in the UV. Objects like Arp220 tend to be

heavily extinguished, with $A_V \sim 15\text{--}45$ mag for Arp220 itself (Scoville et al. 1998; Genzel et al. 1998; Shioya, Trentham & Taniguchi 2001), and to be bright infrared sources (section 3.5).

The rest of section 4 discusses the dust reddening and obscuration properties of the local starburst galaxies with $L_{bol} \lesssim 5 \times 10^{11} L_\odot$. The specific sample contains starbursts that are UV-luminous enough to have been detected by IUE (Kinney et al. 1993); it will be termed ‘UV-selected’ in what follows. The sample is not statistically complete or rigorously defined; however, it is representative of the broad range of properties of local UV-bright starbursts (Heckman et al. 1998). These galaxies are not as extreme in dust extinction and activity level as ULIRGs. They have SFRs per unit area in the range $\sim 0.3\text{--}20 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ and cover a limited range in the parameter space of optical attenuation, $A_{H\alpha} \sim 0\text{--}2.5$ mag. The attenuation refers to the integrated value across the starburst site; individual regions or clumps can have effective extinctions as high as $A_{H\alpha} \sim 30$ mag (Beck et al. 1996; Calzetti et al. 1997). The host galaxies cover a wide variety of late type morphologies, from grand design spirals to irregular and amorphous, to disturbed morphologies that result from interactions or merging processes. The starbursts mostly occupy the inner region of solid body rotation of the host galaxy, with sizes $\sim 0.5\text{--}4$ kpc (Lehnert & Heckman 1996). The UV selection (Kinney et al. 1993; Calzetti, Kinney & Storchi-Bergmann 1994) aids the discrimination from their more opaque and infrared-brighter counterparts. Although the UV selection results in some limitations to the applicability of the obscuration properties discussed below (see end of section 4.2), it does not entirely exclude dusty systems; the sample contains objects in which up to 90%–95% of the bolometric energy is re-processed by dust. Table 4 gives three representative examples each for both the high-luminosity, dust-rich end and the low-luminosity, dust-poor end of the UV-selected starbursts, together with the average of the sample.

4.1. Dust Obscuration Characteristics of Starbursts

Although the UV-selected starbursts form an heterogeneous set, their dust reddening and obscuration properties are remarkably uniform. Higher dust optical depths produce redder UV-to-near-IR SEDs and nebular emission line ratios (Figure 6), almost independent of the details of the dust distribution and of the intrinsic stellar population (Calzetti, Kinney & Storchi-Bergmann 1994; Calzetti 1997a).

The geometry of the dust that best describes the reddening of the ionized gas emission in these systems, in the wavelength range $0.48 \mu\text{m}\text{--}2.2 \mu\text{m}$, is that of a foreground-like distribution. Figure 6, panel b, shows the comparison between observations and the models of section 2.2 for the attenuated-to-intrinsic hydrogen line ratios $H\alpha/H\beta$ and $H\beta/Br\gamma$. Internal dust does not appear to be a major component in the starburst region(s), and the little present is likely to be in compact clumps (Calzetti et al. 1995b). The main source of opacity appears to be given by dust that is external, or mostly external, to the starburst region (although still internal to the host galaxy), similar to a (clumpy) dust shell surrounding a central starburst. This is, of course, verified only in the B-to-K wavelength range where the reddening of the nebular emission lines has been measured;

measurements at longer wavelengths could easily reveal more complex geometries. From a practical point of view, the data in Figure 6, panel b, are well described by a simple foreground, non-scattering dust distribution, with MW extinction curve for the diffuse ISM ($R(V)=3.1$); the reddening of the ionized gas is thus parametrized by the color excess $E(B-V)_{gas}$ (equation 4).

The stellar continuum colors show the trend to become redder for increasing reddening of the hydrogen emission line ratios (Figure 6, panels a–c–d). The implications are twofold: (1) variations of the intrinsic SED from galaxy to galaxy are secondary relative to the trend induced by dust obscuration, and (2) within each starburst, the same foreground-like dust geometry holds for both the ionized gas and the non-ionizing stellar continuum.

The first implication is not surprising, at least at UV wavelengths. Since we are observing the Rayleigh-Jeans part of the massive stars spectrum, the intrinsic UV spectral slope⁸ $\beta_{26,o}$ is relatively constant over a fairly large range of ages, with values $-2.7 \gtrsim \beta_{26,o} \gtrsim -2.2$ for constant star formation over $10^6 \text{ yr} \lesssim \text{age} \lesssim 10^9 \text{ yr}$ (see Leitherer & Heckman 1995, and the Table in Appendix B). In the same conditions, the production of ionizing photons is also constant. In an instantaneous burst of star formation, the ionizing photons are more age-sensitive than the non-ionizing photons that produce the stellar continuum and disappear before appreciable changes in the UV spectral shape can be observed. The observed UV spectral slope β_{26} of the UV-selected starbursts span the range $-2.5 \lesssim \beta_{26} \lesssim +0.4$, much larger than what expected from stellar population variations alone, and increases for increasing values of the attenuated-to-intrinsic hydrogen line ratios (i.e., color excess, Figure 6).

In addition to correlate with the reddening of the ionized gas, the reddening of the UV stellar continuum, as measured by β_{26} , correlates with the the infrared-to-blue and the infrared-to-UV luminosity ratios, L_{IR}/L_B and $L_{IR}/L_{0.16}$ ((Figure 7 and Calzetti et al. 1995b; Meurer et al. 1999). These ratios are a measure of the total dust opacity in the starburst region, because the bulk of the starburst’s energy is coming out in the UV–B. In addition, dust *absorption* is the main process that removes light from the line of sight (Calzetti et al. 1995b); when large galactic regions are observed light scattered by dust out of the line of sight compensates, on average, that scattered into the line of sight. The opacity–reddening correlation means that measurements of reddening can be used to infer the total dust absorption in UV-selected starbursts (Meurer et al. 1999) with an uncertainty, $\Delta A_{0.16} \sim 0.6$ mag for individual objects and $\sim 20\%$ when averaged over large samples (Calzetti et al. 2000), that is dominated by variations in the starburst populations and in the details of the dust geometry from galaxy to galaxy. Such a correlation is expected for a foreground-like dust geometry (Figure 3, panel d; see discussion in Gordon et al. 2000).

The slopes of the correlations in Figure 6 identify the reddening suffered by the stellar continuum, $A_{\lambda_1,star} - A_{\lambda_2,star} = [k^e(\lambda_1) - k^e(\lambda_2)]E(B-V)_{gas}$, with $k^e(\lambda)$ the obscuration curve, while the

⁸ $\beta_{26,o}$ and β_{26} refer to the intrinsic and observed, respectively, UV spectral slope measured between $0.125 \mu\text{m}$ and $0.26 \mu\text{m}$ as defined in Calzetti, Kinney & Storchi-Bergmann (1994), see Appendix B for more details.

total obscuration measurements of Figure 7 provide the zeropoint for $k^e(\lambda)$ (see, also, Calzetti et al. 2000). The intrinsic starburst flux density $f_i(\lambda)$ is thus recovered from the observed flux density $f_o(\lambda)$ via:

$$f_i(\lambda) = f_o(\lambda) 10^{0.4E(B-V)_{gas} k^e(\lambda)}, \quad (7)$$

where the obscuration curve for the stellar continuum, $k^e(\lambda)$, is given by (Calzetti et al. 2000):

$$\begin{aligned} k^e(\lambda) &= 1.17(-1.857 + 1.040/\lambda) + 1.78 & 0.63 \mu m \leq \lambda \leq 2.20 \mu m \\ &= 1.17(-2.156 + 1.509/\lambda - 0.198/\lambda^2 + 0.011/\lambda^3) + 1.78 & 0.12 \mu m \leq \lambda < 0.63 \mu m. \end{aligned} \quad (8)$$

The above expression folds into a single functional form a variety of effects: extinction proper, scattering, and the geometrical distribution of the dust relative to the emitters. It is derived from the spatially integrated colors of the entire stellar population in the starburst, and represents the ‘net’ obscuration of the population itself. As mentioned above, the obscuration curve has mainly an absorption component, as the effects of scattering are averaged out. Thus, it should not be confused with the extinction curve $k(\lambda)$ defined in section 2.1. Equation 8 implies that 1 mag of reddening between B and V for the ionized gas, $A_{B,gas} - A_{V,gas} = 1$ mag, corresponds to $A_{B,star} - A_{V,star} = 0.44$ mag of reddening for the stellar continuum. This fact can be alternatively expressed as:

$$E(B - V)_{star} = 0.44E(B - V)_{gas}. \quad (9)$$

In other words, the stellar continuum suffers roughly half of the reddening suffered by the ionized gas (Calzetti, Kinney & Storchi-Bergmann 1994; Fanelli, O’Connell & Thuan 1988; Mas-Hesse, Arnault & Kunth 1989, see, also, Figure 3, panels e and f). Although $E(B - V)_{star}$ parametrizes the amount of reddening of the stellar continuum, it is not a color excess proper as in the case of individual stars, because of the dust geometry effects folded in the expression of $k^e(\lambda)$. One obvious characteristic of the obscuration curve is the absence of the $0.2175 \mu m$ bump, which is a prominent feature of the MW extinction curve (Figure 1). Dust/emitter geometries that can dilute the bump include mixed distributions with large optical depths (Natta & Panagia 1984; Granato et al. 2000; Gordon et al. 2000). However, mixed geometries do not account for the full range of observational data (Figure 3), because the sources that contribute to the emerging SED are located at progressively lower optical depths τ_V for decreasing wavelength. In particular, the reddest UV slope produced by mixed geometries is $\beta_{26} \sim -0.7$ (Charlot & Fall 2000), to be compared with $\beta_{26} \sim 0$ observed in starburst galaxies (Figure 6, panel a). Thus, the lack of the feature is probably intrinsic to the *extinction curve* of the starbursts (Gordon, Calzetti & Witt 1997), and may be due to the high UV energy densities that characterize these regions (sections 2.1 and 4.2).

4.2. The Physical Origin of the Dust Geometry in ‘UV–bright’ Starbursts

This section describes a dust model that attempts to reconcile two apparently contradictory facts: (1) stars in starbursts are on average a factor ≈ 2 less reddened than the ionized gas (equa-

tion 9), and (2) both stars and ionized gas are affected by the same foreground-like dust distribution (Figure 6). A schematic representation of a dust/star/gas configuration that can at the same time account for both effects is shown in Figure 8. Stars are born within optically thick molecular clouds, and the short-lived, most massive stars remain closely associated with their parental cloud and the gas they ionize for their entire lifetime (e.g., Walborn et al. 1999). These stars and their surrounding gas will be generally highly attenuated. As the starburst population evolves, the inside of the region of star formation becomes depleted of dust (Calzetti, Kinney & Storchi-Bergmann 1996). With energy densities $\gg 100$ times higher than in the local ISM, starburst environments are rather inhospitable to dust. Shocks from supernovae destroy dust grains, via grain-grain collisions and sputtering (Draine & Salpeter 1979; Jones et al. 1994). The average lifetime of a refractory grain is $\sim 8 \times 10^6$ yr, for a supernova rate of 0.05 yr^{-1} and an ISM mass of $5 \times 10^8 M_{\odot}$ (e.g., McKee 1989), about one order of magnitude or more shorter than the typical lifetimes of starbursts (Calzetti 1997a; Calzetti et al. 1997; Greggio et al. 1998; Aloisi, Tosi & Greggio 1999). In addition, hot-star-winds- and supernova-driven outflows evacuate both interstellar gas and dust from the region (Heckman, Armus & Miley 1990; De Young & Heckman 1994; Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000; Heckman et al. 2000). R136, the central cluster in 30 Doradus, is an example of a few million years old cluster surrounded by an evacuating region (Scowen et al. 1998). Ionized gas separated, in projection, from the hot stars has also been observed in nearby starbursts (Hunter & Gallagher 1997; Wang, Heckman & Lehnert 1998; Calzetti et al. 1999; Maíz-Apellániz & Walborn 2000).

The evacuated (clumpy) dust will act as a foreground-like distribution for both the gas (also at the edges of the region) and for the central stars (Figure 8, Calzetti, Kinney & Storchi-Bergmann 1996; Witt & Gordon 2000; Gordon et al. 2000); however, the ionized gas will be more obscured than the stars, because of its spatial location and closer association with the dust (Calzetti 1997a). This gas is more likely to contribute to the nebular emission observed at UV–optical wavelengths than the gas in molecular clouds, because of its milder obscuration. In the presence of multiple generations of starburst populations, the long-lived, non-ionizing stars have time to ‘diffuse’ into regions of lower dust density (Calzetti, Kinney & Storchi-Bergmann 1994; Charlot & Fall 2000; Granato et al. 2000), as their native clusters are disrupted by evaporation or by the host galaxy’s gravitational field (Leisawitz & Hauser 1988; Kim, Morris & Lee 1999; Tremonti et al. 2001). Cool stellar populations in the LMC have, for instance, been observed to be less embedded in dust than hotter stellar populations (Zaritsky 1999). A similar trend is observed in the young (< 20 Myr) open clusters of the Milky Way (Yadav & Sagar 2001). Massive, non-ionizing stars can still produce significant UV emission. Hence, the integrated UV–optical stellar continuum from the combination of the ageing, diffusing populations and the starburst-embedded young populations will be less obscured than the emission from the nebular gas (Calzetti, Kinney & Storchi-Bergmann 1994; Gasda & Leitherer 1996). For the stellar continuum and the ionized gas to have correlated obscuration values (equation 9), multiple starburst generations or long-lasting star formation events (rather than ‘instantaneous’ events) are needed to attain an equilibrium between the number of stars drifting out of molecular clouds/starburst regions and the number of newly-born, dusty stars.

Starbursts hosted in dwarf galaxies are observed to have on-going star formation over $\gtrsim 200$ Myr (Calzetti et al. 1997; Greggio et al. 1998; Aloisi, Tosi & Greggio 1999), and durations could be as long in more massive starburst galaxies (Calzetti 1997a).

Although the obscuration curve can be widely applied to UV-selected starbursts, it is not necessarily applicable to systems with different stellar population or ISM characteristics. In the case of non-starburst galaxies there is no obvious mechanism for creating a foreground-dust-like geometry. In extreme starbursts as the ULIRGs, the non-applicability of the obscuration curve has been demonstrated observationally (Goldader et al. 2001, and Figure 7, panel a). In these galaxies, the high central concentration of gas and dust is likely to induce more extreme geometries than in UV-selected galaxies, and to produce combinations of clumpy mixed and foreground distributions. Galaxies whose infrared properties are intermediate between the ULIRGs and the UV-selected galaxies will progressively deviate from the dust geometry of the latter (Alonso-Herrero et al. 2001; Förster Schreiber et al. 2001). Dust in subsonic HII regions is likely to be mixed with the stars, rather than having been pushed away or destroyed as in starbursts, and scattering of stellar light into the line of sight may be an important component in the attenuation budget (Caplan & Deharveng 1986; Bell et al. 2001). Because of the differences in the physical environment between the two types of objects, the foreground-dust-like approximation no longer holds for subsonic HII regions and equation 8 does not apply. Differences in the star formation history can also contribute to the difference between subsonic HII regions and starbursts, with instantaneous bursts being a better description for the former and extended star formation for the latter; thus, differential attenuation between ionized gas and stars is not necessarily expected in the HII regions. Supersonic HII regions could be at the boundary between the two extremes just discussed; one example is 30 Doradus, that has evolved to the point of resembling a mini-starburst (Walborn 1991).

To conclude, the starburst obscuration curve is a purely empirical result, and its derivation is independent of any assumption about the starburst’s population, the dust geometry, or the details of the extinction curve. It provides statistical estimates of the reddening and obscuration of local UV-selected starbursts, and deviations as large as ~ 0.6 mag from the mean obscuration at $0.16 \mu\text{m}$ are to be expected on a case-by-case basis. The physics of the starburst environment provides an explanation of the ‘foreground-dust-like’ behavior of the curve, of the correlation between the reddening of the ionized gas and that of the stellar continuum, and of the correlation between reddening and total obscuration. As a sample, local UV-selected starbursts are characterized by modest amounts of reddening and obscuration, that are correlated with the star formation activity (equation 6). The median color excess is $E(B-V)_{gas} \sim 0.35$ (Calzetti 1997b), corresponding to UV continuum attenuations of $A_{UV,star} \sim 1.6, 1.4, 1.1$ mag at $0.15, 0.20, 0.30 \mu\text{m}$, respectively (Table 4 and Buat & Burgarella 1998; Meurer et al. 1999).

4.3. Useful Expressions

Observables like the UV slope, the colors, and the luminosities and equivalent widths of the hydrogen lines can be readily related to the dust-induced color excess of the ionized gas and, through equation 9, of the stellar continuum. The UV slope is correlated with $E(B-V)_{gas}$ (Figure 6 panel a), and equation 8 gives:

$$\beta_{26} = 2.08 E(B - V)_{gas} + \beta_{26,0}, \quad (10)$$

where a list of $\beta_{26,0}$ values is given in the Table of Appendix B. The slope of the correlation between β_{26} and $E(B-V)_{gas}$ is somewhat steeper than that measured by Calzetti, Kinney & Storchi-Bergmann (1994) directly from the data (1.88 ± 0.28), but the two are within 1σ of each other. It should also be noted that equation 10 becomes a lower envelope to the data points in Figure 6, panel a, for $\beta_{26,0} < -2.25$, a value appropriate for dust-free, star-forming populations. This indicates that variations of the dust/stars/gas geometry from the schematic model of Figure 8 and/or of the stellar population from the theoretical extreme $\beta_{26,0} \leq -2.25$ has the effect of reddening the UV slope even for $E(B-V)_{gas} \sim 0$. The vertical scatter in Figure 6, panel a should thus be interpreted as due to such variations from galaxy to galaxy.

