MODELING THE PAN-SPECTRAL ENERGY DISTRIBUTION OF STARBURST GALAXIES. IV.
THE CONTROLLING PARAMETERS OF THE STARBURST SED

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ABSTRACT

We combine the stellar spectral synthesis code Starburst99, the nebular modeling code MAPPINGS III and a one-
dimensional dynamical evolution model of H II regions around massive clusters of young stars to generate improved
models of the spectral energy distribution (SED) of starburst galaxies. We introduce a compactness parameter, C,
which characterizes the specific intensity of the radiation field at ionization fronts in H II regions and which controls
the shape of the far-infrared (IR) dust reemission, often referred to loosely as the dust “temperature.” We also investi-
gate the effect of metallicity on the overall SED and in particular, on the strength of the polycyclic aromatic hydro-
carbon (PAH) features. We provide templates for the mean emission produced by the young compact H II regions, the
older (10–100 Myr) stars and for the wavelength-dependent attenuation produced by a foreground screen of the dust
used in our model. We demonstrate that these components may be combined to produce a excellent fit to the observed
SEDs of star formation-dominated galaxies which are often used as templates (Arp 220 and NGC 6240). This fit ex-
tends from the Lyman limit to wavelengths of about 1 mm. The methods presented in both this paper and in the pre-
vious papers of this series allow the extraction of the physical parameters of the starburst region (star formation rates,
star formation rate history, mean cluster mass, metallicity, dust attenuation, and pressure) from the analysis of the
pan-spectral SED.

Subject headings: dust, extinction — galaxies: general — galaxies: starburst — H II regions —
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1. INTRODUCTION

By definition, the bolometric luminosity of a starburst galaxy
is dominated by the young stars it contains. Thus, regardless of
how much or how little of this luminosity is reprocessed through
the dusty interstellar medium (ISM), either through thermal emis-
Sion in the infrared (IR) of dust grains, through fluorescent pro-
cesses, or through heating and reemission in an ionized medium,
the pan-spectral energy distribution (SED) encodes information
about what the star formation rate currently is and what it
has been in the recent past. The first objective of pan-spectral SED
modeling is therefore to be able to reliably infer star formation
rates in galaxies and to provide likely error estimates using obser-
vational data sets which may in practice be restricted to only
certain emission lines or spectral features. In principle, almost
any part of the SED of a starburst can be used as a star formation
indicator, provided that the appropriate bolometric correction to
the absolute luminosity can be made, and observational issues are
accounted for. In practice, each wavelength regime has a different
level of sensitivity to the ongoing star formation which is depen-
dent on these bolometric corrections, with hydrogen emission
lines and the IR part of the SED being the most robust indicators
of the current star formation rate (SFR). These bolometric cor-
rections critically depend on the foreground dust absorption (more
properly called dust attenuation), and the geometry of the em-
bedded dusty molecular clouds, with respect to both the ionizing
stars and the older stellar population. The accurate determination
of such bolometric corrections is a major motivation of our theo-
retical work of pan-spectral SED modeling.

In order to correctly model the SEDs of starburst galaxies, we
first need to understand how the form of the SED is controlled by
the interstellar physics and the geometry of the stars with respect
to the gas. Once these are understood, we can then use our theo-
retical models to attain the objectives of our second motivation
for such SED modeling; to gain insights into the physical param-
ters of starburst galaxies. In particular, we can hope to quantify
the stellar populations, the atomic and molecular gas content, the
star and gas-phase metallicities, physical parameters of their ISM
such as the pressure or mean density, and the nature of the inter-
stellar dust, both its composition and spatial distribution. The phys-
ical parameters so derived on homogeneous samples of objects
can then help develop our insight into the physical processes
which control them.

The dust grain temperature distribution and, therefore, the shape
and peak of the far-IR feature, depends critically on the geomet-
rical relationship between the dust grains and the stellar heating
sources assumed in the model. Models with warmer far-IR colors
will have a more compact disposition of gas with respect to the
stars. The difficulty here is that, in any simple starburst model,
these geometrical relationships are not determined a priori.

In the semiempirical modeling of Dale et al. (2001) and Dale
& Helou (2002), the SEDs of both disk and starburst galaxies
were suggested to form a one-parameter family in terms of dust
temperature. This suggested that starburst galaxies have hotter
dust temperatures. Lagache et al. (2003) (again empirically) have suggested that the absolute luminosity controls the form of the SED. Both of these assertions may be true to some extent, since IR luminous galaxies generally have greater rates of star formation than normal galaxies.

Galliano et al. (2003) take the simplest approach of approximating the starburst by a spherical $H\ II$ region and clumpy dust shell around the central star-forming region. A more advanced approach is used by Siebenmorgen & Kru¨ gel (2007) to model starbursts and ultraluminous infrared galaxies (ULIRGs). While assuming a spherical geometry for the radiative transfer, they also include the effect of the hot dust around young OB stars as well as the diffuse ISM dust surrounding the starburst and older stellar population. The hot dust component is important as it can dominate the mid-IR emission (Kru¨ gel & Siebenmorgen 1994).

Associated with the latter models is the approach by Efstathiou et al. (2000). Likewise concentrating on starburst galaxies, they modeled the starburst as a group of stars surrounded by thick molecular clouds in a manner similar to our approach, and in addition, also included a similar, simple description for the evolution of the distance of the molecular clouds to the illuminating stars. With these models they could explain the observed IRAS distributions and reproduce several Infrared Space Observatory (ISO) observations.

One of the more sophisticated approaches is taken in the GRASIL code by the Padova-Trieste group (Silva et al. 1998; Granato et al. 2003). Their starburst model uses a spherical geometry with King profiles, and their subsequent escape from these regions. This group has since incorporated gas physics by use of the Cloudy code (Ferland et al. 1998; Abel et al. 2005) to provide emission-line diagnostics as well as dust continuum diagnostics (Panuzzo et al. 2003). A similarly advanced approach was used by Piovan et al. (2006a, 2006b), who also assume a spherical geometry with King profiles and young stars in molecular complexes.

In the conceptually sophisticated models of Tagaki et al. (2003a, 2003b) a mass-radius relationship for the star formation region of $r_i/kpc = \Theta(M/10^9 M_\odot)^{1/2}$ is adopted along with a stellar density distribution given by a generalized King profile. The parameter $\Theta$ is a compactness parameter which expresses the degree of matter concentration, and is related to the optical depth of the dust through which the starburst region is seen. For a sample of ultraluminous starbursts, they find that, while most conform to a constant surface brightness of order $10^{12} L_\odot$ kpc$^{-2}$, there are a few objects with surface brightnesses roughly 10 times larger than this, which they ascribe to postmerger systems. In this paper, we adopt a derivative version of this concept of a compactness parameter as the factor which provides the main control on the shape of the far-IR bump.

All the fully theoretical (as opposed to semiempirical) methods used by other groups involve the calculation of essentially a single spherical radiation transfer problem. Unfortunately, real starburst galaxies have many separate clusters of many different ages distributed in a complex spatial distribution. However, gas column densities and pressures can be extremely high, and as a consequence, the size scale of individual $H\ II$ region complexes can be extremely small in comparison to the overall scale of the starburst. It is only when the star-forming complexes join up to produce large-scale collective phenomena as in, for example, the outflow in M82 that we need to go to a full three-dimensional radiative transfer model covering the whole galaxy.

In the earlier papers in this series, we take advantage of the localized radiative transfer approximation to construct our panspectral SEDs. Instead of treating the starburst as a single $H\ II$ region complex covering the whole starburst region, we split the starburst up into many individual $H\ II$ regions, each ionized by the ultraviolet (UV) photons of the clusters within them and each evolving in radius and internal pressure according to the mechanical energy input of the exciting stars through their stellar winds and supernova explosions. The global SED is then the sum of the SEDs produced by each of these $H\ II$ regions and their surrounding photodissociation regions (PDRs) integrated over all cluster ages. Since the radiative transfer problem in each $H\ II$ region is fully treated, in this approach we stand a better chance of capturing the full range of physical conditions encountered in a starburst region. This collective approach is what can be found in many of the sophisticated modeling codes such as that of Piovan et al. (2006a) and GRASIL (Silva et al. 1998). In GRASIL, for example, multiple core molecular cloud systems can be included with differing parameters for each, such as mass and optical depth.

In the first paper (Dopita et al. 2005), we investigated the role that pressure alone plays in changing the compactness of the $H\ II$ regions within the starburst and, hence, in controlling the shape of the far-IR dust emission bump. However, a defect in these models is that they were only run with a single value of mean cluster mass $\langle M_\odot \rangle$. A change in cluster mass directly affects the specific intensity of the radiation field in the $H\ II$ region, and this will in turn change the shape of the far-IR bump.