Reddening expressions for optical colors can be directly derived from equation 8 (see, also, Figure 6, panels c and d). A mixed UV–optical color, $0.28-V$, could be useful to infer the reddening of intermediate redshift ($\langle z \rangle \sim 0.6$) starburst galaxies observed in B and I, and the reddening of one relative to the other is given by:

$$A_{0.28,star} = 1.80 A_{V,star}. \quad (11)$$

Under the assumption that the restframe UV emission and the nebular lines are both due to massive stars, the reddening of the UV continuum relative to the nebular hydrogen emission is given by:

$$A_{0.16,star} = 1.21 A_{H\beta,gas} \quad (12)$$

$$A_{0.16,star} = 1.78 A_{H\alpha,gas} \quad (13)$$

$$A_{0.28,star} = 1.29 A_{H\alpha,gas}. \quad (14)$$

Figure 6, panel e shows the comparison between data of local galaxies and equation (13) (Calzetti 1997b). While the agreement between the data in the first four panels of Figure 6 and equation 8 is a direct consequence of the fact that those data were used to derive the starburst obscuration curve, the match between data and expected trend in the bottom two panels of the figure is a consistency check, since it was not imposed a priori.

One immediate consequence of the differential reddening between gas and stars is that the equivalent widths of the nebular lines depend on the amount of gas obscuration; for the $H\alpha$ and $H\beta$ emission lines the relations are (Calzetti, Kinney & Storchi-Bergmann 1994):

$$\log[EW(H\beta)_a/EW(H\beta)_o] = -0.64E(B - V)_{gas}, \quad (15)$$

$$\log[EW(H\alpha)_a/EW(H\alpha)_o] = -0.40E(B - V)_{gas}, \quad (16)$$

where the attenuated and intrinsic EWs are directly compared. Comparison of these trends with the data points is shown in panel f of Figure 6; the trend given by the obscuration curve marks an upper envelope to the ensemble of observed EWs, because the presence of older stellar populations underlying the starbursts dilutes the contrast between the emission lines and the stellar continuum in the data.

Statistically speaking, the UV slope is a good estimator of the total obscuration affecting the starburst (Meurer et al. 1999, and Figure 7); in particular, the ratio of the dust infrared luminosity, L_{IR} , to the stellar UV or blue luminosity, $L_{0.16}$ or L_B , is related to β_{26} via:

$$\log \left[\frac{1}{1.68} \left(\frac{L_{IR}}{L_{0.16}} \right)_{star} + 1 \right] \simeq \frac{A_{0.16,star}}{2.5} = 0.84(\beta_{26} - \beta_{26,0}), \quad (17)$$

$$\log \left[\frac{1}{3.85} \left(\frac{L_{IR}}{L_B} \right)_{star} + 1 \right] \simeq \frac{A_{B,star}}{2.5} = 0.43(\beta_{26} - \beta_{26,0}). \quad (18)$$

The two constant values on the left-hand-side of equations 17 and 18, 1.68 and 3.85, represent the bolometric corrections of the stellar emission relative to the UV or B. The correction for the B-band is larger and subject to more uncertainties than that for the UV, hence the larger scatter in the data point of Figure 7, panel b. Equation 17 can be rewritten as:

$$\log \left[\frac{1}{1.68} \left(\frac{L_{IR}}{L_{0.16}} \right)_{star} + 1 \right] = 1.76E(B - V)_{gas}, \quad (19)$$

where the equation above represents a lower envelope to the data (Figure (7), panel d and Calzetti et al. 2000), and has a scatter comparable to that of Figure 6, panel a. The nature of the scatter in the β_{26} vs. $E(B-V)_{gas}$ and in the $L_{IR}/L_{0.16}$ vs. $E(B-V)_{gas}$ relations is the same: it is due to variations from galaxy to galaxy of the starburst populations and of the dust/star/gas geometry.

5. Measurements of Dust Opacity in High-Redshift Galaxies

As discussed in the Introduction, the energy balance between UV–optical and infrared cosmic background suggests that there have been infrared luminous galaxies at all epochs. The number density of quasars was >100 times higher at $z \sim 2.5$ than today (e.g., Shaver et al. 1999) and star formation activity was ~ 3 to 10 times higher at $z \gtrsim 1$ than at $z \sim 0$ (Lilly et al 1996; Cowie, Songaila & Barger 1999), flattening or decreasing only beyond $z \sim 1-2$ (Madau et al. 1996; Steidel et al. 1999). If the association between activity and dust opacity observed in the local Universe (equation 6) holds at high redshift as well, galaxies in the past may have been as dusty as or dustier than today (section 5.2).

Among the methods described in section 3, the multiwavelength comparison is the only practical approach for measuring the dust opacity of galaxies beyond the local few hundred Mpc. However, because of observational difficulties, the wavelength coverage of the typical sample is limited to a few windows, often with little overlap from sample to sample. Measures of the content, nature,

and opacity effects of the dust in distant galaxies are therefore still at a very early stage, and the picture is vastly incomplete and controversial.

5.1. Dust in Damped Ly α Systems

The very first evidence for presence of dust in high redshift systems came from studies of Damped Ly α Systems (DLAs, Meyer & York 1987; Fall, Pei & McMahon 1989; Meyer & Roth 1990; Pettini, Boksenberg & Hunstead 1990; Pei, Fall & Bechtold 1991; Pettini et al. 1994; Zuo et al. 1997; Pettini et al. 1997a; Vladilo 1998; Pettini et al. 2000a; Ge, Bechtold & Kulkarni 2001). DLAs are the largest HI column density absorption systems seen in the spectra of background quasars, with $N(\text{HI}) \geq 10^{20.3} \text{ cm}^{-2}$. Their metallicities cover the range $\sim 1/100$ – $1/10$ solar for $z \sim 0.5$ – 4 , with a mean value $\sim 1/13$ solar at $z \sim 0.5$ – 3 and little evidence for evolution with redshift (Prochaska & Wolfe 2000; Pettini et al. 1999, 1997b; Lu et al. 1996). Selection biases against the dustiest, and most metal-rich DLAs and problems with dust depletion corrections have been advocated as possible reasons for the observed weak metallicity evolution (Fall & Pei 1993; Boissé et al. 1998; Savaglio, Panagia & Stiavelli 2000, see, however, Ellison et al. (2001)). The dust fraction in DLAs is measured by comparing the abundance of dust-depleted metals such as Cr II, Fe II, and Si II against that of a metallicity tracer such as Zn II, all of them producing rest-frame UV absorption lines (Meyer & York 1987). The dust-to-metals ratio in DLAs is in the range 50%–60% of the Milky-Way value; this, combined with the generally low metallicities, indicates that DLAs are relatively transparent systems, with dust-to-gas ratios between 2% and 25% of the Milky-Way value (Fall, Pei & McMahon 1989; Pei, Fall & Bechtold 1991; Pettini et al. 1997a; Vladilo 1998). The absence of the $0.2175 \mu\text{m}$ dust absorption associated with DLAs led Pei, Fall & Bechtold (1991) to conclude that the extinction curve in these systems is probably similar to the one observed in the Magellanic Clouds. More recently, though, Malhotra (1997) reported a $\sim 3 \sigma$ detection of the dust absorption feature in the composite spectra of MgII absorbers. Although presence of modest quantities of dust is well established in DLAs, the weak or absent evolution of the metal content and of the cosmological mass density with redshift (Rao & Turnshek 2000) questions their relationship to luminous galaxies, and favors the interpretation that DLAs preferentially trace galaxies with extended gas distributions and low metal and dust contents (Le Brun et al. 1997; Turnshek, Rao & Nestor 2001) and the unevolved outskirts of galaxies (Ferguson, Gallagher & Wyse 1998).

5.2. Dust Emission from Distant Star-Forming Galaxies

In recent years, facilities/instruments like ISO and the Sub-millimeter Common User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT) have achieved high enough sensitivities in the mid- and far-infrared to detect *dust emission* beyond a few μm from statistically significant samples of galaxies at cosmological distances. Studies on the ISO and SCUBA surveys, especially the identification of the optical/near-IR counterparts to the infrared sources and the

redshift measurements, are still ongoing and the results described below should be considered in many instances preliminary.

ISO surveys have yielded $\approx 1,500$ sources in the redshift range $0 \lesssim z \lesssim 1.5$, down to a sensitivity limit of ≈ 0.1 mJy in the mid-IR ($6.75 \mu\text{m}$, $12 \mu\text{m}$, and $15 \mu\text{m}$) and ≈ 0.1 Jy in the far-IR ($90 \mu\text{m}$ and $175 \mu\text{m}$, Rowan-Robinson et al. 1997; Oliver et al. 1997; Taniguchi et al. 1997; Kawara et al. 1998; Clements et al. 1999; Altieri et al. 1999; Aussel et al. 1999; Flores et al. 1999a,b; Puget et al. 1999; Serjeant et al. 2000; Scott et al. 2000; Efstathiou et al. 2000; Dole et al. 2001). Full lists of all surveys are given in Rowan-Robinson et al. (1999) and Elbaz (1999). The number counts at $175 \mu\text{m}$ account for $\sim 10\%$ of the CIB (Puget et al. 1999; Dole et al. 2001), showing that the bulk of the background has not been resolved yet at these wavelengths. Nevertheless, the number counts at mid- and far-IR wavelengths are about 3–10 times above the no-evolution extrapolation of the local IRAS counts (Elbaz et al. 1999; Aussel et al. 1999; Puget et al. 1999; Serjeant et al. 2000; Efstathiou et al. 2000). The implication is a strong luminosity evolution, $L_{IR} \propto (1+z)^{4.5}$, or a combination of luminosity and density evolution of the infrared sources out to $z \sim 1$ (Clements et al. 1999; Xu 2000; Chary & Elbaz 2001; Franceschini et al. 1994; Guiderdoni et al. 1998), that is comparable to or stronger than the luminosity evolution observed at restframe UV wavelengths out to the same redshift (Lilly et al. 1996; Cowie, Songaila & Barger 1999; Sullivan et al. 2000). The ISO counts are thus dominated by luminous infrared galaxies at $z \lesssim 1$, with $L_{bol} \sim L_{IR} \gtrsim 10^{11} h_{65}^{-2} L_{\odot}$ (Rowan-Robinson et al. 1997; Elbaz 1999; Xu 2000). Although this conclusion is based on the highly uncertain conversion of the $15 \mu\text{m}$ emission⁹ to a total infrared luminosity, it is qualitatively supported by the optical counterparts of the ISO sources. Close to 100 mid-IR sources, with median redshift $\langle z \rangle \sim 0.7$ – 0.8 have been so far identified at optical/near-IR wavelengths (Aussel et al. 1999; Flores et al. 1999b; Rigopoulou et al. 2000) [$\langle z \rangle \sim 0.1$ – 0.2 for the $12 \mu\text{m}$ sample (Clements, Desert & Franceschini 2001)]. Many of the restframe optical spectra show characteristics of dusty luminous starbursts, with current bursts of star formation superimposed on a prominent population of A stars, and with attenuation values $A_V \gtrsim 0.5$ – 1.8 mag (Flores et al. 1999b; Rigopoulou et al. 2000; Poggianti & Wu 2000).

At the time of writing, SCUBA surveys at $850 \mu\text{m}$ of ‘blank’ fields and targeted lensed objects have detected a total of ≈ 100 sources with flux densities in the range ~ 0.5 mJy to $\gtrsim 10$ mJy and redshifts between $z \sim 1$ and 3, although sources as far away as $z \approx 5$ may be present (Smail, Ivison & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Smail et al. 1998; Eales et al. 1999; Lilly et al. 1999; Smail et al. 1999; Barger et al. 1999b; Barger, Cowie & Richards 2000; Smail et al. 2000; Eales et al. 2000; Chapman et al. 2001; Fox et al. 2001; Scott et al. 2001). The number counts down to 2 mJy and to 0.5 mJy account for $\sim 20\%$ – 30% and more than 90%, respectively, of the CIB (Hughes et al. 1998; Barger et al. 1998; Eales et al. 1999; Barger, Cowie & Sanders

⁹At $z \sim 1$ the flux density at $15 \mu\text{m}$ is centered on the restframe emission of the aromatic features that dominate the region between $6 \mu\text{m}$ and $12 \mu\text{m}$; the relation between the intensity of the features and the total infrared emission is still unsettled (Boselli et al. 1998; Dale et al. 2001).

1999a; Eales et al. 2000; Blain et al. 1999c). However, the latter fraction is potentially affected by small number statistics: so far only a few sources have flux densities below 2 mJy, the SCUBA confusion limit in blank fields, all of them from the survey of lensed galaxies (Blain et al. 1999a). Observations at 850 μm probe the Raileigh-Jeans tail of the thermal dust emission of galaxies at least to redshift $\approx 5\text{--}7$. A source at $z \geq 1$ and with an 850 μm flux density of 2 mJy corresponds to a luminosity $L_{IR} \sim 2 \times 10^{12} h_{65}^{-2} L_{\odot}$, for typical SEDs of local infrared-selected galaxies (Lisenfeld, Isaak & Hills 2000; Dunne et al. 2000; Dunne & Eales 2001); this is roughly the luminosity of a ULIRG like Arp220. The few optical/near-IR counterparts which have been identified are faint, often with $I > 24$ and $K \gtrsim 20\text{--}21$ (Smail et al. 1998; Barger et al. 1999b; Smail et al. 1999; Lilly et al. 1999; Ivison et al. 2000); in most cases the ratio $L_{IR}/L_R < 0.05$, where L_R is the luminosity in the observer-frame R band, and the infrared emission accounts for more than 95%–99% of the bolometric luminosity. It is indeed widely accepted, also on the basis of the few available multi-wavelength SEDs, that the SCUBA sources are ‘cosmological ULIRGs’ (Hughes et al. 1998; Barger et al. 1998; Lilly et al. 1999; Smail et al. 1998; Ivison et al. 2000), although this generalization has been recently questioned (Eales et al. 2000). The median redshift of the surveys is $\langle z \rangle \simeq 2.5$ (Lilly et al. 1999; Smail et al. 1999; Barger et al. 1999b; Barger, Cowie & Richards 2000; Eales et al. 2000; Smail et al. 2000; Chapman et al. 2001; Fox et al. 2001); however, $< 10\%$ of all the sources have reliable redshift determinations from optical/near-IR counterparts, and a total of $\approx 50\%$ of the sample have photometric redshifts, most often derived from the radio/sub-mm spectral-index relation of Carilli & Yun (1999). The comoving number density of SCUBA sources in the redshift range $z=1\text{--}3$ brighter than 6 mJy is $\sim 3\text{--}5 \times 10^{-5} h_{65}^3 \text{Mpc}^{-3}$ in our cosmology (Barger, Cowie & Richards 2000; Scott et al. 2001), about two orders of magnitude larger than the corresponding number density of local ULIRGs brighter than $10^{12} L_{\odot}$ (Kim & Sanders 1998). A strong luminosity evolution, possibly as strong as $L_{IR} \propto (1+z)^3$ to $z \sim 2$, is also implied by the number counts (e.g., Scott et al. 2001). Although the statistical properties of the sources are often inferred using the star-forming Arp220 as a template, a fraction of AGNs is present in the sample (Ivison et al. 1998; Barger et al. 1999b). Current best estimates, based on the X-ray luminosity of the sources favor an AGN fraction $\sim 20\%$ (Severgnini et al. 2000; Hornschemeier et al. 2000; Fabian et al. 2000; Barger et al. 2001); this value will generally depend on the source luminosity range, as it does in the local Universe (Genzel et al. 1998; Lutz et al. 1998; Veilleux, Kim & Sanders 1999).

5.3. Dust Reddening and Obscuration in Distant Star-Forming Galaxies

Multi-wavelength observations of optically-selected samples of intermediate and high redshift galaxies are generally limited to the rest-frame UV and optical windows, with few exceptions (e.g., Flores et al. 1999b; Chapman et al. 2000). Such surveys suffer the same limitations of local UV-optical samples, with the added complication of the often incomplete wavelength coverage. By probing only the *differential attenuation*, the UV-optical data provide, in principle, lower limits to the actual dust opacity of the galaxy (section 2.2, but see also section 4). In order to differentiate an ageing stellar population from dust as the cause of the SED reddening, a variety of approaches have

been adopted by different authors. Common diagnostics include the Balmer line decrement $H\alpha/H\beta$, line-to-continuum ratios, e.g. $H\alpha/UV$ and $H\beta/UV$, and multi-color SED fitting. Limitations to each of these diagnostics are discussed in section 2.2 and in the sections below, as appropriate.

5.3.1. Galaxies at redshift $z \lesssim 2$

For a UV-selected sample of star-forming galaxies at $z \approx 0.2$, Sullivan et al. (2000) and Sullivan et al. (2001) derive an average attenuation $A_{H\alpha} \sim 0.8$ mag and find tentative evidence that those systems follow an obscuration–SFR correlation similar to that observed in more local galaxies (Wang & Heckman 1996; Heckman et al. 1998; Hopkins et al. 2001). The authors use a combination of UV ($0.20 \mu\text{m}$), optical ($H\alpha$ and $H\beta$) and radio (1.4 GHz) data to analyze their sample, although their reddening estimates are mostly based on the subsample for which they can measure $H\alpha/H\beta$ ratios. If the starburst obscuration curve (section 4) applies to $z \approx 0.2$ star-forming galaxies, an attenuation $A_{H\alpha} \sim 0.8$ mag for the nebular line corresponds to $A_{0.20} \sim 1.3$ and $A_{0.16} \sim 1.4$ for the UV stellar continuum. Although these figures agree with local measurements of the extinction at UV and $H\alpha$ in star-forming galaxies (section 3.6 and Table 3), the UV selection of the sample potentially biases the reddening measures towards low values by excluding more heavily extinguished galaxies.