In the second and third papers (Dopita et al. 2006b, 2006c), we introduced the $R = \langle M_\odot \rangle/P_0$ parameter, which controls the absolute value of the ionization parameter in the $H\ II$ region and its time evolution. The ionization parameter is defined as the ratio of the ionizing photon density to the particle density in the $H\ II$ region: $\Upsilon = L_{UV}/4\pi R_{H\ II}^2 n_p$, where $L_{UV}$ is the flux of ionizing UV photons produced by the central cluster, $R_{H\ II}$ is the mean radius of the $H\ II$ region with particle density $n$, and $c$ is the speed of light. All models having a given value of $R$ and metallicity Z will show the same run of ionization parameter as a function of cluster age and will therefore produce identical line ratios at any given age.

The shape of the dust feature or “bump” in the IR in starbursts is controlled by the distribution of dust temperatures in the starburst galaxy. Within a given $H\ II$ region, this distribution of temperatures is controlled by the specific photon density, meaning that the mean dust temperature of any individual grain is $T_g = \langle T_g \rangle = f(L_{UV}/R_{H\ II}^2)$. Thus, denser and more compact $H\ II$ regions will produce hotter grain temperature distributions. In this paper, we introduce, by analogy with the $R$ parameter, a “compactness parameter,” $C$. All models having a given value of $C$ and metallicity $Z$ will show the same run of grain temperature distribution as a function of cluster age and will therefore produce identical far-IR dust reemission bumps at any given age.

In the following sections of this paper, we discuss the details of our modeling procedure, insofar as this is different from that used in earlier papers in this series, introduce the compactness parameter, and show that this does indeed serve to characterize the far-IR bump for $H\ II$ regions in the age range 0.5–10 Myr. We also investigate the effects of varying metallicity on the form of the far-IR bump and provide templates for the mean SED of compact $H\ II$ regions, of the older (10–100 Myr) stars, and for the attenuation produced by a dusty fractal foreground screen. Finally, we show how these components can be combined to produce excellent fits to frequently-used starburst templates such as Arp 220 or NGC 6240.

2. MODELS

The starburst models calculated here follow the general form described in the previous papers of this series (Dopita et al. 2005,
2006a, 2006c, ; hereafter SED1, SED2, and SED3, respectively). However, apart from being updated to use the latest versions of the modeling codes Starburst99 (Leitherer et al. 1999) and MAPPINGS III (Groves 2004), the models incorporate a number of changes or improvements that we here describe in greater detail. To make this paper self-contained, we briefly recapitulate on the techniques used in the earlier papers of this series.

2.1. Stars and Stellar Clusters

We have used the latest version (2006) of Starburst997 to compute the SED of clusters of stars of any given age. A detailed description of latest stellar atmospheres and stellar evolution physics used within the code are given in Smith et al. (2002) and Vázquez & Leitherer (2005).

In our Starburst99 models, we take an instantaneous burst of $M_d = 10^6 M_\odot$, having a Kroupa (2002) broken power-law IMF between 0.1 and 120 $M_\odot$. Within the code we use the standard combination of the Geneva and Padova tracks for the stellar evolution (Vázquez & Leitherer 2005), and these determine the total mechanical luminosity, $L_{\text{mech}}$. We use the theoretical high-mass-loss tracks for the treatment of the stellar wind. The supernova cutoff mass is $8 M_\odot$. However, since the H II region evolution is run up to only 10 Myr, the exact choice of this cutoff mass is unimportant to the modeling.

We output the stellar spectra at 0.01 Myr, 0.5 Myr, and then every 0.5 Myr after that up to an age of 10 Myr, by which effectively all of the ionizing photons have been emitted (see SED2). Note that the resolution of the starburst model is actually higher at 0.1 Myr, which provides the fine gridding needed to accurately track the mechanical energy input used in the computation of the evolution of the H II regions. For completeness, this model was also extended to 1 Gyr, with spectra computed at longer intervals for older stellar templates.

To determine the parameters for clusters of any given mass, we assume a simple scaling with cluster mass. Such a scaling should hold in starbursting regions where many clusters are forming, as here stochastic effects are generally small, and on average the IMF is well sampled throughout the mass range. However, as a number of authors have pointed out, several of whom are referenced in Smith et al. (2002) and Vázquez & Leitherer (2005), these determine the total mechanical luminosity, $L_{\text{mech}}$. We use the theoretical high-mass-loss tracks for the treatment of the stellar wind. The supernova cutoff mass is $8 M_\odot$. However, since the H II region evolution is run up to only 10 Myr, the exact choice of this cutoff mass is unimportant to the modeling.

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2.2. H II Region Evolution

The H II regions are treated as one-dimensional mass-loss bubbles driven by the mechanical energy input of their stars and supernovae (Castor et al. 1975). Their equation of motion is given by (SED1),

$$\frac{d}{dt} \left[ R \frac{d}{dt} (R^3 \dot{R}) \right] + \frac{9}{2} R^2 \dot{R}^3 = \frac{3 L_{\text{mech}}(t)}{2 \pi \rho_0},$$

where the time-dependent mechanical luminosity, $L_{\text{mech}}(t)$, is determined from the Starburst99 output.

The pressure in the H II region with radius $R$, expanding in an ISM with density $\rho_0$ is then determined as

$$P = n_{\text{HII}} k T_e,$$

$$= \frac{7}{(3850 \pi)^{7/5}} \left( \frac{250}{308 \pi} \right)^{4/15} \left( \frac{L_{\text{mech}}(t)}{\rho_0} \right)^{2/3} \rho_0^{4/3}(t),$$

where $n_{\text{HII}}$ is the density of the ionized gas, with electron temperature $T_e$. This equation is derived from the (Oey & Clarke 1997, 1998) version of the Castor et al. (1975) mass-loss bubble formulae with the assumption that the H II region has the same pressure as the shocked stellar wind and is confined to a thin shell around the periphery of the wind-blown bubble. The ionizing flux at the inner boundary of the H II region is then $L_{\text{UV}}/4\pi R^2$ and the density in the ionized region $n_{\text{HII}}$ is given by the first half of equation (2), from which the ionization parameter of the H II region, $U$, can be derived.

2.3. Nebular Abundances and Depletion Factors

The abundance set and depletion factors used in these models are unchanged from those presented in SED3 and are given in Table 1. The nebular abundance set follows Asplund et al. (2005). As noted previously, the gas phase “Solar” abundance in the models is somewhat offset from the “Solar” abundance set used in Starburst99. While this has been shown to have no significant effect on the models, it does result in a small inconsistency in the models.

The exploration of metallicity effects within the models presented here is limited to those metallicities computed in Starburst99; 0.05, 0.2, 0.4, 1.0, and 2.0 $Z_\odot$. As in SED3, we simply scale the abundances with metallicity, with the following exceptions. For helium we use the empirical relationship to include the primordial component as well as that from nucleosynthesis,

$$\frac{\text{He}}{\text{H}} = 0.0737 + 0.024(Z/Z_\odot).$$

Table 1. The abundance set and logarithmic depletion factors log(D) adopted for each element.

| Element | $\log(Z/Z_\odot)$ | $\log(D)$ |
|---------|------------------|-----------|
| H       | 0.00             | 0.00      |
| He      | -1.01            | 0.00      |
| C       | -3.59            | -0.52     |
| N       | -4.20            | -0.22     |
| O       | -3.34            | -0.22     |
| Ne      | -3.91            | 0.00      |
| Na      | -5.75            | -0.60     |
| Mg      | -4.42            | -0.70     |
| Al      | -5.61            | -1.70     |
| Si      | -4.49            | -1.00     |
| S       | -4.79            | -0.22     |
| Cl      | -6.40            | -0.30     |
| Ar      | -5.44            | 0.00      |
| Ca      | -5.64            | -2.52     |
| Fe      | -4.55            | -2.00     |
| Ni      | -5.68            | -1.40     |

7 See Web site at http://www.stsci.edu/science/starburst99/.
of estimating these. We must also assume that the depletion pattern does not vary with metallicity, as there are currently no good models or observations for the relationship between metallicity and depletion. However, in the starbursting environments modeled here, such an assumption may be adequate (Draine et al. 2007). With this assumption the dust-to-gas ratio is purely a function of metallicity.

2.4. Photoionization Models

For the component H ii regions, we compute both the emission and internal absorption of both gas (line plus continuum) and dust (continuum including polycyclic aromatic hydrocarbons [PAHs]) using the MAPPINGS III code, with the Starburst99 stellar cluster spectra as input. Apart from the effects of burst age and metallicity, here we explore three other parameters within the models; the ISM pressure, \( P_0 \), the cloud covering fraction, \( f_{PDR} \), and the compactness parameter, \( C \), described below, which is a function both of \( P_0 \) and of the mean cluster mass, \( \langle M_\odot \rangle \).

For the models investigated here we examine five different thermal gas pressures; \( P_0/k = 10^4, 10^5, 10^6, 10^7 \), and \( 10^8 \) K cm\(^{-3} \). These five pressures cover the full range expected to be encountered in starbursting galaxies, from regions of enhanced star formation in disk galaxies, to the high-pressure ULIRGs. For each parameter set we compute models at 21 starburst ages, covering the timescale 0.01–10 Myr in steps of 0.5 Myr.