The $z \sim 1$ Balmer–Break sample of Adelberger & Steidel (2000) is also a restframe-UV/blue–selected one. Exploiting the presence of the Balmer discontinuity at $\sim 0.365 \mu\text{m}$ in galaxy SEDs to select $z \sim 1$ candidates (a derivative of the Lyman–Break technique, see next section), these authors have obtained spectroscopic confirmation for ≈ 700 galaxies. The sample contains a large variety of galaxies, from active starbursts to quiescent star-forming to post-starbursts. If the $z \sim 1$ galaxies with blue ($\beta_{26} \lesssim -0.3$) SEDs are analogs of local starbursts and follow the same IR/UV-versus- β relation, they also follow an obscuration–SFR relation similar to the local one, with a comparable range of attenuations (Figure 9, panel a). However, for fixed opacity, the $z \sim 1$ galaxies tend to have on average brighter UV+IR luminosities (larger SFRs) than the $z \sim 0$ galaxies. Thus, even taking selection effects into account, the distant galaxies are, on average, more actively star-forming for the same amount of obscuration than the local starbursts (Adelberger & Steidel 2000).

Glazebrook et al. (1999), Yan et al. (1999), and Moorwood et al. (2000) use restframe $H\alpha$ observations and $H\alpha/UV$ comparisons to infer dust reddening in star-forming galaxies at redshift $z \sim 1$ –2.2. The I-band–selected sample of Glazebrook et al. (1999) corresponds to restframe $\sim V$ for a $z=1$ galaxy: the longer wavelength selection of the samples mitigates, although does not remove completely, the bias against dust obscured galaxies introduced by UV selections [for the Canada-France Redshift Survey employed by Glazebrook et al. (1999), see Lilly et al. (1995), and for the sample used by Yan et al. (1999), see McCarthy et al. (1999)]. The presence of dust reddening in the $z \sim 1$ –2.2 samples is derived from the discrepancy between the measured $L_{H\alpha}/L_{0.28}$

luminosity ratio and the ratio predicted by dust-free models¹⁰. Figure 10 compares the range of attenuated-to-intrinsic values $(L_{H\alpha}/L_{0.28})_a/(L_{H\alpha}/L_{0.28})_o$ derived from data by the three groups of authors¹¹ with predictions from the dust models of section 2.2. Geometries where dust and stars are homogeneously mixed, either in spheroidal or flattened distributions, appear less effective in reproducing the observed $H\alpha/UV$ ratios than foreground geometries (Figure 10). If the foreground and starburst distributions bracket the possible range of dust/emitter morphologies for the $z\sim 1-2$ $H\alpha$ galaxies, the front-to-back optical depths are $\tau_V \sim 0.6-4.9$ mag (Figure 10, bottom panel), and the effective attenuations are $A_{H\alpha} \sim 0.6-4.3$ mag, $A_{0.28} \sim 1.5-5$ mag, $A_{0.16} \sim 3-7$ mag, for SMC extinction. MW-like and SMC-like extinction curves give results that are less than 0.1 mag apart at $\lambda \geq 0.28 \mu\text{m}$, but ~ 1.2 mag different at $\lambda=0.16 \mu\text{m}$, with larger obscurations given by the SMC extinction curve. Uncertainties in the metallicity, IMF, and star formation history of the galaxy stellar populations introduce a factor $\gtrsim 2$ additional scatter on the inferred opacities (Table 3 in Glazebrook et al. 1999). The major limitation is, however, that dust opacities measured from the current $H\alpha$ surveys of galaxies are probably not representative of the $z\sim 1-2$ population as a whole. By number, Glazebrook et al. (1999)’s and Moorwood et al. (2000)’s samples are small (13 galaxies and 5 galaxies, respectively); Yan et al. (1999)’s sample, albeit 2.5 times larger than Glazebrook et al. (1999)’s, does not measure the $H\alpha$ emission on the same galaxies for which UV is available. For such small samples sensitivity limits induce a strong selection effect: the observed galaxies will be among the brightest in $H\alpha$ and, in addition, contamination from AGN/Seyfert nuclei is not excluded (Whittle 1992). Therefore, such surveys sample the high end of the activity and dust obscuration ranges for optically-detectable systems at $z\sim 1-2$ (Glazebrook et al. 1999; Sullivan et al. 2000, and equation 6).

In summary, the limited information available on galaxies at $z\approx 1$ suggests that dust opacities cover a range similar to that of local star-forming and starburst galaxies; they may follow a similar relation $A_\lambda \propto \log(\text{SFR})^\alpha$ (see equation 6), with the proportionality constant revised downward relative to the local sample.

5.3.2. Galaxies at redshift $z > 2$

To date, the surveys that have most efficiently secured large populations of galaxies beyond $z\sim 2$ are those that exploit the Lyman discontinuity at restframe $0.0912 \mu\text{m}$ to identify high-redshift candidates; these are the so-called Lyman-Break Galaxies (LBGs, Guhathakurta, Tyson & Majewski 1990; Steidel & Hamilton 1992; Steidel et al. 1996a,b; Giavalisco, Steidel & Macchetto 1996b; Lowenthal et al. 1997; Giavalisco et al. 1998; Adelberger et al. 1998; Steidel et al. 1999; Adelberger

¹⁰Moorwood et al. (2000) measure the restframe $L_{H\alpha}/L_{0.25}$ ratio; the small extrapolation to $L_{H\alpha}/L_{0.28}$ is done here assuming a constant star formation population.

¹¹The intrinsic ratio $(L_{H\alpha}/L_{0.28})_o$ is an average of $H\alpha$ and UV luminosities for a variety of IMFs, star formation histories, and metallicities of stellar populations, see Table 3 in Glazebrook et al. (1999).

& Steidel 2000). So far, there are $\sim 1,000$ spectroscopically confirmed LBGs at $z \sim 3$, and ~ 70 at $z \sim 4$. The LBG population is a substantial component of the high redshift “zoo”: their comoving number density at $z=3$ is $n(z=3) \sim 3 \times 10^{-2} h_{65}^3 \text{ Mpc}^{-3}$ (Steidel et al. 1999), comparable to the density of local galaxies (Marzke, Huchra & Geller 1994). By selection, i.e. due to the need of presenting a relatively blue continuum longward of $\text{Ly}\alpha$, this high redshift population tends to be biased against systems with predominantly old populations, or systems with large amounts of dust extinction. Indeed, most LBGs show evidence for ongoing or recent star formation activity (Steidel et al. 1996b; Pettini et al. 2000b, 2001; Papovich, Dickinson, & Ferguson 2001). From a purely phenomenological point of view, LBGs resemble local UV-selected starburst galaxies (section 4). The obscuration-corrected SFRs per unit galactic area are $\sim 0.2\text{--}25 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, for a $0.1\text{--}100 \text{ M}_{\odot}$ Salpeter IMF (Steidel et al. 1996b, 1999; Papovich, Dickinson, & Ferguson 2001; Shapley et al. 2001), corresponding to $\sim 0.5\%\text{--}50\%$ the maximum SFR per unit galactic area measured in the local Universe (Lehnert & Heckman 1996; Meurer et al. 1997); this is similar to the observed range in nearby UV-selected starbursts. Restframe UV spectra show a wealth of absorption features, and often P-Cygni profiles in the CIV(1550 Å) line (Steidel et al. 1996b), which indicates the predominance of young, massive stars. Nebular emission lines observed in the brightest LBGs (Pettini et al. 1998; Teplitz et al. 2000a; Pettini et al. 2001) have intensities comparable to those of local starbursts (Meurer et al. 1999). The observed blueshifts in the UV interstellar absorption lines relative to the systemic redshifts of LBGs have been interpreted as bulk gas outflows with velocities $v \sim 200\text{--}500 \text{ km s}^{-1}$ (Pettini et al. 1998, 2000b), again very similar to what is observed in nearby starbursts (Heckman et al. 2000). Finally, more luminous LBGs tend to be dustier (Figure 9, panel b and equation 6; Adelberger & Steidel 2000; Shapley et al. 2001). However, dissimilarities also exist between the two classes of galaxies. Star formation extends over a large fraction of the galactic body in LBGs, typically $5\text{--}30 h_{65}^{-2} \text{ kpc}^2$ (Giavalisco, Steidel & Macchetto 1996b; Giavalisco et al. 1998), while it is confined within the inner kpc^2 in local starbursts. As a result, LBGs are, on average, more rapidly star-forming than either $z \sim 0$ or $z \sim 1$ galaxies (Figure 9; Adelberger & Steidel 2000; Shapley et al. 2001). The bulk outflows in LBGs have velocities that are similar to those of local infrared-bright starbursts like NGC6240 and a few times larger than those of HII galaxies (Heckman et al. 2000; Heckman & Leitherer 1997; Kunth et al. 1998; Gonzalez Delgado et al. 1998). The implications of such differences are not fully understood yet.

Establishing how much dust LBGs contain is the subject of ongoing debate. Metals are definitely present in these systems. Although the exact value of the metallicity has not been constrained, it most likely lies between $0.1 Z_{\odot}$ and $0.7 Z_{\odot}$ (Pettini et al. 2000b; Leitherer et al. 2001; Pettini et al. 2001). The UV spectral slopes of LBGs have median value $\beta_{26} \sim -1.5$ (Adelberger & Steidel 2000), significantly redder than the value $\beta_{26,0} \sim -2.2\text{--}2.7$ expected for a dust-free star-forming population (Appendix B). If interpreted in the same fashion as the UV slope of nearby UV-selected starbursts, LBGs suffer from dust obscuration at the level of $A_{0.16} \sim 1\text{--}2 \text{ mag}$ (Calzetti 1997b; Pettini et al. 1998; Dickinson 1998; Meurer et al. 1999; Steidel et al. 1999; Adelberger & Steidel 2000), and, possibly, more (Meurer et al. 1997; Sawicki & Yee 1998). However, a number of uncertainties and systematics limit the usefulness of UV data alone to derive obscuration estimates. First and

foremost, the high redshift galaxy for which reddening corrections are sought needs to possess active, on-going star-formation (i.e., not to be a post-starburst); this appears to be true for the LBGs as a population, but may not be true on an individual basis (Papovich, Dickinson, & Ferguson 2001). Second, for most LBGs the UV slope is derived from photometry alone; the conversion of $G-R$ colors¹² to β_{26} suffers from uncertainties due to the presence of both intrinsic (stellar lines and Lyman break) and intervening (Lyman α Forest) absorption in the photometric filters (Adelberger & Steidel 2000; Pettini et al. 2001). Finally, because of the age–dust degeneracy, the intrinsic UV slope is a free parameter that can lead to >1 mag difference in the derived obscuration value at $0.16 \mu\text{m}$ (compare Sawicki & Yee 1998; Steidel et al. 1999).

Supplementing the UV with restframe optical data provides further leverage for determining the level of dust reddening in LBGs. The negligible correlation between $L_{H\beta}/L_{0.16}$ and the UV slope found for a sample of $\lesssim 15$ luminous LBGs¹³ supports the notion that LBGs are subject to modest reddening (Pettini et al. 1998; Teplitz et al. 2000a; Pettini et al. 2001). Although this result is still dominated by the large scatter induced by both observational and model uncertainties (Pettini et al. 2001), it is consistent with what is observed in local UV-selected starbursts¹⁴, for which an obscuration of 1–2 mag at $0.16 \mu\text{m}$ corresponds to the modest reddening $A_{0.16}-A_{H\beta} \sim 0.15-0.3$ (section 4.3).

Although the age–dust degeneracy cannot be easily broken even with the addition of long wavelength data, extending the wavelength coverage of LBGs to the restframe optical has helped delimiting the locus of allowed combinations in the age–dust plane (Papovich, Dickinson, & Ferguson 2001; Shapley et al. 2001). Using complementary datasets of LBGs in terms of luminosity range, Papovich, Dickinson, & Ferguson (2001) and Shapley et al. (2001) have established that there is an inverse correlation between the age of the stellar populations in a galaxy and the amount of dust reddening it suffers: the older the galaxy, the lower its reddening. In agreement with previous results (Sawicki & Yee 1998), LBGs whose SEDs are compatible with young ($\lesssim 10^8$ yr) stellar populations are also dusty. Whatever dust is present, it is not preferentially obscuring selected regions of the galaxies, because of the similarity between the restframe UV and optical morphologies (Bunker 1999; Dickinson 2000). A typical LBG obscuration of $A_{0.16} \sim 1-2$ mag, with a median of ~ 1.5 mag and a high-end tail around 4.5–5 mag (Steidel et al. 1999; Papovich, Dickinson, & Ferguson 2001;

¹²The G and R filters have central wavelengths $0.483 \mu\text{m}$ and $0.693 \mu\text{m}$, respectively (Steidel & Hamilton 1992).

¹³Measures of dust reddening obtained by comparing the UV continuum with the [OIII]($0.5007 \mu\text{m}$) emission line (Teplitz et al. 2000a) are not discussed because of the strong dependence of the nebular line intensity, up to one order of magnitude variation, on the chemical and physical conditions of the gas (Jansen 2000; Charlot & Longhetti 2001).

¹⁴All considerations are based on the assumption that the dust in LBGs is distributed like that of local UV-selected starbursts. If, instead, the most appropriate dust geometry is a homogeneous spheroid or a face-on flattened disk, the average UV slope $\beta_{26} \sim -1.5$ corresponds to obscurations $A_{0.16} \sim 1.2$ mag and $A_{H\beta} \sim 0.50$ mag, and a differential obscuration between the two of ~ 0.7 mag; the latter is probably too large to be reconciled with observational data. Highly inclined disks are not considered in the obscuration budget, as they would probably be too dim in the UV to be selected as LBGs.

Shapley et al. 2001), is currently the most broadly accepted value.

Despite all the uncertainties in estimating dust obscuration in LBGs, the inferred opacity values are modest enough that the high redshift galaxies are expected to be faint sub-mm emitters, with 850 μm flux densities at or below the SCUBA detection limit of $\sim 1\text{--}2$ mJy (Adelberger & Steidel 2000; Peacock et al. 2000). Out of $\gtrsim 10$ LBGs targeted with SCUBA, only a couple have been detected (Chapman et al. 2000; van der Werf et al. 2001). Table 5 gives three examples (two LBGs and one SCUBA source) of highly reddened $z\sim 3$ galaxies, plus the average values of a typical LBG. The three examples are meant to show some of the most attenuated cases that are also detected at restframe UV. Table 5 demonstrates that the exact prediction of the flux density at restframe ≈ 200 μm is heavily dependent on the adopted dust temperature(s) and emissivity, because long infrared wavelengths only probe the Rayleigh-Jeans tail of the thermal dust emission in galaxies (Figure 11). Local galaxies, although extensively used as analogs of high redshift galaxies, are of limited help in this respect, given the wide range of properties they show. If the flux density of a local galaxy beyond 60–70 μm is parametrized by a modified blackbody with dust emissivity $\propto \nu^\epsilon$:

$$f_{IR} \propto \nu^\epsilon B(\nu, T), \tag{20}$$

ULIRGs and bright IR-selected galaxies tend to be well described by either a single-temperature component with $T\sim 40$ K and $\epsilon \sim 1.5$ (Lisenfeld, Isaak & Hills 2000; Blain et al. 1999a) or by a warm/cool two-temperature model with $\epsilon=2$ (Dunne & Eales 2001); however, there is tentative indication that UV-bright, metal-poor starbursts have hotter dust SEDs, with $T\sim 50$ K and $\epsilon=2$ (Tol1924–416, Calzetti et al. 2000). Equation 20, which is used for purely illustrative purposes, is clearly an over-simplification of the dust SED in local galaxies, which is characterized by a range of temperatures and, at restframe $\lambda \lesssim 40\text{--}70$ μm , by the emission from non-equilibrium dust grains (Sellgren 1984; Draine & Anderson 1985; Li & Draine 2001, see, also, section 2.1). In starbursts, the latter component represents $\sim 25\%$ of the total infrared emission. Given the uncertainty of the sub-mm measures and the current poor understanding of the detailed physics of dust emission in both local and high-redshift galaxies, the opacity of LBGs is still relatively unconstrained by sub-mm observations (Ouchi et al. 1999; Sawicki 2001, and Table 5). Further complications (and uncertainties) arise when the comparison between predictions and observations of infrared flux densities is made for individual objects (van der Werf et al. 2001; Sawicki 2001; Baker et al. 2001); reddening/obscuration corrections at UV-optical wavelengths are accurate only in a statistical sense and, generally, do not apply on a one-to-one basis to individual objects. For instance, if the dust geometry in a particular system is such that the scattering out of the line of sight is larger than that into the line of sight, the infrared energy, which is due to the absorption part of the extinction only, will be overestimated when derived from UV data.

5.4. Summary

There is so far limited overlap between infrared and optical surveys at intermediate and high redshift (e.g., Aussel et al. 1999; Flores et al. 1999b; Barger et al. 1999b; Rigopoulou et al. 2000; Chapman et al. 2000). Consequently multi-wavelength coverage from the restframe \sim UV–optical to the infrared is available only for a small number of galaxies. To make matters worse, observational limitations lead to vastly different selection criteria for the optical surveys in different redshift bins (Glazebrook et al. 1999; Yan et al. 1999; Moorwood et al. 2000; Steidel et al. 1996b). Thus, conclusions about the dust opacity of galaxy populations as a whole and as a function of redshift are at the moment based on ‘reasonable’ extrapolations of existing data, rather than hard evidence.

Available infrared and optical data support the scenario that $z \approx 1$ star-forming galaxies cover at least the same range of dust opacities as local galaxies. The luminosity (or combined luminosity and density) evolution implied by the ISO counts suggests that luminous infrared galaxies, with $L_{bol} \sim L_{IR} \gtrsim 10^{11} h_{65}^{-2} L_{\odot}$, were common at $z \lesssim 1$. The range of dust attenuation values at UV wavelengths inferred for optically-selected $z \sim 1$ galaxies is comparable to those of local disk galaxies and UV-selected starbursts (Figure 9), although the distant galaxies tend to be more luminous (more active) on average. Larger samples with more extended wavelength coverage are needed before a more complete picture can be drawn in this redshift range.