Finally, for each age we run two models. The first model is of the H ii region alone; the region within which 99% of the hydrogen line emission arises and within which almost all of the ionizing photons are absorbed. It is within this region that the hottest dust emission arises. The second model corresponds to the PDR surrounding the H ii region. This region is the transition layer between the H ii region and surrounding dense molecular cloud, from which the stellar cluster is thought to have formed. In the PDR, a large fraction of the stellar light is absorbed and most of the PAH and dust far-IR emission produced. We follow the radiative transfer beyond the ionization front in the H ii region until a total hydrogen column depth of \( N(H\text{ i}) = 10^{22} \) cm\(^{-2} \) is achieved. The column depth of \( 10^{22} \) cm\(^{-2} \) is based on both observations and on theoretical considerations. The observational data come from measurements of individual molecular clouds both within our galaxy (Larson 1981; Solomon et al. 1987; Heyer et al. 2001) and in neighboring galaxies such as M33 (Rosolowsky et al. 2003) which all give hydrogen column densities of \( \sim 10^{22} \) cm\(^{-2} \) independent of cloud radius. This value is not unexpected, since it indicates that all giant molecular clouds are marginally stable against gravitational collapse, provided that their virial temperatures are a few tens of degrees kelvin.

These two models, H ii and PDR, are combined through our final parameter, \( f_{PDR} \), the starburst cloud covering fraction. This parameter is a simplified version of the clearing timescale introduced in SED1, and discussed in other dust models (e.g., Silva et al. 1998; Charlot & Fall 2000). We introduce this parameter because a starbursting system will be a conglomerate of bursts of different ages and sizes, unlike a single molecular cloud around an individual cluster. Thus, while the molecular cloud clearing timescale offers a more physical picture for an individual cluster, the starburst cloud covering fraction better represents what is likely to be encountered in a starbursting system.

The multiple star clusters forming in a starburst will be of all possible masses and, sampled at any instant in time, of all possible ages. To account for this we compute the luminosity-weighted average of all 21 ages computed between 0–10 Myr. In Figure 1 we show the SEDs of the 21 calculated ages of an individual H ii region and a H ii region with its PDR, along with the summed final average SED for each. These figures clearly show the evolution of both the stellar and nebular spectrum with age, and reveal the decreasing cluster UV flux and cooling dust temperatures as the clusters age and the H ii bubble expands.

In all, we have computed a total 300 starburst H ii region models covering five metallicities, six values of the \( C \) parameter (described below), five values of the ISM pressure, and a separate H ii region and H ii region plus PDR model for each set of parameters (corresponding to \( f_{PDR} = 0 \) and 1, respectively). All models are scaled in flux to correspond to a SFR of \( 1 M_\odot \) s\(^{-1} \) continued over the 10 Myr lifetime of the H ii regions.

2.5. Dust Physics

The treatment of dust within the photoionization code MAPPINGS III was discussed in SED1. Here, we concentrate only those areas where changes have been made to the dust parameters within the code.

In brief, our dust model consists of three components: graphite, silicates, and PAHs. The optical data for each of these come from Laor & Draine (1993), Li & Draine (2001), and Weingartner & Draine (2001)\(^8 \). The IR spectrum arising from dust, excluding the effects of PAH emission, is calculated self-consistently, including

\[^8\] See Web site at http://www.astro.princeton.edu/~draine/dust/dust.diel.html.
the effects of stochastic heating in small grains (all dust calculations are discussed in detail in Groves [2004]). The total dust-to-gas ratio within the code is set by the fraction of metals depleted from the gas onto dust, given in Table 1.

The heavy elements removed from the gas phase are distributed between the two main types of dust, carbonaceous and siliceous, with the carbonaceous dust being further divided into graphite and PAHs. The graphite and silicate dust is distributed across a grain with the carbonaceous dust being further divided into graphite and PAHs. The graphite and silicate dust is distributed across a grain size distribution arising from grain destruction processes (SED1);

\[
dN(a)/da = ka^{-3.3} \frac{e^{-\left(a/a_{\text{max}}\right)^3}}{1 + a^3/a_{\text{max}}^3},
\]

with \( k \) defined by the dust-to-gas ratio. The minimum grain size of graphite and silicates are \( a_{\text{min}} = 20 \) and \( 40 \) Å, respectively, while the maximum grain size is the same for both species at \( a_{\text{max}} = 1600 \) Å.

### 2.6. PAHs

PAHs are treated somewhat separately to the other types of dust. They are given a characteristic size and an opacity similar to coronene, the best-studied catacondensed PAH. We have constructed an empirically based IR emission spectrum described in more detail below. The PAH-to-gas ratio is defined through the PAH-to-carbon dust ratio, which is set at 30% in these models. While this may not be accurate for all environments and metallicities (Draine et al. 2007), it provides a reasonable match to current observations of nearby star-forming galaxies. Differences between the template IR emission spectrum and those actually observed will provide limits on parameters such as dehydrogenation, the relative abundance of catacondensed and pericondensed species, and the degree of nitrogen substitution within the carbon skeleton, which affects the 6.2 μm C−C stretch feature (Peeters 2002).

There is now a great deal of observational evidence that PAHs are destroyed within the ionized parts of the H II region complexes, with Spitzer observations of Galactic H II regions showing clear boundaries between the outer PDR PAH-emitting zone and the inner photoionized zone (e.g., Churchwell et al. 2006; Povich et al. 2007). The exact destruction mechanism is uncertain, but is likely to be photodestruction through stochastic heating and/or photoionization and dissociation. To simulate this process within the MAPPINGS III code, we previously introduced the Habing photodissociation parameter, \( \mathcal{H} = F_{\text{FUV}}/n_{\text{H}2} \), a far-UV (FUV) analogy of the standard dimensionless ionization parameter \( U \) (see eq. [17] and associated section in SED1). In a series of test models, we found that for typical, solar metallicity starbursts, \( \mathcal{H} \sim 10^{-3} \) at the ionization front. We hereafter assume this value to be the destruction point for PAHs within our models. For typical H II densities of \( 10^3 \) cm$^{-3}$, this implies a radiation field \( \sim 2-20 \) times the Habing (1968) local interstellar radiation field, consistent with the range up to which PAHs are observed to survive (Compiègne et al. 2007). At values of \( \mathcal{H} < 10^{-3} \), PAHs exist in either neutral or singly charged states, are heated by the diffuse FUV/optical field, and emit in the classic PAH mid-IR bands.

This emission spectrum is determined by the natural modes of vibration, bending, and other deformations of the planar carbon skeleton. This spectrum is dependent on the size and the electric charge state of the molecule, and is modified by the effect of non-hydrogenic end groups, including simple dehydrogenation and skeletal atomic substitution (Peeters 2002).

Thanks to the advent of space-borne IR observatories, the PAH emission spectrum has now been observed in many galaxies and situations, ranging from beautiful maps of Galactic H II regions (Churchwell et al. 2006) to detailed mapping of the features in both starburst galaxies (Beirão et al. 2007) and QSOs (Schweitzer et al. 2006).

Given the wide ranges of possible molecular forms, it is surprising that the form of the PAH emission spectrum in the mid-IR is so similar between different regions and galaxies (Brandl et al. 2006). Only small variations in the relative strengths of the PAH features have been observed within our own Galaxy and in nearby galaxies (Smith et al. 2007).

The accuracy of using a PAH template to represent the series of bands in the mid-IR can be estimated from the study of the variation of these bands in nearby galaxies by Smith et al. (2007). They find on average variations of a factor of 2 around the mean ratios of the different PAH bands (their Table 7), with the most significant differences occurring in galaxies hosting weak active galactic nuclei (AGNs; such as LINERs). This suggests that our PAH template is accurate to about this factor, with significant variations indicating differences such as PAH ionization state, or correspondingly, the presence of a weak AGN in the starburst galaxy. The differences between our models and the observed PAH bands could therefore be used as diagnostics of ISM physics or host nuclear properties.

As discussed in SED1, we parameterize the template using a sum of Lorentzian profiles. The Lorentzian fits to the spectrum take the form

\[
F_\nu(x) = \frac{f_0}{1 + (x - x_0)^2/\sigma^2},
\]

where \( x = \lambda / \lambda_0 \), the central wavenumber of the feature is \( \lambda_0 \), the FWHM is \( 2 \sigma \), and the peak value is \( f_0 \) (ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$).

To derive the PAH emission spectrum template currently used in these MAPPINGS III models, we have fit Spitzer IRS observations of NGC 4676 and NGC 7252. These two interacting galaxy pairs show strong, clear PAH emission, making them good choices for a template spectrum. In both objects we subtract the underlying dust continuum assuming a combined power law and exponential form to fit the PAH-free, long-wavelength end of the spectra. The combined, continuum-subtracted observed spectrum is shown with our best-fitting template in Figure 2.
TABLE 2

| wavelength (cm⁻¹) | f₀ (ergs cm⁻² s⁻¹ Hz⁻¹ sr⁻¹) | σ (cm⁻¹) |
|------------------|-----------------------------|----------|
| 3040.3           | 1.00E⁻⁰⁴                   | 22.4     |
| 1897.0           | 1.00E⁻⁰⁴                   | 40.0     |
| 1754.0           | 1.00E⁻⁰⁴                   | 40.0     |
| 1608.5           | 3.420E⁻⁰⁴                 | 37.8     |
| 1608.5           | 4.600E⁻⁰⁴                 | 14.4     |
| 1593.9           | 2.140E⁻⁰⁴                 | 34.9     |
| 1490.0           | 5.000E⁻⁰⁵                 | 30.0     |
| 1400.0           | 3.420E⁻⁰⁴                 | 100.0    |
| 1313.0           | 1.200E⁻⁰³                 | 28.0     |
| 1270.0           | 1.280E⁻⁰³                 | 35.0     |
| 1200.0           | 3.200E⁻⁰⁴                 | 30.0     |
| 1163.1           | 8.900E⁻⁰⁴                 | 27.0     |
| 998.0            | 1.630E⁻⁰³                 | 129.1    |
| 940.0            | 1.600E⁻⁰³                 | 13.0     |
| 890.0            | 1.700E⁻⁰³                 | 7.0      |
| 883.0            | 1.800E⁻⁰³                 | 14.1     |
| 836.0            | 4.200E⁻⁰⁴                 | 14.1     |
| 813.0            | 2.000E⁻⁰⁵                 | 15.0     |
| 800.0            | 5.300E⁻⁰⁴                 | 70.7     |
| 788.0            | 1.200E⁻⁰³                 | 13.0     |
| 737.0            | 3.000E⁻⁰⁴                 | 18.2     |
| 702.0            | 2.570E⁻⁰⁴                 | 12.9     |
| 670.0            | 8.550E⁻⁰⁵                 | 18.3     |
| 635.0            | 1.710E⁻⁰⁴                 | 18.3     |
| 607.0            | 7.800E⁻⁰⁴                 | 7.5      |
| 588.0            | 8.300E⁻⁰⁴                 | 5.8      |
| 576.0            | 4.280E⁻⁰⁴                 | 4.0      |
| 571.0            | 2.140E⁻⁰⁴                 | 20.0     |
| 562.0            | 8.550E⁻⁰⁵                 | 3.8      |
| 530.0            | 1.450E⁻⁰⁴                 | 7.0      |

TABLE 2: Normalized Parameters of the Lorentzian Components of the PAH Emission Band

Corresponding parameters for each of the Lorentzian profiles given in Table 2.

As discussed in SED1, PAH emission within the MAPPINGS III code is treated as an energy-conserving process. In equilibrium all the energy gained by a PAH through the absorption of photons can be either lost through photoelectric processes or IR emission. Once the fraction of the energy lost through photoelectric processes is determined using the photoelectric cross-sections, the remaining energy fraction is remitted in the IR according to our empirical template. This is not an exact treatment, as the PAH molecules will likely undergo stochastic heating processes and will lose some of their energy through IR continuum emission instead of via these fluorescent bands. However, the code does allow for the stochastic treatment of both very small graphite and silicate grains.

3. THE C PARAMETER

We now deal with the parameter which controls predominantly the form of the far-IR continuum. Fundamentally, this continuum is a function of the probability distribution of the grain temperatures throughout the starburst. At any point within an H II region or its surrounding PDR, this is determined by the intensity and the SED of the stellar radiation field. Thus, at radius R in a spherical nebula for any individual grain species, s,

$$\langle T_{gr}(s) \rangle = f_L / 4\pi R^2 \bar{v},$$

where $\bar{v}$ is the mean photon energy of the radiation field, which depends both on the age of the cluster and the solution of the radiative transfer problem out to radius R. Thus, if we wish to find a variable in which H II region models evolve along a unique grain temperature distribution in time, $(T_{gr}(s, t))$, these models must also preserve the run of $L_s(t)/4\pi R(t)^2$. Then, because all models of this kind give a similar run of grain temperature distributions, they will also produce very similar global far-IR dust emission distributions. With a particular choice of cluster luminosity, physically denser H II region models have smaller radii and, hence, have hotter dust temperature distributions.

We therefore define a compactness parameter, $C$, in the form

$$C \propto \left( \frac{L_s(t)}{(R(t))^2} \right).$$

This variable is akin to the compactness factor found in the models of Tagaki et al. (2003a, 2003b) in that it directly determines the dust grain temperature distribution. The ratio on the right is also comparable to the ratio $m_{10}/r_{10}^2$ discussed in Silva et al. (1998), which controls the SED of their molecular clouds, and, therefore, the resulting hot dust SED of their models. The stellar luminosity $L_s(t)$ scales with the cluster mass $M_{cl}$, and the radius and pressure at any instant scale according to the simple mass-loss bubble approximation of (Castor et al. 1975)

$$R = \left( \frac{250}{308} \right)^{1/5} \left( \frac{L_{mech}}{P_0} \right)^{1/5} t^{3/5},$$

$$P = \left( \frac{7}{3850\pi} \right)^{2/5} \left( \frac{L_{mech}}{P_0} \right)^{3/5} t^{-4/5},$$

where $L_{mech}$ is the instantaneous mechanical luminosity of the central stars of the burst (which can be assumed to scale as the mass of the cluster) and $P_0$ the density of the ambient medium. Note that the ambient number density is $n_0 = \rho_0/(\mu m_{H})$ and ambient pressure $P_0 = n_0 k T_0$.

From these equations it follows that

$$C \propto \left( \frac{L_s(t)}{(R(t))^2} \right) \propto \frac{L_s}{L_{mech}^{1/5} P_0^{2/5}} M_{cl}^{3/5} P_0^{2/5}.$$

This product remains to be normalized. By analogy with the $R$ parameter introduced in SED3, we choose to adopt as the normalized definition of the compactness parameter

$$\log C = 3 \log \left( \frac{M_{cl}}{M_{10}} \right) + 2 \log \left( \frac{P_0/k}{cm^{-3}K} \right),$$

where $M_{cl}$ should now be understood as the mean (luminosity-weighted) cluster mass in the starburst. The likely allowable physical range on $\log C$ in starburst environments is, roughly, 3–7.5. These extremes correspond to $log((P/k)/(cm^{-3}K)) \approx 4$ and $log(M_{cl}/M_{10}) \approx 3.5$ and $log((P/k)/(cm^{-3}K)) \approx 8$ and $log(M_{cl}/M_{10}) \approx 7$, respectively.

In Figure 3 we show the variation of $L_s/R_i^{2}$ with time for six different $C$ parameters. These display a strong decrease of the incident flux and, therefore, of dust temperature with time. Specific flux changes several orders of magnitude over 10 Myr. This decrease is due to both the increase of the H II bubble radius with time (see Fig. 1 in SED1), and the decreasing cluster luminosity as the higher mass stars die out. Note that because of the underlying power-law behavior of $C$, on this log scale the curves for different $C$ parameters are offset from each other in proportion to the change in $\log C$.

In order to demonstrate the constancy of the dust temperature distribution at constant $\log C$, in Figure 4 we show overplotted
five SEDs for Solar metallicity PDRs, which all have the same compactness parameter of \( \log C = 5.0 \), but which have different pressures and stellar cluster masses. Although these five SEDs appear indistinguishable, they are not exactly the same, because their nebular excitation parameters \((R\); see SED3\) are quite different, and consequently, their nebular continuum and emission lines are different.

Provided that we could independently determine \( R \) (from the nebular spectrum) and \( C \) (from the form of the dust continuum), then in principle we could solve independently for the mean pressure, \( P_0/k \), and mean cluster mass, \( M_{\text{cl}} \):

\[
\log \left( \frac{M_{\text{cl}}}{M_\odot} \right) = \log C + \frac{2}{5} \log R, \tag{14}
\]

\[
\log \left( \frac{P_0}{k} \right) \text{ cm}^{-3} \text{ K} = -\frac{3}{5} \log R. \tag{15}
\]

In practice, the separation of these variables would be assisted by a direct measurement of the gas pressure. For \( P_0/k > 10^6 \text{ cm}^{-3} \text{ K} \) we can use the ratio of the \([\text{S II}] \lambda 6717, 6731\) lines for this purpose.

To show the effect of varying \( C \) on the form of the far-IR SED, we present in Figure 5 six model PDR SEDs having the same metallicity \((1Z_\odot)\) and pressure \((P/k = 10^5)\), with \( C \) varied by varying the cluster mass. In the optical and near-IR, the model SEDs show stellar emission, and the extinction of all six SEDs is the same, as they pass through the same column depth of dust and gas. At longer wavelengths, the progression in the dust temperatures with increasing \( C \) is obvious.

4. PDR COVERING FRACTION

In § 3, our Figures 4 and 5 corresponded to a complete covering fraction of molecular clouds; \( f_{\text{PDR}} = 1 \). In this extreme, the molecular gas and dust surrounding the H II regions act as a dust bolometer, absorbing essentially all of the stellar UV continuum, and reradiating it into the far-IR bump and the PAH features. However, in the case of isolated H II region complexes in both starburst and in normal disk galaxies, the placental molecular cloud is quickly cleared away by the stellar winds, and by photoevaporation. In older clusters, the disruption of the cluster by this gas ejection will cause the exciting stars to disperse away from the regions of high extinction, although the timescale for this may be greater than the H II region lifetime (Boily & Kroupa 2003a, 2003b). This process is cutely referred to as “infant mortality.”