The ISM of $z \sim 3$ galaxies has been observed to be metal-polluted to at least $\approx 0.1 Z_{\odot}$, implying that non-negligible amounts of dust must be present in the galaxy population at large by $z=3$ and, in many cases, earlier (Shapley et al. 2001). The observed properties of the $z > 1$ SCUBA sources and of the LBGs suggest that both objects are the high redshift analogs of local actively star-forming galaxies, where dust content and level of activity determines a continuum of characteristics. The SCUBA sources are at the high end of such continuum, with powerful activity, both thermal and non-thermal, and large dust contents that make them similar to local ULIRGs; more than 95% of their bolometric light is absorbed by dust. LBGs appear to span a larger range of the continuum of dust content and activity level, although they tend to have, on average, lower values than the SCUBA sources. Typical UV attenuations are $A_{0.16} \sim 1\text{--}2$ mag, corresponding to 35%–95% of the bolometric light being absorbed by dust.

Assuming the local infrared luminosity function can be applied to high redshift sources as well, the comoving number density of $z \approx 3$ SCUBA galaxies with 850 μm flux densities brighter than 2 mJy and 0.5 mJy (corresponding to $\sim 2 \times 10^{12} L_{\odot}$ and $\sim 5 \times 10^{11} L_{\odot}$ for an Arp220-like SED) would be $\approx 4 \times 10^{-4} h_{65}^3 \text{ Mpc}^{-3}$ and $\approx 10^{-2} h_{65}^3 \text{ Mpc}^{-3}$, respectively. High-redshift infrared galaxies as bright as Arp220 are almost 100 times less numerous than LBGs; for comparison, in the local Universe ULIRGs are more than 4 orders of magnitude less numerous than optically selected galaxies. At lower 850 μm luminosities, $z \sim 3$ SCUBA sources are about as numerous as LBGs at the same redshift, but there could be large overlap between the two samples at the mJy level. LBGs are, in fact, predicted to occupy the faint end of the SCUBA 850 μm source counts, with flux densities of a few mJy or less (Adelberger & Steidel 2000). Thus, although SCUBA sources

down to 0.5 mJy at all redshifts already account for >90% of the CIB, a non-negligible fraction of this, at least 25%, could be due to LBGs (Peacock et al. 2000; Adelberger & Steidel 2000; van der Werf et al. 2001).

6. Intracluster and Intergalactic Dust

Intracluster and intergalactic dust are briefly discussed in view of their potential importance in the interpretation of the intermediate and high redshift Universe. The amount, nature, and sources of the dust in the intracluster (ICM) and intergalactic (IGM) media are still a controversial matter, despite the large number of independent researches tackling the issue.

The metallicity of the present-day ICM is fairly high, about 1/3–1/2 solar, implying that a non-negligible fraction of the gas in the ICM has been ejected from the cluster’s galaxies (Mushotzky et al. 1996; Mushotzky & Loewenstein 1997; Voit & Donahue 1997). The high metallicity is not automatically accompanied, however, by a high dust content of the ICM. The ICM hot gas effectively destroys dust through sputtering. The typical timescale for sputtering in a $\gtrsim 10^7$ K hot ambient gas is $t_{sput} \approx 10^6 a/n$, where t_{sput} is measured in yrs, a is the size of the dust grain in μm , and n is the density of the ICM in cm^{-3} (Draine & Salpeter 1979; Dwek, Rephaeli & Mather 1990). In the high-density cores of clusters ($n \gtrsim 10^{-3} \text{ cm}^{-3}$), a 0.1 μm dust grain survives a few times 10^8 yr, with smaller grains being destroyed on shorter timescales than the large grains (Dwek, Rephaeli & Mather 1990). Small grains can survive only outside the cores of clusters, i.e., beyond the central $\approx \text{Mpc}$. Dust needs to be constantly replenished in the ICM, and the likely sources are enriched winds from the cluster’s galaxies, intracluster stars, and, in dynamically young clusters, winds from infalling spiral galaxies (Dwek, Rephaeli & Mather 1990; Popescu et al. 2000). The timescales for the dust injection in the ICM are of order 10^9 yr or longer, implying that the grain size distribution, and therefore the shape of the extinction curve, depends mainly on the sputtering efficiency at the selected cluster location (Dwek, Rephaeli & Mather 1990).

Various direct and indirect methods have been employed to detect dust in the ICM. Deficits in background counts of galaxies, quasars, and clusters behind galaxy clusters of various richness have been interpreted as extinction in the range $A_B^o \sim 0.2\text{--}0.5$, with patches that can exceed $A_B^o \approx 1$ mag (Zwicky 1957; Karachentsev & Lipovetskii 1969; Bogart & Wagoner 1973; Boyle, Fong & Shanks 1988; Szalay, Hollósi & Tóth 1989; Romani & Maoz 1992). Conversely, reddening measurements of cluster members (Ferguson 1993) or background galaxies (Maoz 1995) give upper limits of $A_B^o \sim 0.2$ mag. The two methods thus give contradictory results and neither is completely bias-free: deficits in background counts can be due not only to dust, but also to confusion; low reddening values can be attributed to a gray extinction curve, greyer than a Milky-Way-like curve, because of the selective destruction of small grains in the ICM. Tentative infrared detections of ICM dust emission, using IRAS and ISO data (Wise et al. 1993; Stickel et al. 1998), are either at low significance level, or have been argued to be due to emission from cluster members (Quillen et al. 1999).

Presence of dust is well established in the centers of cooling flow clusters (see discussion in section 3.4), but the issue of its origin is still controversial. In particular, it is not clear whether this is an extended component, such as condensates from the cooled cluster gas or a by-product of star formation triggered by the cooling flow, (Hu et al. 1983; Hu 1992; Fabian, Johnstone & Daines 1994; Allen 1995; Hansen, Jørgensen & Nørgaard-Nielsen 1995; Crawford et al. 1999; Edge 2001), or is directly associated with the central galaxy, possibly from a merging event that the galaxy underwent (Sparks, Macchetto & Golombek 1989; Sparks, Ford & Kinney 1993; Donahue et al. 2000). The Milky-Way-like form of the extinction curve in the central galaxies has been extensively used as an argument to support the galactic origin of the dust in cooling flow clusters; as remarked above, ICM-processed dust would tend to be depleted in small grains and therefore produce a gray extinction (Sparks, Macchetto & Golombek 1989; Sparks, Ford & Kinney 1993; Donahue et al. 2000). However, if soft X-ray absorption is present in the centers of the clusters, dust absorption in the cooling flow would appear to be the direct physical explanation (Voit & Donahue 1995). The tentative detection of the neutral oxygen edge, and thus of dust, in the Perseus cluster (Arnaud & Mushotzky 1998) and the widespread presence of CO emission in low-radio-emitting cooling flow clusters (Edge 2001) are countered by XMM data that do not support the presence of large amounts of cool gas in the center of some of the clusters and, therefore, do not require a large amount of dust to explain the soft X-ray spectral shape (Tamura et al. 2001; Kaastra et al. 2001; Peterson et al. 2001).

At present times, the presence and nature of dust in the IGM is even more uncertain than that in the ICM, though it is widely accepted that the IGM is metal-enriched. Hydrodynamical CDM simulations identify the Ly α forest as the IGM, i.e., modest baryon density fluctuations in a ionizing background (Cen et al. 1994; Petitjean, Muecket & Kates 1995; Zhang, Anninos & Norman 1995; Hernquist et al. 1996; Theuns et al. 1998). The Ly α forest accounts for a significant fraction, $>50\%$, of the baryons at $z\approx 3$ (Rauch et al. 1997); its metallicity at $z\sim 2.5-3$ is $\sim 0.2-1\% Z_{\odot}$ down to column densities $N(\text{HI})\sim 10^{14.5} \text{ cm}^{-2}$ (Tytler et al. 1995; Songaila & Cowie 1996; Ellison et al. 1999), while metallicity values at lower column densities remain uncertain (Ellison et al. 2000). These values could be lower limits to the IGM metallicity, if there is a ‘missing metals’ problem as pointed out by Renzini (1999) and Pettini (1999) on the basis of the metals produced by star formation by $z\sim 2.5$. The metallicity of the Ly α forest increases for decreasing redshift, being ~ 10 times more metal rich at $z\sim 0.5$ than at $z\sim 2.5-3$ (Barlow & Tytler 1998). In the local Universe, the Ly α forest accounts for only $\approx 20\%$ of the baryons (Penton, Shull & Stocke 2000) and matter associated with galaxies and clusters for another $\approx 25\%-30\%$ (Fukugita, Hogan & Peebles 1998; Cen & Ostriker 1999); thus, $\sim 50\%$ of the baryons at $z=0$, and possibly of the metals, are contained in a yet undetected phase of the IGM, proposed to be hot gas (Cen & Ostriker 1999). Various mechanisms have been considered for the metal, and possibly dust, pollution of the IGM; they include supernova ejecta from galaxies and/or subgalactic structures, dynamical encounters between galaxies, ram-pressure stripping, and population III stars (Ostriker & Gnedin 1996; Nath & Trentham 1997; Gnedin 1998; Ferrara, Pettini & Shchekinov 2000; Cen & Bryan 2001; Madau, Ferrara & Rees 2001; Aguirre et al. 2001). The different mechanisms are non-exclusive, although

each one could be dominant relative to the other at specific cosmological epochs.

Early attempts to detect diffuse dust in the IGM investigated the evolution of the mean quasar spectral index with redshift (Wright 1981; Cheng, Gaskell & Koratkar 1991), with the basic result that presence of IGM dust is negligible for Milky-Way-like extinction, up to at least $z \approx 2$ (Cheng, Gaskell & Koratkar 1991). Milky-Way-like IGM dust should also leave an imprint on the Cosmic Microwave Background, as it would re-emit in the sub-mm/mm regime the absorbed background radiation (Rowan-Robinson, Negroponte & Silk 1979; Wright 1981; Bond, Carr & Hogan 1991). The tight COBE upper limit to deviations from blackbody emission (Fixsen et al. 1996) limits the IGM dust to $A_V \lesssim 0.3$ mag to $z=5$, with negligible value to $z=3$ (Loeb & Haiman 1997; Ferrara et al. 1999b). However, if sputtering is efficient in the hot IGM, dust has a greyer extinction than Milky-Way-like (Aguirre 1999, for a challenge to the sputtering argument see Simonsen & Hannestad (1999)). Gray IGM dust can be present in larger quantities than Milky-Way-like dust without violating the COBE limits, but its emission would represent $\gtrsim 75\%$ of the CIB at $850 \mu\text{m}$ (Aguirre & Haman 2000). Source counts with SCUBA account already for $>90\%$ of the CIB (section 5.2), which challenges the case for large amounts of gray dust. So far, the strongest limits have come from observations of cosmological supernovae. For gray dust with minimum grain size $\sim 0.1 \mu\text{m}$, Aguirre (1999)’s model gives $A_B - A_V \lesssim 0.01$ and $A_B - A_I \sim 0.2$ for $A_V \sim 0.2-0.3$ to $z=0.5$; at $z=2$, $A_V \sim 0.6-0.7$ mag. Using observations of Type 1a supernovae at $z \sim 0.5$ and $z \sim 1.7$, Riess et al. (2000) and Riess et al. (2001) have placed a limit of $A_V \sim 0.1-0.15$ to the amount of diffuse, gray IGM dust to $z=0.5$. In summary, although the actual numbers are still not settled, IGM dust is likely to produce small attenuations at most redshifts.

7. Conclusions and Future Developments

Current observational data indicate that the population of local galaxies is characterized by modest values of the dust opacity. Typically, 50% or less of the total stellar energy is absorbed by dust. The same evidence points out that the definition of ‘modest opacity’ is wavelength-dependent; for example, in the UV, at $0.15 \mu\text{m}$, a non-active galaxy can lose up to 80% of its energy to dust. Luminous, intermediate-to-late type spirals are dustier than ellipticals, by $\sim 1.0-1.4$ mag in the UV, and than irregulars, by 0.5–0.8 mag. Luminous galaxies are on average more metal-rich and dust-rich than their faint counterparts. Dust opacity also increases with thermal and non-thermal activity, with the high-end of the distribution given by the ULIRGs.

Although the wealth of data and wavelength coverage for local galaxies has started to uncover the dust opacity of these systems, we are still missing a few crucial pieces of the puzzle. The largest among these is the one-to-one relation between absorbed stellar SEDs and dust emission SEDs. At first order, hotter stars are expected to heat the dust to higher temperatures than cooler stars (Helou 1986), but we don’t have yet the direct link between individual dust emission and heating components; we don’t know the dependence of the dust SED on parameters like metallicity, radiation field, gas density, galactic environment, etc.; and questions still surround the relation

between radiation intensity and PAH emission, despite the progresses made with ISO (Cesarsky et al. 1996; Genzel & Cesarsky 2000; Dale et al. 2001). The main reason for these limitations to our comprehension of the dust absorption–emission relationship is the large mismatch in angular resolution between UV-to-near-IR observations and current mid/far-infrared data. While observations probing the direct stellar light can easily reach sub-arcsecond resolution, existing data on dust emission are at the arcminute resolution level, especially at wavelengths above $\sim 40 \mu\text{m}$ where the bulk of the energy from dust emerges. Upcoming infrared missions like SIRTf (the Space InfraRed Telescope Facility), SOFIA (the Stratospheric Observatory for Infrared Astronomy), and FIRST (now the Herschel Space Observatory) promise to bridge this gap. They will also push the wavelength coverage all the way to 600–700 μm , thus probing the cold dust emission in local galaxies, which is the repository of most of the dust mass.

UV- and optical-selected, intermediate and high redshift, galaxy surveys carry the inherent limitation that physical parameters directly derived from the observations are affected by dust in a non-easily quantifiable way. This is further complicated by the fact that instrumental sensitivity limits favor detection of the luminous representatives of any galaxy class, that may tend to have relatively high dust content. Estimates of the SFRs in intermediate and high redshift galaxies using Balmer lines (Glazebrook et al. 1999; Yan et al. 1999; Moorwood et al. 2000) and infrared emission (Flores et al. 1999b; Blain et al. 1999d; Barger, Cowie & Richards 2000) are generally a few times higher than the analogous estimates using the restframe UV emission (Lilly et al 1996; Madau et al. 1996; Steidel et al. 1999). As discussed in section 5, presence of dust in galaxies at cosmological distances is reasonably established, but the quantification of its effects as a function of redshift is still an ongoing process. Linked to this is the puzzle of the nature of the UV-selected and IR-selected sources, and of their relationship: whether they represent overlapping populations, or the two ends of a continuum of properties possibly parametrized by activity and dust content is still an open question.

The absence of full characterization of the dust emission and absorption in distant galaxies is mostly due to the scant overlap between optically-selected and infrared-selected surveys. This is due to sensitivity limitations at both ends of the spectrum, to angular resolution limitations at long wavelengths, to the small number of objects in some of the samples, and to the sparse wavelength coverage of the dust emission SED by current sub-mm/radio instrumentation. SIRTf and FIRST initially, and then ALMA (the Atacama Large Millimeter Array) and NGST (the Next Generation Space Telescope) will be able to fill the gaps. In particular the last two instruments, with their sub-arcsecond resolution and high sensitivities, should mark a break-through in our understanding of the high redshift Universe and of its stellar, gas, and dust content up to $z \sim 20$.

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A. Adopted nomenclature for extinction and obscuration

The dimming effects of light are generally termed ‘extinction’ only in the simple geometrical case of a point source behind a dust screen (section 2.1), where the attenuation suffered by the source can be directly related to the optical depth of the dust screen. In this review, the extinction at wavelength λ is indicated as:

$$A_{\lambda}^o = 1.086 \tau_{\lambda}, \tag{A1}$$

(equation 2). The dimming of background galaxies due to the dust in a foreground galaxy can generally be considered extinction, because the foreground galaxy can be modeled in first approximation as a homogeneous screen in front of point sources (section 3.1).

For more general distributions of dust and emitters, the dimming and reddening of the light is no longer directly related to the extinction or the optical depth of the dust layer, and is called indiscriminately ‘effective extinction’, ‘obscuration’, or ‘attenuation’. The effective extinction A_{λ} is defined as:

$$A_{\lambda} = m_{\lambda,a} - m_{\lambda,o}, \tag{A2}$$

where $m_{\lambda,o}$ is the magnitude of the dust-free source and $m_{\lambda,a}$ is the measured (attenuated) magnitude; A_{λ} measures the magnitudes of attenuation suffered by an extended source at the specified wavelength/band. By definition, $A_{\lambda} \equiv A_{\lambda}^o$ for a foreground, homogeneous, non-scattering dust screen.

For dust/emitter distributions that do not have spherical symmetry, such as spiral galaxies, the face-on effective extinction is termed $A_{\lambda,f}$, while A_{λ} indicates the effective extinction averaged over all inclinations.

B. The definition of the UV spectral slope β

Throughout this review, two different definitions of the UV spectral slope, β and β_{26} have been used. In this context, the spectral slope is derived from the fit $f(\lambda) \propto \lambda^{\beta}$ within a specified wavelength range, with $f(\lambda)$ the flux density of the source. The various definitions reflect historical reasons driven mostly by observational constraints.

The default β adopted in this review (section 2.2) is measured between $0.125 \mu\text{m}$ and $0.30 \mu\text{m}$, using a set of wavelength windows that avoid the strong stellar and interstellar absorption features. An example of such windows is given in Calzetti, Kinney & Storchi-Bergmann (1994), although the ones used to derive β here are better tuned for use with model spectra rather than with observed spectra, and extend all the way to $0.3 \mu\text{m}$. This definition of β has been adopted to ensure an

appropriate comparison between different extinction curves and dust models, as in Figures 2 and 3, because the fitting windows are selected to avoid the strong and wide dust feature at $0.2175 \mu\text{m}$.