Previously in SED1 and SED2, we parameterized this uncovering of the exciting stars by the introduction of a molecular cloud clearing or dissipation timescale, \( \tau_{\text{clear}} \), where the covering fraction of molecular cloud PDRs around a stellar cluster is given by:

\[
f_{\text{PDR}} = \exp \left( -t/\tau_{\text{clear}} \right). \tag{16}\]

In SED2, we found that, for Galactic star-forming regions at least, this timescale is quite short, on the order of 1–2 Myr. However, this certainly does not represent all star-forming regions and is probably far too short for ULIRGs which have an extremely generous sink of molecular material. In these objects, the H II regions of individual clusters may merge, but the complex is still surrounded by molecular gas. Thus, the clearing timescale is likely to show a large range and will depend on the local environment. In addition, situations like the commonly observed “blister H II
regions,” where the star formation occurs on the edge of a molecular cloud, are not so well represented by this formalism.

To deal with this problem, we introduce here the much simpler system of \( f_{\text{PDR}} \), which is defined as the time-averaged PDR covering fraction during the \( H \ii \) region lifetime. Starbursts in which the PDRs entirely surround their \( H \ii \) regions have \( f_{\text{PDR}} = 1 \), while uncovered \( H \ii \) region complexes have \( f_{\text{PDR}} = 0 \).

In Figure 6 we show two series of SEDs to illustrate the effect of a changing PDR covering fraction. Both represent a solar metallicity starburst with a compactness \( C = 10^5 \) and pressure \( P_0/k = 10^6 \) K cm\(^{-3}\), and are luminosity-weighted integrations scaled to a SFR of 1.0 \( M_\odot \) yr\(^{-1}\). The upper set of SEDs show the change in SED using \( f_{\text{PDR}} \), evolving from a pure \( H \ii \) spectrum (\( f_{\text{PDR}} = 0 \)) to a pure PDR spectrum (\( f_{\text{PDR}} = 1.0 \)). The \( H \ii \) region-only SED (the same in both series) is characterized by a strong stellar UV continuum, absent or weak PAH features, and hot dust emission from within the \( H \ii \) region itself. By contrast, the \( H \ii \) region plus PDR models show strongly attenuated blue and UV continua (\( A_V \sim 0.8 \) at \( f_{\text{PDR}} = 1.0 \)), strong PAH features and a broad, cool far-IR feature.

As a comparison, the second plot shows a series in \( \tau_{\text{clear}} \), going from \( \tau_{\text{clear}} = 0 \) Myr (pure \( H \ii \) region) to \( \tau_{\text{clear}} = 32 \) Myr. Clearly, these two formulations of the covering factor are broadly equivalent. On close examination it is possible to see some stronger older star features in the \( \tau_{\text{clear}} \) spectra relative to a matching \( f_{\text{PDR}} \) model, but these are small. Concurrent with this is the slightly wider IR feature in the \( f_{\text{PDR}} \) models relative to the \( \tau_{\text{clear}} \) models due to the stronger presence of dust heated by “old” (~10 Myr) star cluster light.

Note that as we increase the covering factor, there is an increase in the mid-IR from around 4 \( \mu \)m up to 15 \( \mu \)m caused by the increasing contribution of PAHs. The far-IR dust reemission feature progressively increases and broadens as the contributions of cool dust in the PDR becomes more important. The contribution of this cool dust in the PDR can be traced at shorter wavelengths through the steepening of the 20–35 \( \mu \)m slope. This spectral region has few emission lines and there are now available many Spitzer IRS spectra of starbursts, e.g., Brandl et al. (2006). Thus, the 20–35 \( \mu \)m slope may be a useful diagnostic of the PDR fraction in starbursts. However, this region is also affected by the contribution of ultracompact \( H \ii \) regions (\S 6.1) and by attenuation at high \( A_V \) (\S 6.3).

Note also the insensitivity of the SED to the covering factor in two regions of the spectrum; the 1–4 \( \mu \)m region and at around 20 \( \mu \)m. The 1–4 \( \mu \)m emission is dominated by the older stars in the starburst, and for these the PDR acting by itself is insufficient to produce a significant dust attenuation. The constancy of flux in the ~20 \( \mu \)m wave band is somewhat more interesting and is directly related to the strong correlation between the 24 \( \mu \)m Spitzer flux and the SFR (Calzetti et al. 2005). The models reveal that almost all of the warm dust emission arises from the hot dust embedded within the \( H \ii \) region itself. The cooler dust in the surrounding PDR makes little contribution to the global flux at these wavelengths. This result agrees with the spatially resolved observations of nearby galaxies where the 24 \( \mu \)m emission peaks in \( H \ii \) regions while the PAH emission is much more diffuse. In NGC 5194 about 85% of total galaxy 24 \( \mu \)m emission arises within the defined \( H \ii \) regions, while only ~60% of the 8 \( \mu \)m emission arises within these regions (Calzetti et al. 2005). This result is also in agreement with the earlier theoretical calculations of Popescu et al. (2000) for the edge-on galaxy NGC 891. In this galaxy, the star-forming disk \( H \ii \) regions have to be associated with a dominant hotter dust emission component.

Our models also demonstrate that the relationship between SFR and 24 \( \mu \)m emission is not one to one, because the warm dust continuum is also sensitive to the compactness parameter, \( C \), as is demonstrated in Figure 5. This finding also agrees with the observations, since variations of two or three in the ratio of the 24 \( \mu \)m emission to the SFR have been observed between galaxies (Dale et al. 2001; Calzetti et al. 2005).

5. COLUMN DEPTH IN THE PDR

As stated in \S 2.4, we use a hydrogen column density of \( \log N(H \text{ } i) = 22.0 \) (cm\(^{-2}\)) to define the extent of the PDR. While this value is typical of molecular clouds in our own galaxy, it is quite likely that those in starburst regions cover a broader range in column depths. In Figure 7 we show the effect of varying the column density in the model. For this exercise, we use our fiducial starburst model with solar metallicity, compactness parameter of \( C = 10^5 \), ISM pressure of \( P_0/k = 10^6 \) K cm\(^{-3}\), and test a range of PDR column depths; \( \log N(H \text{ } i) \sim 0 \) (corresponding to the \( H \ii \) region spectrum), 21.5, 22.0 (our standard PDR model spectrum), 22.5, and 23.0.

Note that as more of the UV and visible photons are absorbed, the total flux in the far-IR bump becomes correspondingly greater, and the feature also becomes wider as the contribution of the
colder dust heated by softer photons deep within the PDR becomes more important. Note also that the contribution of the PAHs to the SED is apparently almost complete by $N(H) = 21.5$.

In many respects, the effect of increasing the column depth of the PDR is similar to that obtained by applying a diffuse dusty screen (see §6). As we increase in column depth the optical depth increases (relative to the $H\alpha$ model). The effective model $A_V$ for each model is 0.2, 0.8, 2.6, and 8.4 as $N(H) \alpha$ increases from 0 to $10^{23} \text{ cm}^{-2}$. At $N(H) = 10^{23} \text{ cm}^{-2}$ the IR starts to become optically thick, with a corresponding steepening in the $20-30 \mu m$ slope. The increase in the silicate feature depth, $T_{2.2 \mu m}$ becomes obvious somewhat earlier, at $N(H) = 10^{22} \text{ cm}^{-2}$. Note that differences in the dust composition and dust geometry ensure that the attenuation law of the diffuse dust (shown in Fig. 12) is slightly different to that experienced in the PDR, with the silicate grains more prominent in the PDR (as seen by the stronger silicate absorption feature and flatter extinction).

The main difference in our model between the PDR region and a dusty screen is the inclusion of the self-consistent dust emission. By $N(H) = 22$ most of the UV-optical flux has been absorbed and reemitted as the strong far-IR feature. At larger depths the average temperature of the dust is quite cold ($\sim 10-20K$) and emits only at long ($>100 \mu m$) wavelengths. However, in starburst regions such temperatures may not be reached, as it is likely that neighboring clusters, as well as the underlying diffuse population, would prevent the dust from reaching such temperatures. Only in the largest molecular clouds, or the most distant dust, would such temperatures be reached. It is for this reason that we limit our PDRs to $N(H) = 22.0$ and use the diffuse population to represent this cool dust (§6.4).

6. OTHER COMPONENTS OF THE SED

6.1. UCH$\alpha$ Regions

The modeling presented thus far assumes that the stars in stellar clusters inflate a common H$\alpha$ region, and that the cluster can be treated as a single, centrally concentrated source of radiation and mechanical luminosity. However, in the earliest stages of the cluster lifetime ($\lesssim 10^8$ yr after formation), the individual stars composing the clusters are likely to be still buried in their separate birth clouds. In addition, we know that the massive stars start burning hydrogen even before they reach the main sequence and while they are still accreting matter from their parental molecular cloud (Bernasconi & Maeder 1996). During this phase, the cluster acts as an ensemble of ultra-compact H$\alpha$ regions (UCH$_\alpha$s), each trapped at subparsec scales around their individual massive parent stars (see Churchwell 2002 for a detailed review of UCH$_\alpha$ regions).