The UV slope β_{26} used in section 4 is a fit through the 10 windows of Calzetti, Kinney & Storchi-Bergmann (1994), and corresponds to deriving the slope in the wavelength range $0.125\text{--}0.26 \mu\text{m}$, using spectral regions mostly devoid of strong absorption lines. This definition of the UV slope is observation-driven, as it was used to obtain measurements from IUE spectra of a local UV-selected starburst sample. The wavelength range is bluer than that of β above, and was chosen by Calzetti, Kinney & Storchi-Bergmann (1994) to avoid including in the fits the older stellar populations underlying the starbursts. These older populations can contribute to the spectra starting around $0.27\text{--}0.28 \mu\text{m}$, when the fluxes of F-stars become non-negligible. For reference, a list of β_{26} values for dust-free stellar populations, both for instantaneous burst and for constant star formation, is given in Table 6.

An convenient definition of the UV-slope for studies of high-redshift galaxies is β_{18} , measured roughly between $\sim 0.12 \mu\text{m}$ and $\sim 0.18 \mu\text{m}$. At $z \sim 3$, the optical window give information shortward of $\sim 0.2 \mu\text{m}$, thus forcing the UV slope fitting to a much shorter range than possible with local galaxies. The details of the actual wavelength range vary with redshift and with the observing technique (whether spectroscopy or imaging, and depending on the filters used).

The relation between the three quantities, as given by models of stellar populations reddened by the starburst obscuration curve of section 4, is:

$$\beta_{26} = (1.020 \pm 0.018)\beta - (0.018 \pm 0.065), \quad (\text{B1})$$

$$\beta_{18} = (1.156 \pm 0.013)\beta_{26} + (0.454 \pm 0.075). \quad (\text{B2})$$

The error bar following each coefficient refers to the maximum variance observed by varying a number of parameters in the models and fits: (a) stellar populations from both Leitherer et al. (1999) and Bruzual & Charlot (2001) models; (b) stellar populations with constant star formation in the range $5\text{--}1000 \text{ Myr}$, and instantaneous bursts in the age range $5\text{--}12 \text{ Myr}$; (c) both $0.2 Z_{\odot}$ and Z_{\odot} metallicities; (d) fitting windows that progressively include or exclude weak absorption lines in the spectra. The latter turns out to be the main driver of the variance, while changes in the characteristics of the stellar populations have only a small impact. The relations between the three slopes would, however, change from equations (B1)–(B2) if more extreme cases of stellar population mix, such as the addition of an old (age $> 1 \text{ Gyr}$) component, were considered; in this case, β and β_{26} would be strongly affected, because of the long wavelength baseline.

Of interest for high-redshift studies is the consideration that while β_{26} and β follow each other closely, β_{18} is always redder (more positive) than the other two, and the discrepancy increases for increasing value of the slopes. The reason for this counter-intuitive behavior is the presence of the well-known ‘iron curtain’ at long UV wavelengths: this is a wide dip in the $0.23\text{--}0.28 \mu\text{m}$ range of the UV spectra due to the presence of a large number of closely spaced Fe absorption lines (Leitherer et al. 1999). The UV slopes fitted with the longer wavelength baseline have windows

in this continuum-depressed region, hence their more negative values. Increasing dust obscuration affects the short-wavelength slope more than the long-wavelength ones; hence the trend for β_{18} to become progressively redder than β_{26} as their values increase (i.e., as the UV spectra become more dust reddened).

Meurer et al. (1999) derive an empirical relation between β_{26} and a short-wavelength UV slope β_{SW} (close, but not identical, to β_{18}) from IUE spectra of the UV-selected starbursts. Their findings, that $\beta_{26} = \beta_{SW} - 0.16$, are consistent with the long wavelength slope being bluer than the short wavelength one. However, they do not measure an increasingly redder β_{SW} for increasing values of both slopes. A possible reason is that noise in the IUE data may have prevented the detection of such effect. In this review, it is assumed that equations (B1)–(B2) are valid for UV-selected starbursts.

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Fig. 1.— Examples of extinction curves in local galaxies. The Milky-Way extinction curve is shown for three different values of $R(V)$, 3.1 (continuous red line), 5.0 (dashed red line), and 2.0 (dotted red line) (Cardelli, Clayton & Mathis 1989; Fitzpatrick 1999). The extinction curve of the Large Magellanic Cloud’s 30 Doradus region (dashed black line) and of the Small Magellanic Cloud’s bar (continuous black line) are reported for $R(V)=2.7$ (Gordon & Clayton 1998; Misselt, Clayton & Gordon 1999). The starburst obscuration curve (section 4) is shown (blue line) here for a purely illustrative comparison. The comparison should not be taken at face value, because the dust obscuration of galaxies is conceptually different from the dust extinction of stars. The latter measures strictly the optical depth of the dust between the observer and the star, while the former expresses a more general attenuation, in that it folds in one expression effects of extinction, scattering, and the geometrical distribution of the dust relative to the emitters (section 4).

Fig. 2.— Predicted reddening and attenuation values for five simple models of plane-parallel dust/emitter distributions (section 2.2 and Natta & Panagia 1984; Calzetti, Kinney & Storchi-Bergmann 1994; Wang & Heckman 1996): a homogeneous, non-scattering dust screen foreground to the light source (red squares); a homogeneous, scattering dust screen foreground to the light source (red circles); a Poissonian distribution of clumps in front of the light source, with average number $\mathcal{N}=10$ (red triangles); an homogeneous mixture of dust and emitters (black squares); a homogeneous distribution averaged over all inclination angles, with increasing star-to-dust scale-height ratio from UV (and ionized gas emission) to K (black circles). Both the MW extinction curve for diffuse ISM (continuous lines) and the SMC-bar extinction curve (dashed lines) are used in the models. The reddening and attenuation given by the starburst obscuration curve (section 4) are also shown for comparison (blue line). τ_V is the front-to-back optical depth of the dust layer. Panels a and b show the relation between τ_V and the effective extinction A_V and color $V-I$. Panels c–f show the effects of dust reddening on the UV, optical, and near-IR colors of a stellar population. The default population is a 300 Myr constant star formation one. U, V, I are standard Johnson magnitudes; K has central wavelength $2.163 \mu\text{m}$ and zeropoint -26 . $m_{0.15}$ is defined as $-2.5 \log[f(0.15)] - 21.1$, where $f(0.15)$ is the flux density at $0.15 \mu\text{m}$.

Fig. 3.— The same models of Figure 2 for additional spectroscopic and photometric quantities. The dust optical depth τ_V is defined in the previous figure. $R_{\alpha\beta}$ and $R_{\beta\gamma}$ are the attenuated-to-intrinsic $H\alpha/H\beta$ and $H\beta/\text{Br}\gamma$ ratios, respectively (equation 3 and Table 2). The UV spectral slope β is defined in Appendix B. L_{dust} is the dust luminosity, corresponding to the stellar light removed (absorbed and scattered) by dust from the line of sight. This is generally larger than the dust infrared luminosity, which only includes the *absorbed* fraction of the energy, unless scattering in and out of the line of sight compensate each other. The latter can be often safely adopted for large samples of galaxies with random inclinations (exemplified by the fifth model). $L_{H\alpha}$ is the luminosity of the nebular emission at $H\alpha$. Continuum luminosities at $0.15 \mu\text{m}$ and $0.28 \mu\text{m}$ are given as $L_\lambda = 4\pi D^2 \lambda f(\lambda)$, where D is the galaxy distance and $f(\lambda)$ is the flux density at wavelength λ ; the reference wavelengths are chosen to span the UV spectrum while avoiding prominent absorption lines (including the broad $0.2175 \mu\text{m}$ bump in the MW extinction curve). The large deviation of

the starburst reddening curve from the other models in the last two panels is due to the differential obscuration between ionized gas and stellar continuum (section 4).

Fig. 4.— The comparison of colors and absolute magnitude between an ageing instantaneous burst of star formation in the range 1-80 Myr (black line) and a fixed-age (6 Myr) stellar population subject to increasing dust obscuration (red line). The model used for the dust obscuration is a foreground clumpy distribution, with optical depth range $\tau_V = 0-6.3$.

Fig. 5.— The UV to IR flux ratio as a function of the sum of the UV and IR luminosities for star-forming galaxies (reproduction of Figure 4 of Wang & Heckman (1996)). The UV flux is centered at $0.20 \mu\text{m}$ and is defined as $F_{UV} = \lambda f(\lambda)$. The IR emission in this figure (called ‘FIR’) is the integrated emission in the 40–120 μm IRAS window, which contains roughly between 35% and 60% of the dust bolometric emission (Dale et al. 2001). The ratio UV/IR is a measure of the total opacity of a star-forming galaxy (see, also, section 4). The plot shows that more luminous galaxies are more opaque. The symbols indicate: spirals (filled squares), irregulars (crosses), elliptical/lenticulars (empty squares), amorphous (stars), unknown (circles). The lines show predictions for a range of parameters from the model described in Wang & Heckman (1996). Figure reproduced with permission from the author and the publishing journal.

Fig. 6.— Panels a, c, and d show UV-to-near-IR colors of ~ 50 UV-selected starbursts as a function of the attenuated-to-intrinsic hydrogen emission line ratio $H\alpha/H\beta$ (filled circles). The relation between $R_{\alpha\beta}$ and the color excess of the ionized gas $E(B-V)_{gas}$ (section 4.1) is given by equation 4. The starburst obscuration curve (blue line) is derived from these data. Increasing values of $R_{\alpha\beta}$, i.e. larger amount of dust intercepted by the gas, correspond to redder colors of the stellar continuum (adapted from Calzetti, Kinney & Storchi-Bergmann 1994; Calzetti 1997a). For the definition of β_{26} see Appendix B; $f(0.16)$, $f(J)$, and $f(K)$ are flux densities at the indicated wavelengths. Panel b shows the correlation between the attenuated-to-intrinsic ratios of the hydrogen line pairs $H\alpha/H\beta$ and $H\beta/Br\gamma$; plotted with the data points are trend of the dust models of section 2.2 (with the same coding of Figure 3). Homogeneous mixtures of gas and dust, either face-on or inclination-averaged, are excluded by the data, indicating that there is little internal dust in the starburst site (adapted from Calzetti, Kinney & Storchi-Bergmann 1996). Panels e and f give for both the luminosity ratio $L_{H\alpha}/L_{0.16}$ and the equivalent width of $H\alpha$ the comparison between data points and expected trend of the starburst obscuration curve.

Fig. 7.— The dust bolometric luminosity, L_{IR} , normalized to the UV and B stellar luminosities ($L_{0.16}$ in panel a and L_B in panel b, respectively) shown as a function of the UV spectral slope β_{26} for the same starburst sample of Figure 6 (circles) and for nine ULIRGs (stars in panel a; Trentham, Kormendy & Sanders 1999; Goldader et al. 2001). For most galaxies, where only IRAS measurements are available, the infrared luminosity in the 40–120 μm window is transformed into a dust bolometric luminosity using the correction: $L_{IR} = 1.75 L_{(40-120)}$ (Calzetti et al. 2000). The blue luminosity is that of the starburst region, from the data of McQuade, Calzetti & Kinney (1995) and Storchi-Bergmann, Kinney & Challis (1995). The luminosity ratios measure the starburst total

dust opacity, while the UV slope is a measure of the UV reddening. The correlations imply that measuring the reddening in a UV-bright starburst gives a good handle on its global obscuration (adapted from Calzetti et al. 1995b; Meurer et al. 1999). In panel a the predicted trend from some of the models of section 2.2 (coded in the same fashion as in Figure 3) are reported; in panel b, only the starburst obscuration curve is shown. ULIRGs deviate from the behavior of UV-selected starbursts, and combinations of clumpy distributions and homogeneous mixtures of dust and stars seem to better account for the data. Panels c and d show the same data of panel b, as a function of the galaxy metallicity and of the attenuated-to-intrinsic $H\alpha/H\beta$ ratio, respectively. Dust opacity correlates with the metal content in starbursts (Heckman et al. 1998).

Fig. 8.— A schematic representation of the dust/star distribution in starburst galaxies, that can account for most observational constraints. The starburst region (center of figure) contains the newly formed stellar population, including the short-lived, massive stars (dark starred symbols), some still embedded in the parental clouds. Gas outflows induced by hot star winds and supernova explosions from previous stellar generations have displaced dust and gas (dark-gray circles) to the edges of the region. The ionized gas, located at the boundaries of the site, ‘sees’ the surrounding dust as a ‘foreground distribution’. The galaxy’s diffuse ISM (light-gray circles) is also surrounding the starburst. Both the galactic and the starburst-associated dust are clumpy (Gordon, Calzetti & Witt 1997; Charlot & Fall 2000). Thus, the stellar continuum light will often emerge from regions that are not necessarily spatially coincident (in projection) with those of the dust and ionized gas (Calzetti 1997a). If star formation has been on-going for longer than the lifetime of massive stars ($>10^7$ yr), the surroundings of the current starburst site become populated by the less massive, long-lived stars from previous starburst generations (light starred symbols), that are diffusing into the less opaque general ISM or have dispersed their parental clouds (Calzetti, Kinney & Storchi-Bergmann 1994; Charlot & Fall 2000). This model should be regarded as a simple approximation of the more realistic distribution of emitters and absorbers in starburst galaxies.

Fig. 9.— The UV to IR luminosity ratio as a function of the total UV plus IR luminosity for star-forming galaxies at $z\sim 1$ (panel a) and $z\sim 3$ (panel b). From Figure 11 of Adelberger & Steidel (2000), with data kindly provided by K. Adelberger (2001, private communication) and modified to our selected cosmology, $\Omega_M=1$, $\Omega_\Lambda=0$ and $H_0=65$ km s $^{-1}$ Mpc $^{-1}$. The (blue) circles are the high-redshift data, the shaded region shows the locus occupied by the local star-forming and starburst galaxies (Wang & Heckman 1996; Heckman et al. 1998), the (black) stars are the ULIRGs from Goldader et al. (2001) and Trentham, Kormendy & Sanders (1999). The infrared luminosity of the high redshift galaxies is derived using UV data and the β -versus- L_{IR}/L_{UV} correlation (equation 17 and Adelberger & Steidel 2000). For fixed UV/IR ratio, the faint luminosity end of the high redshift galaxy distributions is determined by selection effects, while the bright luminosity end is free from such effects. Thus, if UV/IR-vs.- β relationship holds for the distant star-forming galaxies, more actively star-forming galaxies are on average more opaque, similar to the trend observed in local galaxies (Wang & Heckman 1996; Heckman et al. 1998, see also Figure 5). It also highlights that at fixed UV/IR ratio (fixed opacity), higher redshift galaxies tend to be brighter at the high

luminosity end than local galaxies. Since the sum of the UV and IR luminosities measures the SFR, high redshift galaxies tend to be more actively star forming than local galaxies for fixed dust opacity (Adelberger & Steidel 2000).

Fig. 10.— The attenuated-to-intrinsic $L_{H\alpha}/L_{0.28}$ ratio in $z\sim 1-2$ galaxies, $R_{H\alpha,0.28}=(L_{H\alpha}/L_{0.28})_a/(L_{H\alpha}/L_{0.28})_o$, as a function of the obscuration at $H\alpha$ (panel a) and of the dust optical depth τ_V (panel b). The range of observational values is marked by the two horizontal lines. The models of dust/emitter distribution are coded as in Figure 3, but only the case of the SMC extinction curve and of the starburst obscuration curve are shown.

Fig. 11.— The UV-to-IR SED of a 1 Gyr constant star formation population, attenuated by the starburst obscuration curve (equation 8), is shown for increasing amounts of dust: $E(B-V)_{gas}=0.05$ (blue, continuous), 0.20 (blue dashed), 0.40 (black), 0.55 (red dashed), and 0.75 (red continuous). All SEDs are arbitrarily normalized to the flux density at $0.17 \mu\text{m}$. The infrared SED is schematically represented by a single-temperature dust component with $T=50 \text{ K}$ and $\epsilon=2$ (panel a) and $T=40 \text{ K}$ and $\epsilon=1.5$ (panel b), to highlight differences in the long-wavelength regime.

Table 1. Properties of Radiative Transfer Models

Dust ^a Geometry	Medium ^b Structure	Stellar ^c Distrib.	Reference	Extinction ^d Curves	Comments
spherical	homog.	central/ spherical	Witt, Thronson & Capuano (1992)	MW	multiple density profiles, multiple scale-lengths starburst/IR modelling, central source only multiple scale-lengths also external source multiple dust/star density profiles starburst/IR modelling, multiple spheres, central source only updated albedo/phase function values
			Rowan-Robinson & Efstathiou (1993)		
			Wise & Silva (1996)		
			Városi & Dwek (1999)		
			Ferrara et al. (1999a)	MW,SMC	
Efstathiou et al. (2000)					
Witt & Gordon (2000)	MW,SMC				
spherical	clumpy	central/ spherical	Witt & Gordon (1996)	MW	central source only also external source updated albedo/phase function values
			Városi & Dwek (1999)		
			Witt & Gordon (2000)	MW,SMC	
plane-paral.	homog.	plane-paral.	Bruzual, Magris & Calvet (1988)	MW,LMC	multiple scale-heights no scattering multiple scale-heights multiple scale-heights
			Disney, Davies & Phillips (1989)		
			Di Bartolomeo, Barbaro & Perinotto (1995)	MW	
			Xu & Buat (1995)		
expon.	homog.	expon.	Kylafis & Bahcall (1987)	MW	edge-on only, isothermal vertical distribution no scattering stellar bulge, multiple scale lengths/heights face-on only stellar bulge stellar bulge, multiple scale lengths/heights
			Disney, Davies & Phillips (1989)		
			Byun, Freeman & Kylafis (1994)	MW	
			Corradi, Beckman & Simonneau (1996)	MW	
			Kuchinski et al. (1998)	MW	
Ferrara et al. (1999a)	MW,SMC				
expon.	clumpy	expon.	Kuchinski et al. (1998)	MW	stellar bulge stellar bulge, IR modelling clumping of stars as well
			Silva et al. (1998)	MW	
			Bianchi et al. (2000)	MW	
arbitrary	homog./ clumpy	arbitrary	Trewhella, Madore & Kuchinski (1999)		Multi-phase clumpy medium and emitters
			Gordon et al. (2001); Misselt et al. (2001)	All	Multi-phase clumpy medium and emitters, polarization, IR modelling

^aThe dust geometrical distribution: spherical, plane-parallel slab, double-exponential, or arbitrary.

^bThe structure of the dust, i.e., homogeneous or clumpy (clumpy media can be two-phase or multi-phase).

^cThe distribution of the stellar population: central to the dust distribution, diffuse through the spherical dust distribution (with variable scale length), plane-parallel, double-exponential, or arbitrary. In most cases, a single SED is assumed and multiple stellar populations are not included.

^dThe adopted extinction curve(s): MW=Milky Way; LMC=Large Magellanic Cloud; SMC=Small Magellanic Cloud; All=MW,LMC,SMC.

Table 2: Reddening between Hydrogen Emission lines

Line Ratio	λ_1, λ_2 ($\mu\text{m}, \mu\text{m}$)	$L_{\lambda_1}/L_{\lambda_2}$ ^a	$k(\lambda_2) - k(\lambda_1)$
H α , H β	0.6563, 0.4861	2.87	1.163
H α , H γ	0.6563, 0.4340	6.16	1.628
Br γ , H β	2.166, 0.4861	0.0302	3.352
Br γ , Pa β	2.166, 1.282	0.175	0.457
Pa α , H α	1.876, 0.6563	0.123	2.104

^aVariations in the ratio due to variations in the gas temperature between 5000 K and 20000 K amount to $\sim 5\%$ – 10% (Osterbrock 1989).

Note. — The table columns list: (1) The pair of hydrogen emission lines; (2) the vacuum wavelengths of the two lines; (3) their intrinsic luminosity ratio for temperature $T=10,000$ K and case B recombination (Osterbrock 1989); (4) the differential extinction between the two wavelengths, for a foreground non-scattering dust screen and a MW extinction curve for diffuse ISM (Cardelli, Clayton & Mathis 1989). Note that $k(\text{V})=3.1$ and $k(\text{H}\alpha)=2.468$.

Table 3. Average Dust Attenuation in Local Galaxies

Galaxy Type	L_{dust}/L_{bol}^a	$A_{0.15,f}^b$	$A_{0.15}^c$	$A_{B,f}^b$	A_B^c	$A_{I,f}^b$	A_I^c	$A_{K,f}^b$	A_K^c
E/S0	0.05–0.15	0.10–0.20	...	0.05–0.10	...	0.02–0.04	...	<0.02	...
Sa–Sab	...	0.40–0.65	0.90–1.25	0.20–0.40	0.50–0.75	0.10–0.15	0.30–0.40	$\lesssim 0.05$	$\lesssim 0.15$
Sb–Scd	0.45–0.65	0.60–0.80	1.20–1.45	0.30–0.50	0.65–0.95	0.15–0.20	0.40–0.45	0.05–0.10	0.15–0.20
Irr	0.25–0.40	0.30–0.45	0.60–0.75	0.10–0.15	0.30–0.40	~ 0.05	~ 0.15	$\lesssim 0.02$	$\lesssim 0.06$

^aFraction of the bolometric radiation absorbed and/or scattered by dust.

^bFace-on attenuation, in magnitudes, at the specified wavelength/band. The B-band and I-band values are derived from various authors (see text). The other wavelengths are from model 4 for E/S0s, and from model 5 of section 2.2 for disks and irregulars.

^cInclination-averaged attenuation for the disk and irregular galaxies, from model 5 of section 2.2. For observational data at 0.15 μm , see Bell & Kennicutt (2001).

Table 4: Local UV-selected Starbursts

Name	D (Mpc)	Morphology	L_{bol} (L_{\odot})	SFR ($M_{\odot} \text{ yr}^{-1}$)	L_{dust}/L_{bol}	$A_{0.15}$ (mag)	A_B (mag)	A_I (mag)	$A_{H\alpha}$ (mag)
The Dust-Rich Starbursts ^a									
NGC1614	74.	SBc, merger.	4.8E+11	54.9	0.91	5.67	2.78	1.20	3.08
NGC4194	40.	IBm, merger	1.1E+11	9.9	0.86	3.20	1.57	0.68	1.74
NGC6090	135.	Sd, merger	4.1E+11	52.4	0.88	3.41	1.67	0.72	1.85
The Dust-Poor Starbursts ^a									
NGC1140	23.	IBm	9.1E+09	1.1	0.59	0.83	0.40	0.17	0.45
NGC1510	12.	SA0	8.1E+08	0.06	0.42	0.52	0.25	0.11	0.28
Tol1924–416	44.	Irr	1.9E+10	2.8	0.42	0.52	0.25	0.11	0.28
The Average UV-Selected Starburst ^a						1.60	0.78	0.34	0.86

^aExamples of three dust-rich (top) and three dust-poor (middle) starbursts in the UV-selected sample of Calzetti, Kinney & Storchi-Bergmann (1994). The obscuration properties of these two extremes can be compared with those of an average UV-selected starburst (last line of Table). Dustier systems are associated with more luminous host galaxies (Heckman et al. 1998).

Note. — The table columns give: (1) the galaxy name; (2) its distance in Mpc, for $H_o=65 \text{ km s}^{-1} \text{ Mpc}^{-1}$; (3) the galaxy morphology; (4) the bolometric luminosity, in solar units; (5) the star formation rate, calculated from the obscuration-corrected $Br\gamma$ or $H\alpha$ line emission (Calzetti 1997a), using the conversion $\text{SFR}=8.2 \times 10^{-40} L_{Br\gamma} = 7.9 \times 10^{-42} L_{H\alpha}$ (Kennicutt 1998); (6) the fraction of bolometric luminosity re-processed by dust in the infrared; (7)–(10) the obscuration of the 0.15 μm , B and I stellar continuum and of the $H\alpha$ emission line (Calzetti, Kinney & Storchi-Bergmann 1994; Calzetti 1997a; Calzetti et al. 2000). For UV-selected starbursts, $A_{H\beta}=1.47 A_{H\alpha}$.

Table 5: Reddening and Obscuration of $z\sim 3$ Galaxies

Parameter	SMMJ14011+0252	MS 1512–cB58	West MMD11	L* LBG
1 z	2.565	2.729	2.982	~ 3
2 $AB_{\mathcal{R}}$	21.25 ^a	20.41 ^a	24.05	~ 24.5
3 $G-\mathcal{R}$	0.69 ^b	0.72	0.80	0.6
4 β_{26}	-0.74 ^c	-1.34 ^d	-0.90 ^e	-1.5 ^f
5 $A_{0.16,star}$	3.1	1.8	2.7	1.5
6 $E(B-V)_{star}(UV)$	0.31	0.18	0.27	0.15
7 $E(B-V)_{star}(H\beta)$...	0.1 \pm 0.1 ^g	0 \pm 0.2	...
8 $F_{pred}(IR)$	3.7E-13	2.3E-13	1.9E-14	3.2E-15
9 $f_{obs}(450)$	42 \pm 7	...	22 \pm 23	<10
10 $f_{pred}(450)$ ^h	25.9, 71.6	19.5, 51.9	2.1, 5.3	0.36, 0.89
11 $f_{obs}(850)$	15 \pm 2	<4	5.5 \pm 1.4	<1
12 $f_{pred}(850)$ ^h	4.0, 19.0	3.2, 14.6	0.4, 1.6	0.06, 0.27

^aThe AB magnitudes of SMMJ14011 and MS 1512–cB58 are not corrected for the lens magnification factor. $AB_{\mathcal{R}}$ of MS 1512–cB58 is at the observer’s wavelength 0.654 μm (Ellingson et al. 1996), and has intrinsic value $AB_{\mathcal{R}} \simeq 24.5$.

^bThe $G-\mathcal{R}$ color of SMMJ14011+0252 has not been corrected for the opacity of the intervening Lyman α Forest (Adelberger & Steidel 2000).

^cAs derived by Adelberger & Steidel (2000).

^dDerived from $\beta_{18}=-1.10$ using equation B2. β_{18} was directly measured from the UV spectrum kindly provided by M. Pettini & C. Steidel (2000, private communication).

^eDerived by convolving a 1 Gyr constant star formation synthetic SED reddened by Ly α Forest and dust absorption with the G and \mathcal{R} bandpasses (moved to the galaxy’s restframe) until the observed color is reproduced, and then fitting a power law through the UV windows of Calzetti, Kinney & Storchi-Bergmann (1994).

^fFrom Figure 12 of Adelberger & Steidel (2000).

^gThe measured H α /H β emission line ratio of MS 1512–cB58 (Teplitz et al. 2000b) yields $E(B-V)_{star}=0.03^{+0.10}_{-0.03}$.

^hDerived for dust temperature T=50 K and emissivity $\epsilon=2$ (left hand-side value), and for T=40 K and $\epsilon=1.5$ (right hand-side value).

Note. — Predicted and observed values for three highly reddened $z\sim 3$ galaxies, the two lensed SMMJ14011+0252 and MS 1512–cB58, and West MMD11, compared with the average $z\sim 3$ L* LBG. SMMJ14011+0252 is SCUBA-discovered star forming galaxy (Ivison et al. 2000; Adelberger & Steidel 2000). The listed parameters are: (1) the redshift; (2) the AB magnitude at the observer’s frame 0.693 μm (see note for MS 1512–cB58); (3) the $G-\mathcal{R}$ color (corresponding to a 0.12–0.17 color for a $z=3$ galaxy), corrected for the opacity of the intervening Lyman α Forest (Pettini et al. 2001); (4) the UV slope β_{26} (Appendix B); (5)–(6) the stellar obscuration at 0.16 μm and the color excess derived from the UV slope β_{26} (section 4.3), assuming an intrinsic UV slope $\beta_{26,0} = -2.2$, which is equivalent to a ~ 1 Gyr continuous star formation population; (7) the stellar color excess derived from the $L_{0.16}/L_{H\beta}$ luminosity ratio (for a discussion of the uncertainties due to model assumptions see Pettini et al. 2001); (8) the predicted infrared flux, in $\text{erg s}^{-1} \text{cm}^{-2}$, of the dust emission, using the IR/UV–vs.– β correlation (equation 17); (9) and (11) the observed flux densities at 450 μm and 850 μm , in mJy, from Ivison et al. (2000) for SMMJ14011+0252, Sawicki (2001) and van der Werf et al. (2001) for MS 1512–cB58, and Chapman et al. (2000) for West MMD11; (10) and (12) predicted flux densities at 450 μm and 850 μm , in mJy, for a single-temperature modified blackbody (equation 20), and two choices of the dust temperature and emissivity; for reference, the predicted 1.2 mm flux densities are 1.0 mJy (T=50 K and $\epsilon=2$) and 5.7 mJy (T=40 K and $\epsilon=1.5$) for MS 1512–cB58, to be compared with the observed value 1.06 \pm 0.35 mJy (Baker et al. 2001).

Table 6: Ultraviolet Spectral Slopes

Age (Myr)	β_{26}^{inst}	β_{26}^{const}
2	–2.70	–2.68
5	–2.50	–2.61
10	–2.45	–2.57
15	–2.30	–2.55
30	–2.09	–2.50
50	–1.93	–2.45
100	–1.61	–2.38
300	–0.20	–2.28
500	...	–2.26
900	...	–2.23

Note. — The UV spectral slope β_{26} , as defined in Appendix B, is given for both instantaneous burst (second column) and constant star formation (third column) populations at selected ages, for the dust-free case. The model populations are from Leitherer et al. (1999), for solar metallicity.