The period of time in which the winds of cluster stars cannot operate collectively may occupy a significant fraction of a massive star’s lifetime (Rigby & Rieke 2004 and references within). During this UCH$_\alpha$ region phase the optical emission will be totally obscured, with $A_V \sim 50$mag. As the UCH$_\alpha$ region is so compact, it also displays a hot IR emission (Peeters et al. 2002). This compactness also ensures that the dust is very successful in competing against the gas for the ionizing photons (Dopita et al. 2003), which makes the region still more compact and ensures that radiation pressure effects in the ionized plasma are important. Thus, UCH$_\alpha$ regions are qualitatively different from normal cluster-driven H$\alpha$ regions.

The technique of modeling the SEDs of individual compact and UCH$_\alpha$ regions was fully described in Dopita et al. (2006a). Briefly, these use the TLUSTY models, which were interpolated and rebinned to the energy bins used in our code, MAPPINGS III. On the basis of the results presented by Morisset et al. (2004), we can expect the SEDs that we derive will be very similar to those using either the WM-Basic or the CMFGEN models. Unlike the TLUSTY atmospheric models, these latter two are fully dynamical atmospheric models. The TLUSTY models used cover three abundances, 0.5, 1.0, and 2.0 $Z_\odot$. Here the definition of solar abundance is effectively the same as used in the Starburst99 models.

We made MAPPINGS III photoionization models for the structure of radiation-pressure dominated dusty H$\alpha$ regions and their surrounding PDRs. The models are started close to the central star (1% of the computed [dust-free] Str"omgren radius) so that the ionized gas effectively fills the Str"omgren sphere of these models. We use the same dust model as for the cluster SED computations. The models that we used here have fixed external pressure $log P/k = 9.0 \text{ K cm}^{-3}$, and are terminated at a $H\alpha$ column density of $log N(H) = 21.5$. The mass range of the central stars is $16.7-106.9 M_\odot$. This corresponds to a stellar effective temperature range of $32, 500 \leq T_{\text{eff}} \leq 52, 500 K$, which is covered in bins each $2500 K$ wide. The computed SEDs for individual UCH$_\alpha$ regions correspond to the zero-age main sequence (ZAMS) of the central stars.

The starburst galaxy compact H$\alpha$ region SED is constructed by co-adding the SEDs computed for each stellar mass bin, luminosity weighted to that corresponding to a Kroupa initial mass function (over the effective mass range $15-120 M_\odot$) and scaled to represent a massive SFR of $1.0 M_\odot \text{ yr}^{-1}$ continued over a period $0.0-1.0$ Myr.

The resulting SEDs for each metallicity are shown in Figure 8. The small changes in the apparent normalization of these spectra is due to the change of the stellar luminosity with abundance. Note that all the three spectra are very similar, with very weak PAH features, a hot dust far-IR continuum, similar line spectra, and heavy (but abundance-dependent) obscuration at shorter wavelengths.

Because the spectra are quite similar, it is clear that any one of them could be used as a UCH$_\alpha$ template across the full metallicity range. However, for closest consistency, we recommend the use of the 2.0 $Z_\odot$ model with the 2.0 $Z_\odot$ Starburst99 cluster templates, the 1.0 $Z_\odot$ model with the 1.0 $Z_\odot$ Starburst99 cluster

\footnote{Available online at http://tlusty.gsfc.nasa.gov.}
models and the 0.5 $Z_\odot$ model with the 0.05, 0.2 and 0.4 $Z_\odot$ Starburst99 cluster models.

As an example, in Figure 9 we demonstrate how the inclusion of UCH ii emission alters the SED by $f_{UCH\, \text{ii}}$, the scale of the UCH ii contribution. A $f_{UCH\, \text{ii}} = 1.0$ implies that 50% of the massive stars younger than 1.0 Myr are surrounded by UCH ii regions. As the UCH ii regions emit predominantly in the mid-IR, this parameter affects both the mid-IR slope and PAH equivalent widths, as seen in Figure 9. The emission lines are also affected by the inclusion of the young $H$ ii regions, with the contribution greater in the mid-IR than the optical due to the high optical depth of the UCH ii regions.

6.2. The Older Stellar Contribution

The discussion so far has concerned itself only with the stars younger than 10 Myr. However, a typical starburst will continue for a dynamical timescale of a galaxy, typically $\sim 10^8$ yr. Over this time period, most of the young star clusters will have dispersed into the field and away from the active star-forming regions (Whitmore et al. 2007; Fall et al. 2005). As a consequence, the older (>10 Myr) stellar population may dominate the optical and UV parts of the SED, since it suffers much less extinction than the starburst itself, having long escaped its original molecular birth clouds (Charlot & Fall 2000). However, it is in the optical-UV range that most of the work has been done in constraining the star formation history (SFH) of galaxies, using features such as the 4000 Å break due to hydrogen and stellar absorption lines like the Lick indices to constrain the age and metallicity of the dominant stellar population, or even the evolution of star formation and metallicity (e.g., Panter et al. 2007).

In order to represent this older stellar contribution in our starburst models we use a luminosity weighted sum of the 10–100 Myr starburst spectra from Starburst99, having the same parameters as the models used to generate the $H$ ii spectra. We generate the “old” stellar spectra for each metallicity and assume that the metallicity of the starburst the old population are the same. The resulting spectra for each metallicity are shown in Figure 10, scaled to a continuous SFR of 1 $M_\odot$ yr$^{-1}$.

The inferred ratio of the starburst fraction in the <10 Myr population to the fraction in the age range 10–100 Myr can provide information about the progress of the starburst, whether the starburst activity is accelerating or decelerating in recent time. This fraction may be constrained by comparing the flux at some wavelength in the far-IR bump with the stellar continuum flux at any wavelength shorter than about 5 $\mu$m. In Figure 11 we demonstrate this sensitivity. Here we have added this old stellar contribution to a solar metallicity starburst with $log\ C = 5$ and $log\ P/k = 5$. We have normalized the SED, assuming a continuous and constant SFR of 1 $M_\odot$ yr$^{-1}$ up to the maximum starburst age of 10$^8$ yr. To emphasize the effect of the older population we have taken a totally obscured <10 Myr starburst ($f_{PDR} = 1$), as shown in the lower curve, and added a completely unobscured contribution from the older stars to provide the upper curve.

These models show how it is possible to produce a systematic difference between the dust attenuation in the UV and the dust attenuation of the $H$ ii regions as measured by the Balmer Decrement. Such a systematic difference has long been known to exist from observations of starbursts (Calzetti et al. 1994; Calzetti 2001), in the sense that the Balmer Decrement indicates greater attenuation than the UV and visible stellar continuum.

Finally, the ratio of the two stellar components, young/old, is related to the $b$-parameter recently used by Kong et al. (2004)
which is the ratio of the current versus past-averaged SFR. This parameter was introduced to help understand the relationship between the UV and IR, through concentrating in particular on the correlation of the UV slope and IR excess (Meurer et al. 1999). In our case we parameterize the contribution of the old stellar population through the parameter $f_{\text{old}}$. Figure 11 presents a case of $f_{\text{old}} = 1$, with continuous star formation, and $f_{\text{old}}$ greater and lower than one represents cases where the past average SFH is greater and less than the current star formation respectively.

### 6.3. Diffuse Dust Attenuation

The simple H II region plus PDR models presented in the previous sections provide a maximum attenuation of $A_V \sim 0.8$ for a solar metallicity starburst and $A_V \sim 2.5$ for 2 $Z_\odot$. This is lower than observed in many ULIRGs (Farrah et al. 2007). In order to properly account for the total attenuation, we need to include the attenuation produced by a by a foreground dusty screen associated with gas in the starburst host galaxy, but not necessarily partaking in the starburst, to account for these heavily obscured starbursts. This foreground screen will also attenuate the older stars associated with the starburst (discussed in § 6.2).

The properties of such a turbulent foreground attenuating screen were discussed in a series of papers by Fischera & Dopita (2003, 2004, 2005). They showed that turbulence which produces a lognormal distribution in local density will also, to a high level of approximation, produce a lognormal distribution in column density. They also showed that the resulting attenuation curve is unlike that of a normal extinction law, showing lower attenuation in the UV and larger attenuation in the IR, due to the spatially varying extinction across the face of the dust-obscured object. Here we adopt the theoretical attenuation curve computed in those papers, which is shown in Figure. 12 and which provides a close approximation to the empirically derived Calzetti extinction law (Calzetti 2001). This curve does not allow for the possible destruction of PAHs in the diffuse medium and the computed 2175 Å absorption feature may be rather too strong to be applicable to starburst environments.