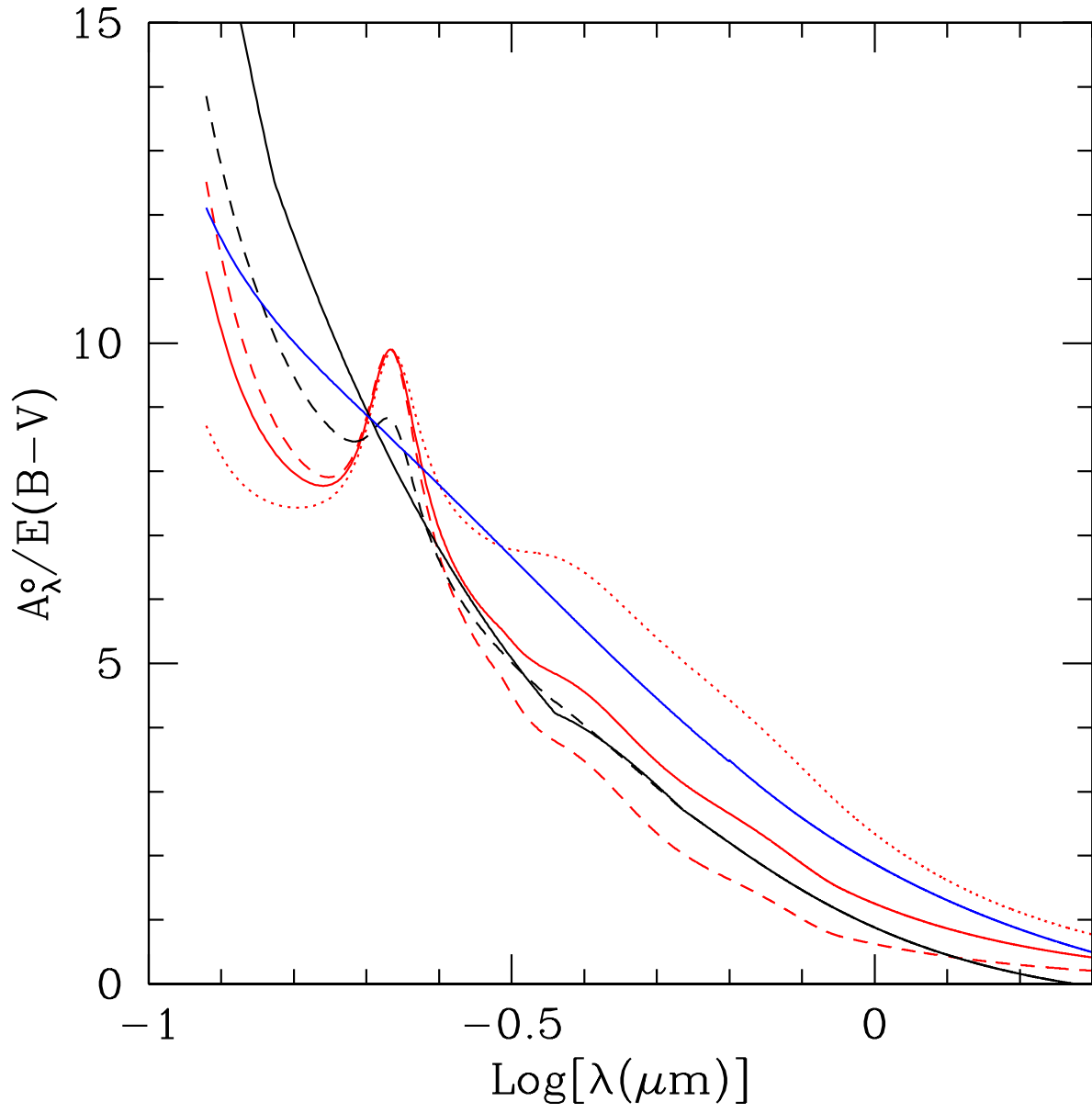


Fig. 1.—

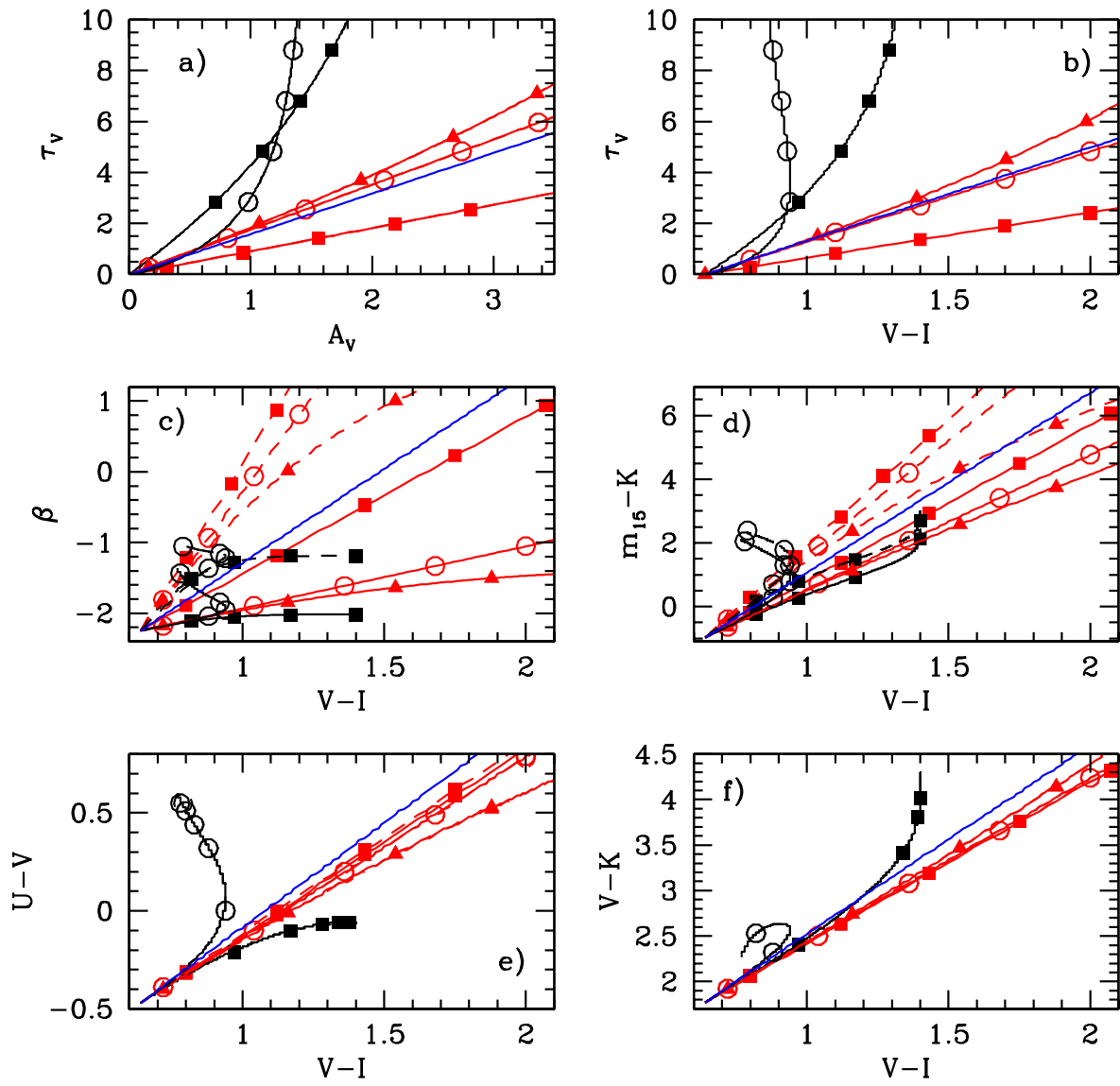


Fig. 2.—

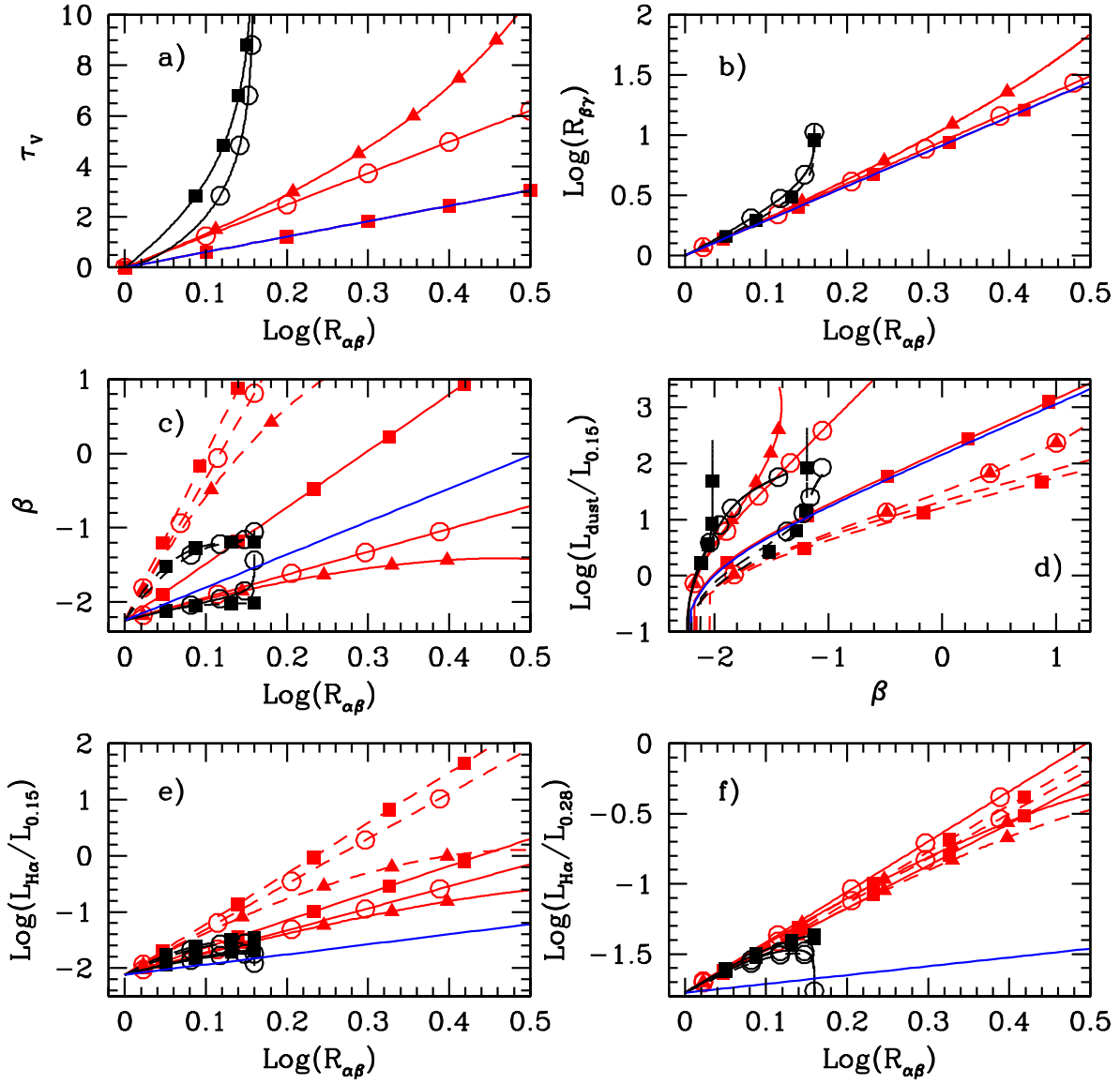


Fig. 3.—

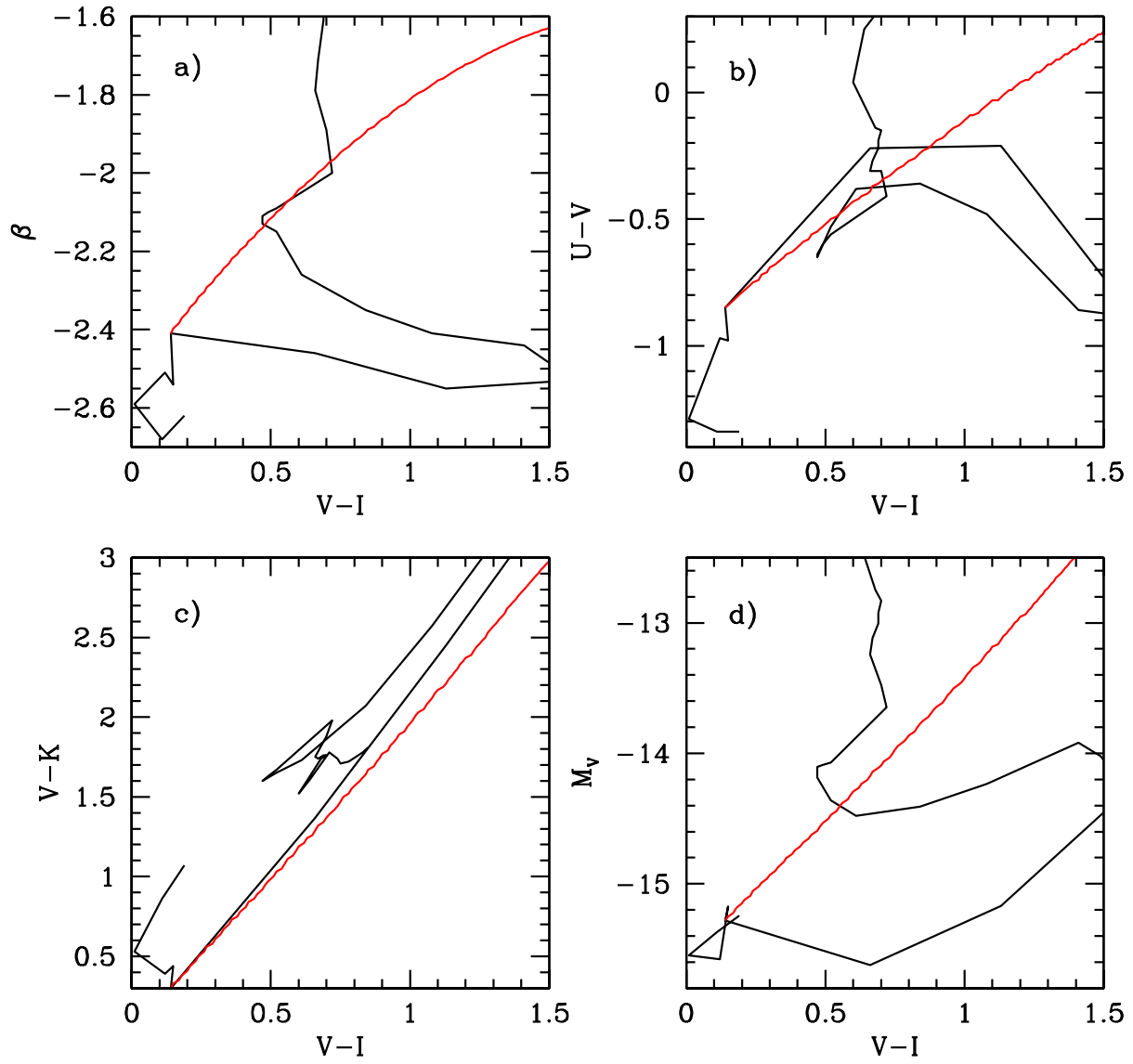


Fig. 4.—

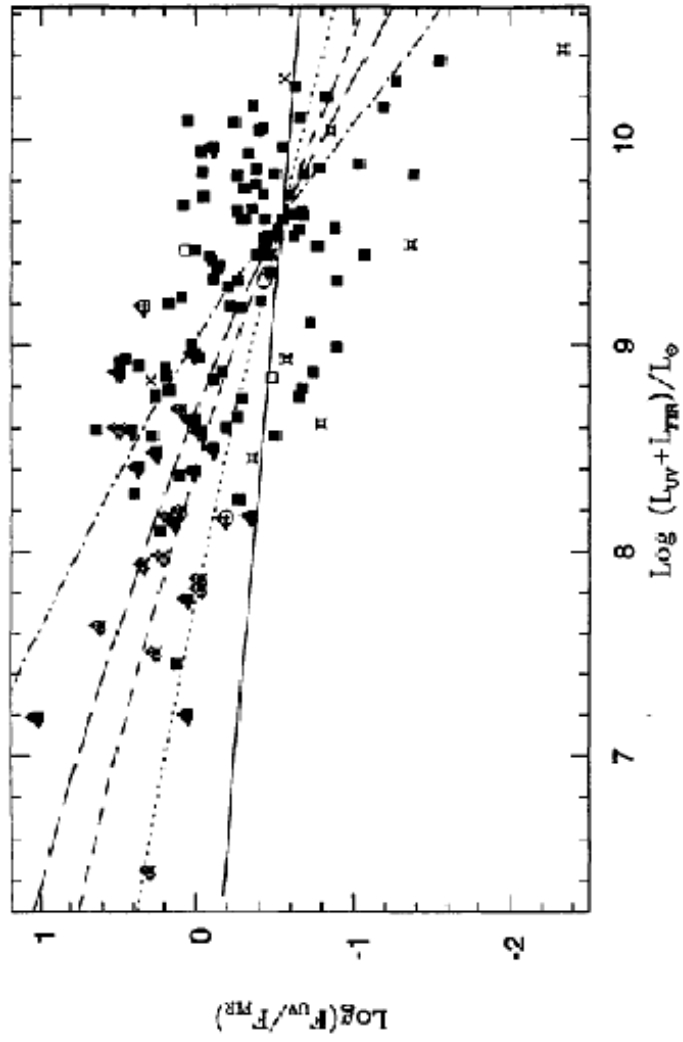


Fig. 5.—

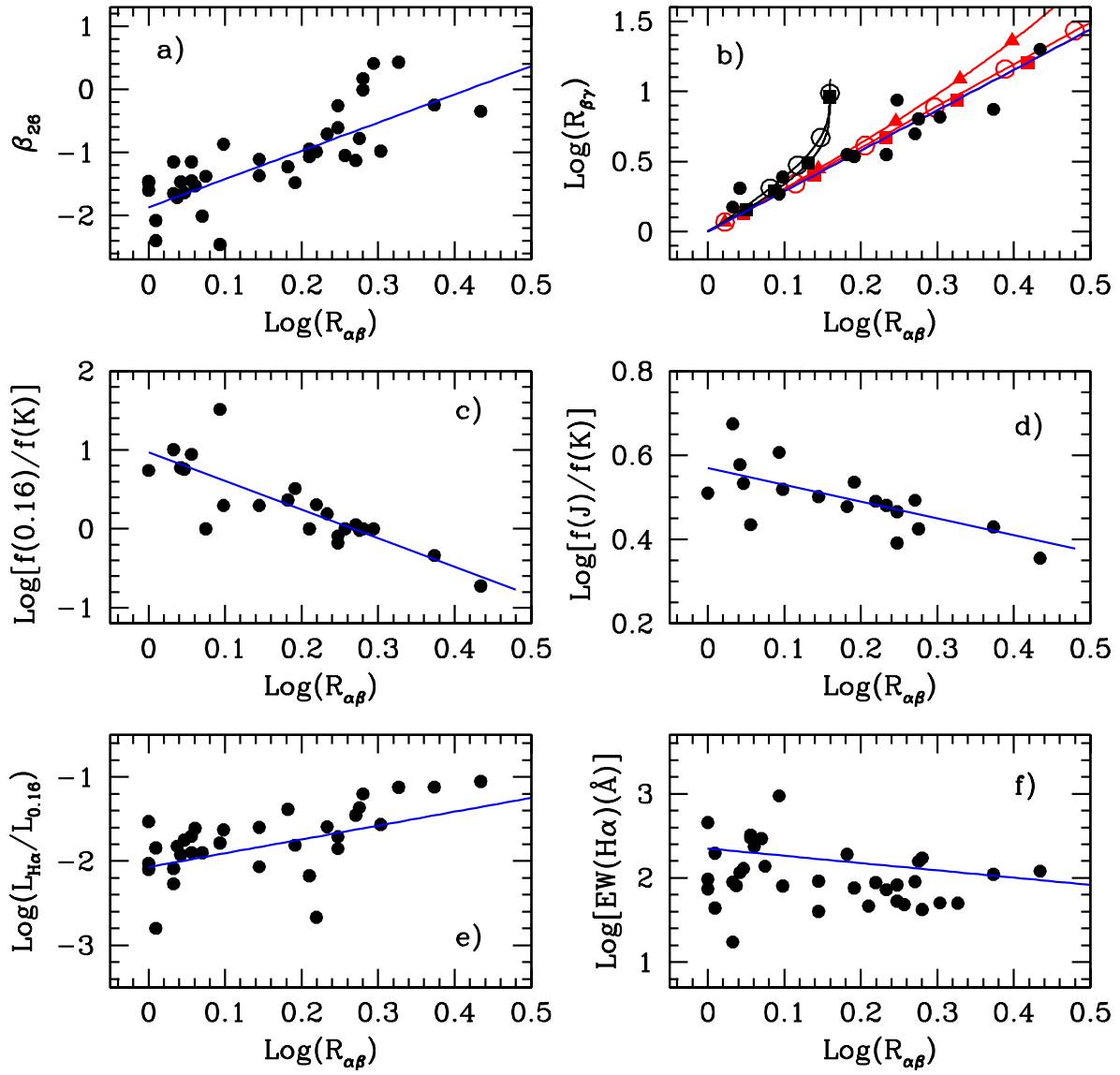


Fig. 6.—