In Figure 13 we show the effects of this dusty screen on a starburst with solar metallicity, compactness parameter of $C = 10^5$, ISM pressure of $P_0/k = 10^5$ K cm$^{-3}$, and covering factor of $f_{\text{PDR}} = 0.5$. We show both low and high attenuation, with 10 SEDs plotted in Figure 13 with $A_V$ of 0.0, 0.5, 1.0, 2.0, 4.0, 6.0, 10.0, 15.0, 30.0, and 40.0, with a clear depletion of the UV and optical flux as the $A_V$ increases. To emphasize the effects of the attenuation on the IR emission we do not include the diffuse cool-dust emission that would be expected with such attenuation. We note that beyond $\sim 60$ $\mu$m there would be a contribution due to thermal emission from this cool dust, and care should be taken with any interpretations made beyond this wavelength. The effect of this emission is discussed in § 6.4.

The attenuation and reddening of the underlying starlight at the optical and UV wavelengths is very evident. However, it is only at $A_V \gtrsim 5$ that absorption in the 9.7 and 18 $\mu$m silicate features becomes apparent. With $A_V/\tau_{9,18\mu m} \sim 16.6$ (Rieke & Lebofsky 1985) this feature is weaker than the optical opacity, but it is observed to be visible or very strong in a large number of starburst galaxies, proving that a good deal of the starburst activity will be totally obscured in the visible thanks to large column densities in $f_{\text{PDR}} = 0.5$.
the surrounding molecular gas. Note also that at the highest $A_V$ even the 20–35 $\mu$m slope steepens to the “reddening” effect of the dust attenuation.

The $A_V > 20$ mag dusty screen needed to provide the observed depth of the silicate absorption troughs seen in some ULIRGs has little effect on the global energy balance of the starburst. By an $A_V$ of 1.0, most of the FUV-optical radiation from stars, almost 80%, has been absorbed (or scattered) by dust. The decline in the luminous flux through the PDR, accompanied with the softening of the radiation field naturally produces the dust temperature gradient which Levenson et al. (2007) believe is required in the obscuring material.

6.4. Diffuse Dust Emission and Scattering

A complete model of a starburst environment should not neglect the contribution to the far-IR emission by diffuse cool dust. Some of this may well be the same dust that produces the foreground screen absorption. The optical photons that are absorbed by the diffuse galactic dust at high $A_V$ are still capable of heating the dust in the diffuse ISM. In addition, the star-forming regions may not be fully coenosed by its surrounding PDR cloud, so that some fraction of the cluster UV radiation may escape and heat this diffuse dust. This cool galactic dust will mostly contribute to the $>100$ $\mu$m to submillimeter region. A portion of this radiation may also be scattered into our sight line, which mostly affects the far-UV SED. In our modeling we have not included this component due to our limited geometry.

The exact temperature distribution of the grains will also depend on the geometry of the starburst, preexisting stellar population, and dust within the starbursting galaxy. Because of the limited geometry of our simple models, we are unable to model such distributions. Instead we follow the work of Dale et al. (2001) and calculate the diffuse cool dust emission in terms of the average interstellar radiation density. This allows us to model both distributed starbursts where the average radiation field is high, and nuclear starbursts, where the rest of the galactic scale dust is only weakly heated.

To represent the average radiation field we have used the luminosity weighted average of a Starburst99 cluster from 10–100 Myr discussed in the § 6.2. While this is younger than the average age of the preexisting stars in a starburst host galaxy, these stars are nonetheless likely to provide the dominant dust-heating radiation field.

We then calculate the cool dust emission using the MAPPINGS III code, assuming the same dust properties as before and a column depth of $\log N(H) = 22.5$ (cm$^{-2}$). For the heating flux we scale the radiation field in terms of the local Habing (1968) interstellar radiation field (ISRF: FUV $\sim 1.6 \times 10^{-3}$ ergs s$^{-1}$ cm$^{-2}$). We set the radiation field from 0.1 to 100.0 times this value, in steps of 0.3 dex. The resulting IR emission is shown in Figure 14.

As expected, low ISRF leads to very cold dust, and the high ISRF has dust temperatures similar to those encountered in our PDRs. The actual contribution of this diffuse dust emission component to the global starburst SED is not constrained by these models. This would require a more sophisticated geometrical model of the starburst, its outflows, and any more extended disk or tidal structure around the starburst core.

In Figure 15 we show the effect of adding this diffuse dust emission component with a total intensity of 10% of our fiducial model starburst with solar metallicity. For clarity we add only four of the diffuse emission models, heated by a Habing radiation field, $G_0$ of 1000.0, 100.0, 10.0, and 1.0 times the local ISRF (ISRF$\text{local}$), respectively. The attenuation associated with the diffuse dust emission is not included here.

The model with 1000.0 times ISRF$\text{local}$ has hotter dust than the log $C = 5$ PDR and is therefore likely to be unphysical. The 100.0 times ISRF$\text{local}$ model has a similar dust temperature as the PDRs, and so the diffuse field serves only to increase the total flux of the IR. This probably represents the extreme case for a starbursting galaxy, and may lead to the narrow and strong FIR features seen in some ULIRGs.

The cooler diffuse emission models, with $G_0 < 10.0$ times ISRF$\text{local}$, are both applicable to less energetic starburst galaxies. In such cases, the diffuse emission acts to broaden the IR feature, as well as shift the peak to longer wavelengths, while leaving the shorter wavelengths ($<60$ $\mu$m) relatively unaffected.

7. STARBURST METALLICITY

The metallicity of a starburst affects the SED in several ways; through the intrinsic change in the stellar SED with metallicity,
through the changing gas-phase abundances, which determine the temperature and the line emission of the H II regions, through the opacity of the ISM in the dust, and through the metallicity-dependent change in grain composition. A full discussion of the effect of metallicity on the emission-line spectra of the H II regions was given in SED3. In this section we systematically investigate the remaining effects.

In Figure 16 we show our fiducial (H II region and PDR) starburst with log C = 5 and log P/k = 5 computed using the five standard Starburst99 metallicities. As the PDR is defined through a constant column depth of hydrogen, lower metallicity leads to lower column of dust. This leads to a strong decrease in the optical-ultraviolet opacity as the metallicity is decreased.

The metallicity-dependent effects on the H II emission-line spectrum have previously been remarked on in SED3. As the metallicity decreases, the stellar spectrum becomes harder due to the decreasing opacity of the stellar atmospheres and winds. In addition, for a given size, a stellar cluster of lower metallicity has a higher ionizing luminosity and lower mechanical luminosity. This leads to more compact H II regions, and higher ionization parameters in the surrounding H II region. The fraction of radiation absorbed by the dust in the H II region depends on the product of metallicity and ionization parameter (Dopita et al. 2003). This product remains approximately constant with metallicity, ensuring that the flux under the far-IR bump remains approximately constant for the H II region SEDs.

In the PDRs, the UV to optical SEDs clearly show the effect of increasing opacity with metallicity. The far-IR features change in several ways. First, there is a systematic increase in the relative strength of the PAH emission features with metallicity. This is a consequence of the increase in the C/O ratio with metallicity, which ensures that PAHs account for more absorption at higher metallicity relative to the silicates, combined with the higher mean dust temperatures which characterize lower metallicities. Another factor is the increased strength and hardness of the average radiation field in the constant column PDR with decreased metallicity. As a consequence, the Habing PAH survival criterion is only met deeper in the cloud, resulting in overall weaker PAH emission.

Such a decrease in the PAH strength with decreasing metallicity has been observed with both *Spitzer* and ISO (Engelbracht et al. 2005; Rosenberg et al. 2006; Wu et al. 2006; Madden et al. 2006; Jackson et al. 2006). However, the observed depletion of PAHs in the low-metallicity environments may be even greater than that computed in our models, and both Wu et al. (2006) and Jackson et al. (2006) implicate grain destruction processes as acting more efficiently in the lower metallicity environments. We would hope that our models, applied to these low-metallicity systems, would be able to better confirm and quantify this effect.

In the PDRs, the IR flux can also be seen to increase and become broader with metallicity up until Z\~1.0 Z\odot, after which it stays approximately constant. This is predominantly due to the increased dust column. The shift of the IR peak to longer wavelengths is also partly due to the increased dust column but is also due to the increasing mechanical luminosity of the starburst with metallicity, which results in larger H II regions, with cooler average dust temperatures.

**8. COMPARISON WITH OBSERVATIONS**

#### 8.1. Data Sources

In order to compare the models with data, we require as close a homogeneous data set as available, covering as wide a wavelength range as possible. For this purpose, we have selected a pair of popular template starburst galaxies, NGC 6240 and Arp 220 from the 41 ULIRGs observed with ISO by Klaas et al. (2001). This data set is ideal for our purpose because their SEDs are well sampled over the full wavelength regime 1–200 \micron.

Flux densities at other wavelengths were collected using the NASA/IPAC Extragalactic Database (NED) supplemented with a wide selection of online catalogs and papers. Generally, the UV/optical fluxes are taken from the *Third Reference Catalog of Bright Galaxies*, version 3.9 (de Vaucouleurs et al. 1991). Many optical and near-IR fluxes were taken from Spinoglio et al. (1995) or from the APM and 2MASS databases.