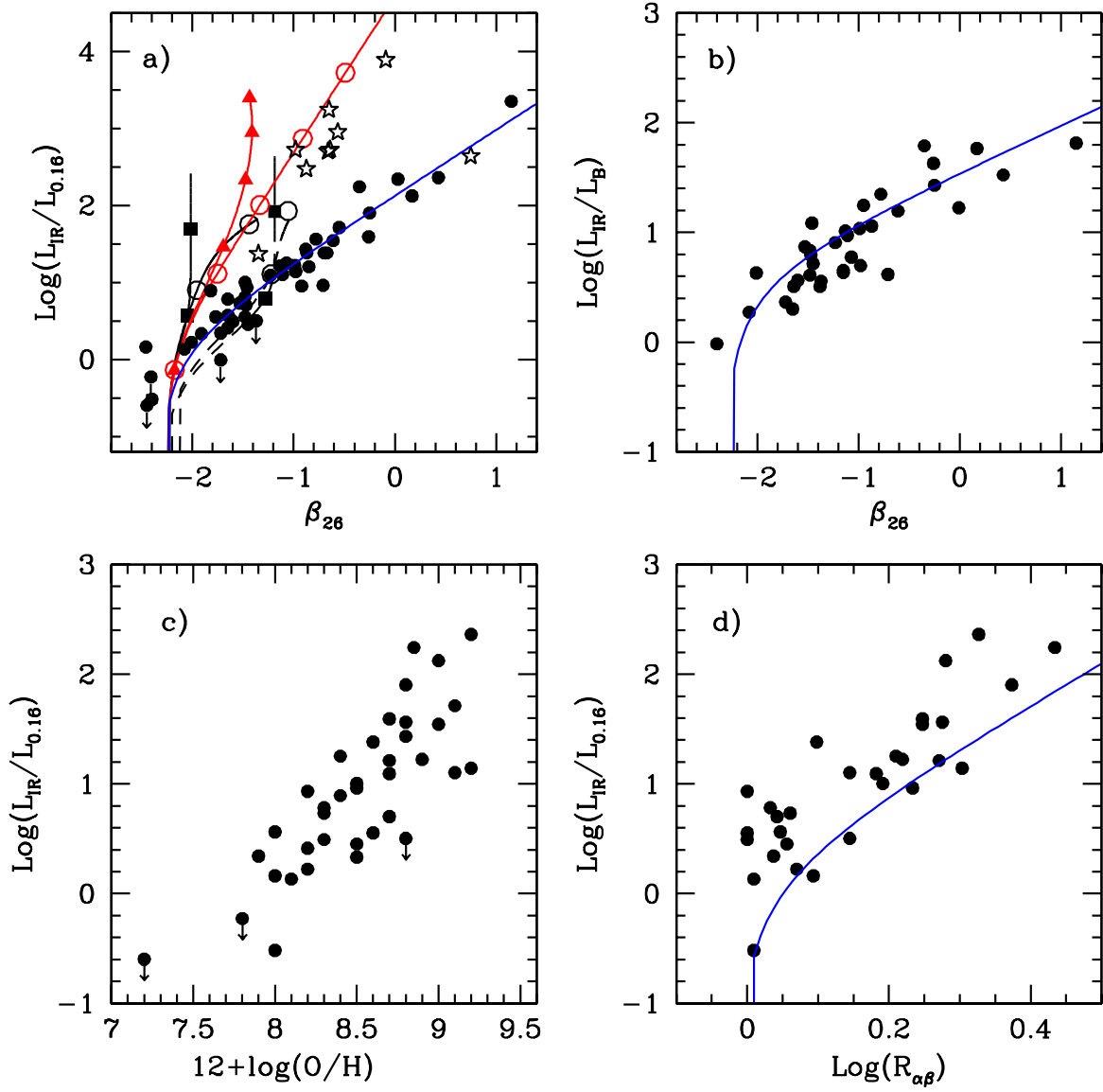


Fig. 7.—

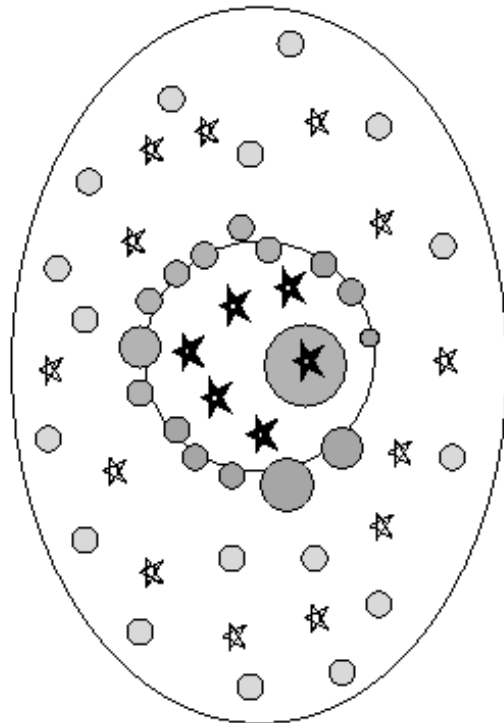


Fig. 8.—

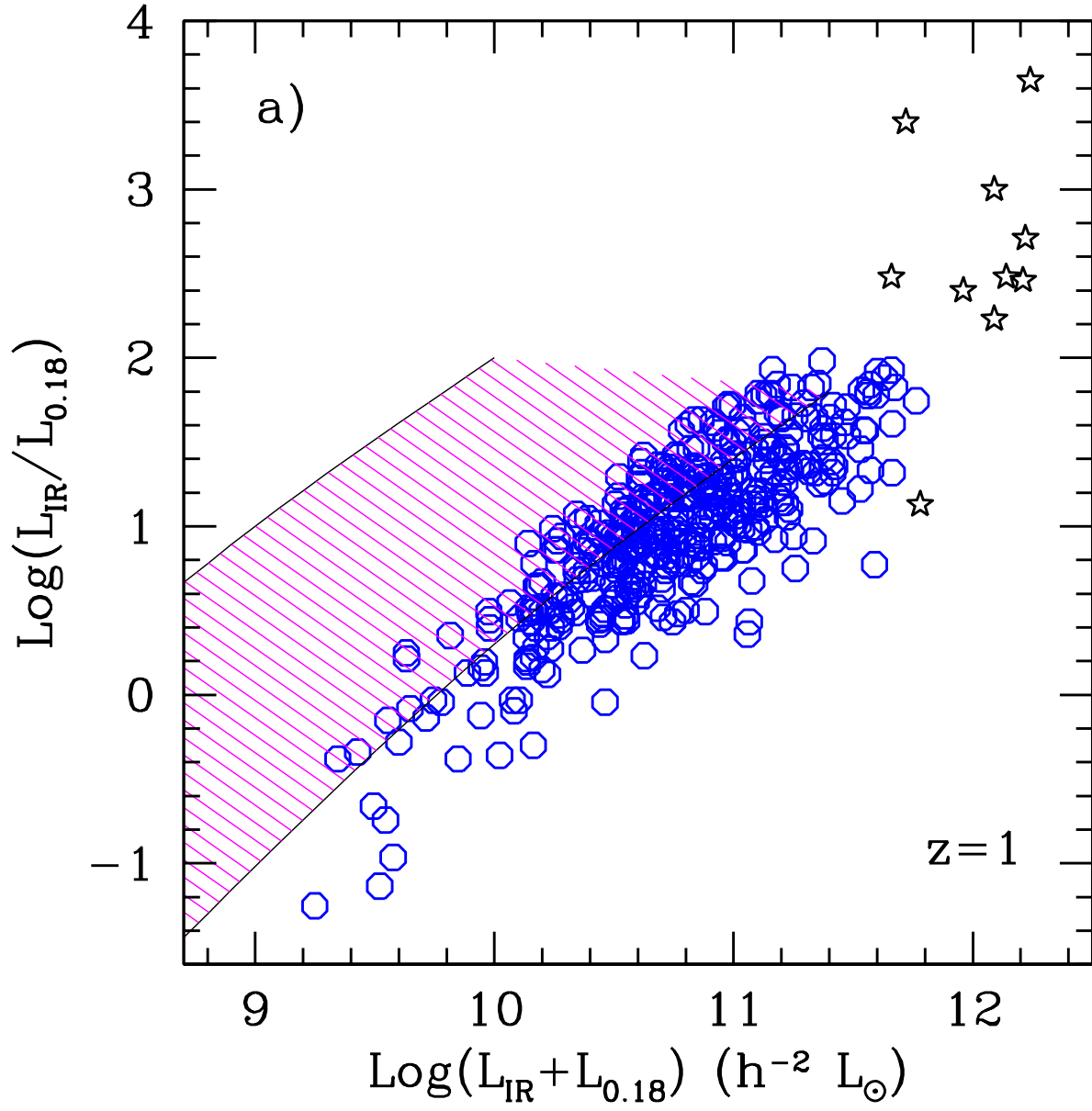


Fig. 9a.—

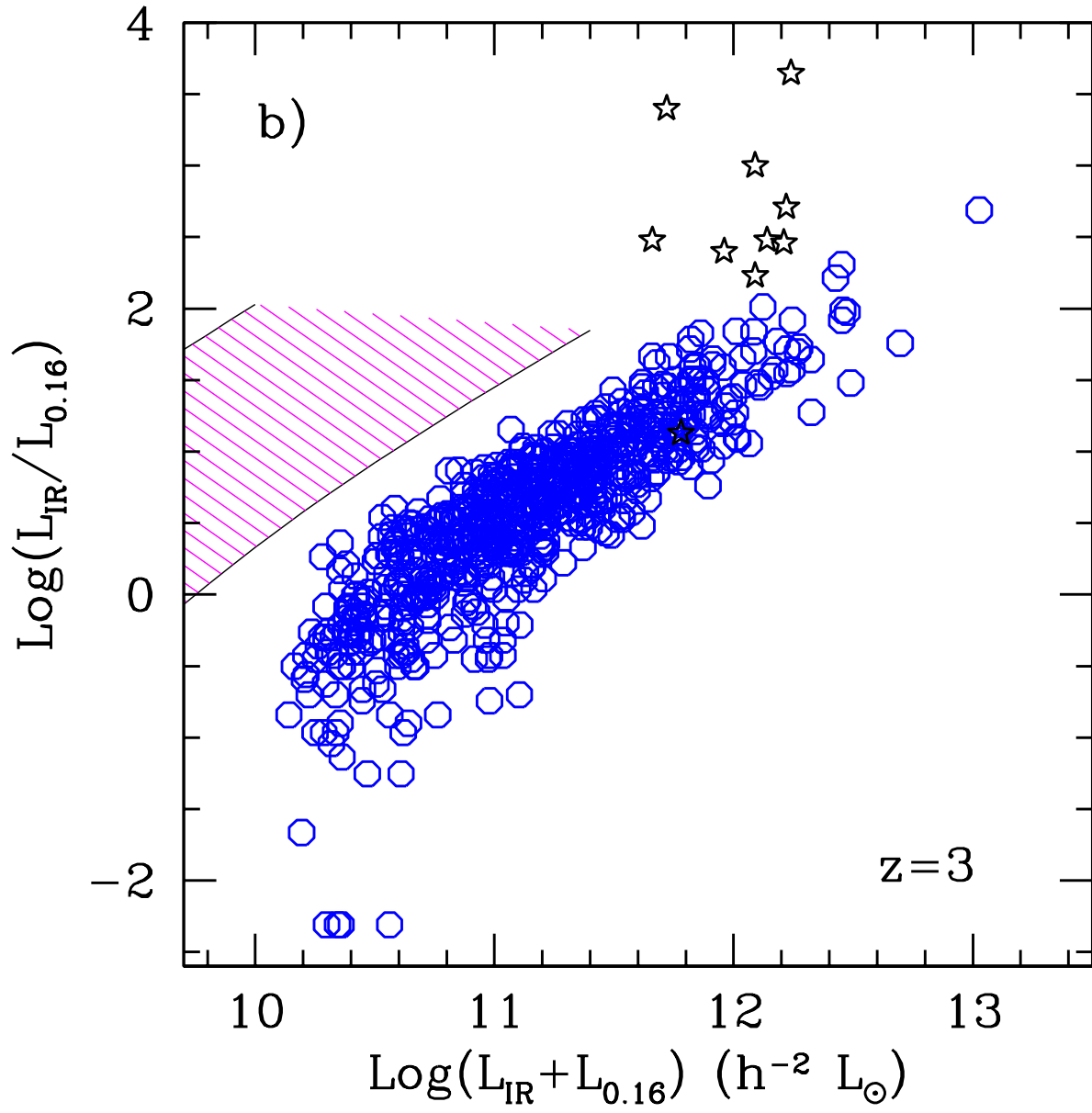


Fig. 9b.—

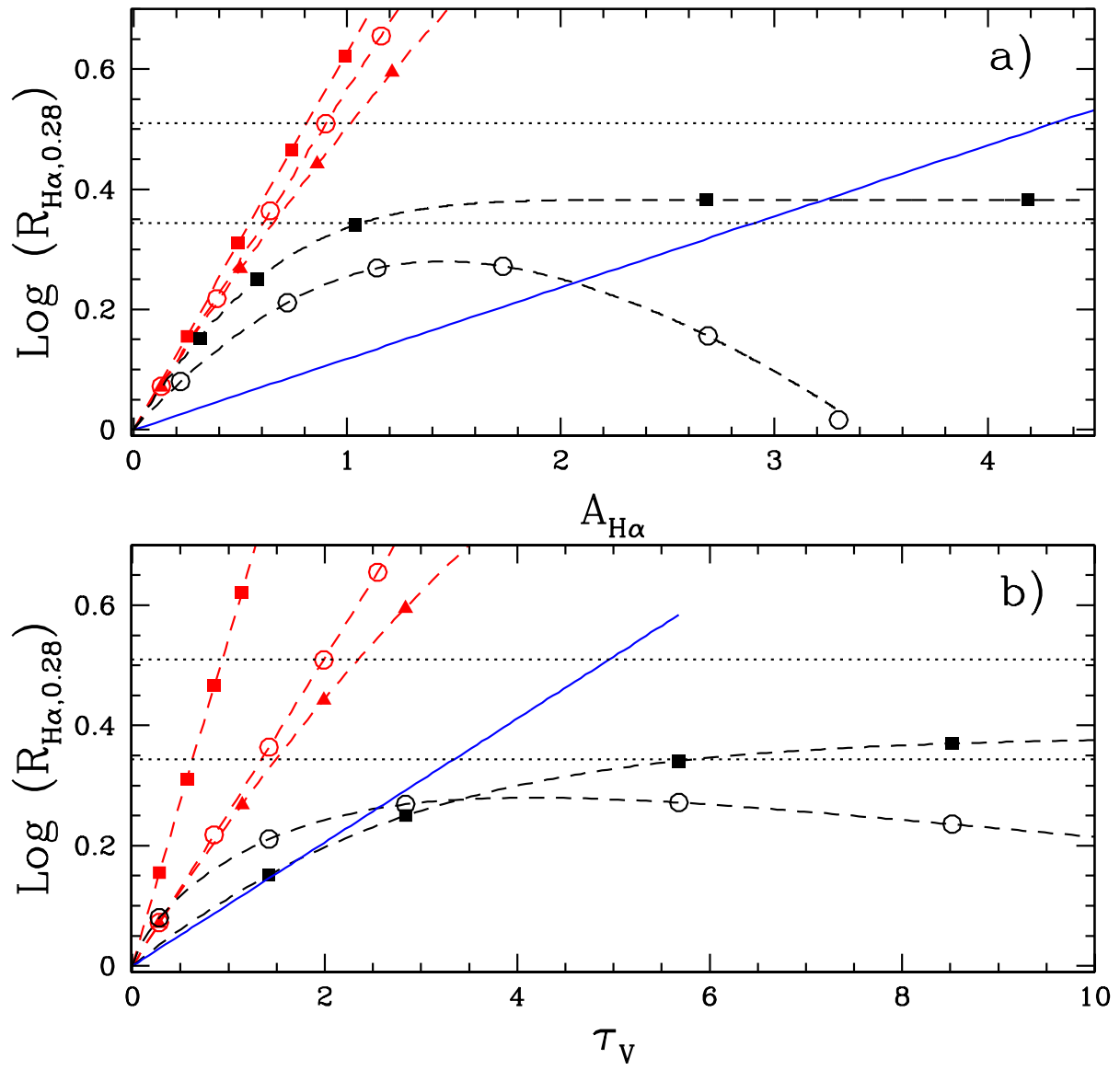


Fig. 10.—

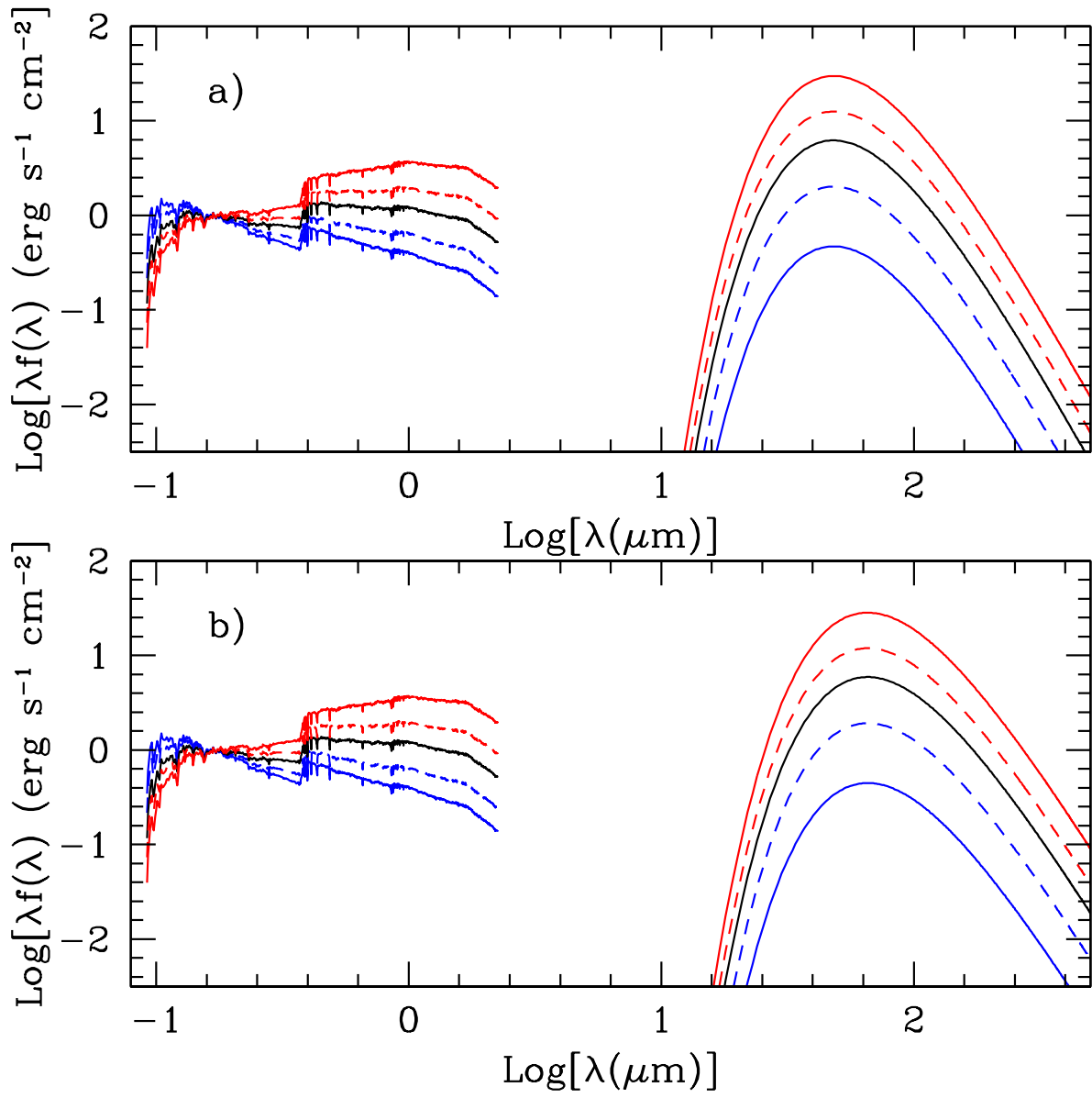


Fig. 11.—