The majority of data points in the 1–1300 \micron wavelength range come from Klaas et al. (1997, 2001). Additional data points were taken from Sanders et al. (1988a, 1988b), Murphy et al. (1996), Rigopoulou et al. (1996, 1999), Surace & Sanders (2000), Lisenfeld et al. (2000), Dunne et al. (2000), Dunne & Eales (2001), Scoville et al. (2000), and Spoon et al. (2004) and references therein.

When available, the UV/optical and near-IR (JHK-band) points include aperture corrections to allow a direct comparison with the larger aperture mid- and far-IR fluxes (see, for example, Spinoglio et al. 1995). All UV to near-IR fluxes have been corrected for Galactic extinction using the E(B - V) values based on *IRAS* 100 \micron cirrus emission maps (Schlegel et al. 1998) and extrapolating following Cardelli et al. (1989).
For comparison of the models with a typical Spitzer IRS spectrum of a starburst, we have used the latest (recalibrated) version of the spectrum of NGC 7714 from Brandl et al. (2006).

8.2. Pan-Spectral Fitting

Our library of models contains the following elements:

1. An ensemble of H II regions surrounding young clusters with ages <10 Myr characterized by mean compactness C and metallicity Z.
2. A set of PDRs surrounding these H II regions with a mean geometrical covering factor, \( f_{\text{PDR}} \).
3. A population of young (<1.0 Myr) UCH\( \alpha \) regions and their PDRs surrounding individual massive stars, characterized by a fraction \( f_{\text{UCH}\alpha} \), where \( f_{\text{UCH}\alpha} = 1.0 \) would imply that 50% of massive stars younger than 1.0 Myr were surrounded by UCH\( \alpha \) regions.
4. An older stellar population with ages 10 \( \leq t \leq 100 \) Myr. The flux of this component is scaled by a factor \( f_{\text{old}} \), where \( f_{\text{old}} = 1 \) would correspond to continuous star formation over a total period of 100 Myr.
5. A foreground turbulent attenuating dust screen, characterized by an optical depth in the V band, \( A_V \).
6. A reemission component from the diffuse ISM, characterized by the mean Habing field intensity \( G_0 \) and scaled to a percentage of the total bolometric flux of the starburst (\( \leq 20\% \)).

Ideally, all of these elements should be fitted via a nonlinear least-squares procedure. However, lacking this tool for the time being, we have elected to make handcrafted fits to a few template objects. In addition, we have chosen to make the following simplifying assumptions:

1. We treat the <10 Myr stellar population as an ensemble of H II + PDR regions with \( f_{\text{PDR}} = 1.0 \). This approximation is justified by the observation that the global obscuration of a starburst increases with the small SFR (Buat et al. 1999; Adelberger & Steidel 2000; Dopita et al. 2002; Vrij et al. 2003). This is a natural consequence of the Kennicutt (1998) star formation law, connecting the surface density of star formation to the surface density of gas: \( \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{n} \), with \( n \sim 1.3-1.6 \). Noting that \( A_V \propto \Sigma_{\text{gas}} \), it follows that intense starbursts are highly dust enshrouded.
2. We ignore the contribution of the diffuse dust in the far-IR emission. As has already been noted in § 6.3, the contribution this makes is small and significant only above 100 \( \mu m \).

With these assumptions, we show in Figure 17 the fit we obtain for the galaxy NGC 6240. As can be seen, with five free parameters we obtain an excellent fit to the observations over nearly 3.5 decades of frequency. In this figure, the data have been scaled to a SFR of 1.0 \( M_\odot \) yr\(^{-1} \) in order to make this SED comparable to the others in this paper. The scaling factor required indicates a total SFR of 120 \( M_\odot \) yr\(^{-1} \) for this galaxy, a little higher than the value of 102 \( M_\odot \) yr\(^{-1} \) derived from the IRAS far-IR luminosity by Dopita et al. (2002). However, the H\( \alpha \) luminosity for this galaxy (also measured by Dopita et al. 2002), which comes from the extended gas indicates a SFR of 14.6 \( M_\odot \) yr\(^{-1} \), provided that it is dominated by star formation and not by an obscured active nucleus (see below). Since the far-IR comes from the obscured starburst and the visible H\( \alpha \) from the regions which are relatively unobscured, these figures suggest that the total SFR is indeed close to 120 \( M_\odot \) yr\(^{-1} \).

As can be seen in Figure 17, with a model with only five free parameters we have obtained an excellent fit to the observations over nearly 3.5 decades of frequency. However, this quality of fit to a model which only includes elements of a starburst system is at first sight extraordinary. NGC 6240 has long been implicated with an active nucleus and shows both a strong nonthermal radio excess, extended radio emission (Gallimore & Bestwick 2004), and X-ray emission associated with a highly dust-obscured AGN (e.g., Ikebe et al. 2000; Risaliti et al. 2000; Kewley et al. 2000). Recently Armus et al. (2006) have directly detected the active nucleus via the [Ne v] 14.3 \( \mu m \) line using the IRS on the Spitzer Space Telescope. From this, they estimate that the AGN has a flux of 3%–5% of the bolometric luminosity. At such low levels, it would account for the slight excess in the flux in the vicinity of the 6–14 \( \mu m \) PAH features seen in the observations when compared to our model, but is not sufficient to compromise the rest of the fit.

NGC 6240 has an unusually strong contribution from older stars, suggesting either that the starburst is rather old in this object, or that the current starburst is the second episode in this galaxy, or that there is an important contribution of stars older than \( \sim 10^8 \) yr. All of these hypotheses are consistent with the known status of NGC 6240 as a postmerger system.

What about the uniqueness of this fit? Fortunately, the different parameters of the fit act on different parts of the pan-spectral SED, so it is fairly easy to separate them when we have data covering such a large range in wavelength. We have performed the test of varying each of the major parameters, excluding metallicity, systematically around the best-fit solution, and the result is shown in Figure 18.

The effect of varying metallicity is shown in Figure 16, and has perhaps the most profound effect on the spectrum. To summarize, the metallicity is most easily determined from the shape and absorption-line intensities of the stellar continuum and by the emission-line techniques discussed in SED3. It also has an effect on both the strength of the PAH features and the width of the far-IR bump. High metallicity gives strong PAH features and wide far-R bump. In the fitting described in this section we have mostly relied on these latter characteristics to estimate the abundance.
For the remaining parameters, Figure 18 shows that each affects a different part of the SED. A change in log $C$ only changes the far-IR bump, shifting it in peak wavelength without appreciable change in the total width. A change in $f_{\text{old}}$ simply scales the 0.091–5 $\mu$m spectrum up and down, leaving the rest of the SED unchanged. A change in $A_V$ affects the slope of the visible-UV spectrum. Note that when $A_V$ is higher than about 5–10 mag, the 9.7 and 18.0 $\mu$m silicate absorption features appear and can be used to constrain the extinction when the visible-UV part of the spectrum is too attenuated. The UCH$\alpha$ region fraction $f_{\text{UCH}\alpha}$ mostly affects the 10–30 $\mu$m part of the spectrum. In Figure 18, the apparent sensitivity of the SED to this parameter seems small, but this is because the inferred log $C$ for this galaxy is very high.

Thus, the flux of the ordinary H$\alpha$ regions is high in the 10–100 $\mu$m region where the UCH$\alpha$ population is important, and the contribution of the UCH$\alpha$ regions is veiled. Galaxies with lower log $C$ show the UCH$\alpha$ contribution much more clearly (see Fig. 9).

As another example of a famous starburst, we present in Figure 19 our fit to Arp 220, the predominantly used template of starburst SEDs. This galaxy is characterized by a greater optical extinction, lower compactness parameter, and a lower contribution of the old star population than NGC 6240. In addition, a lower chemical abundance is indicated by the weaker PAH features, and the narrower, more sharply peaked far-IR bump.

Arp 220, as the local ULIRG, has quite often been used as a testbed for SED modeling. Examples of these can be seen in Silva

Fig. 18.—Sensitivity of fit to the starburst galaxy NGC 6240 to the various parameters. As can be seen, for this galaxy, log $C$ is constrained within $\pm$0.25 dex, $A_V$ to $\pm$0.3 mag, and $f_{\text{old}}$ to within 20%. The fraction of UCH$\alpha$ regions, $f_{\text{UCH}\alpha}$, is not very well constrained in this galaxy, owing to its high compactness, but would be much better constrained in galaxies with log $C$ < 5. [See the electronic edition of the Supplement for a color version of this figure.]
et al. (1998, their Fig. 9), Tagaki et al. (2003b, their Fig. 8), and Siebenmorgen & Krügel (2007, their Fig. 5) to name a few. While all these models (including our own) can be seen to fit quite reasonably the available observations of Arp 220, they differ in their model parameters, making direct comparisons difficult. However the main physical conclusions drawn from the models are the same, and comparisons here can give insight into both the models and Arp 220 itself.

All models suggest a SFR for Arp 220 of \( \sim 300 \, M_\odot \, \text{yr}^{-1} \). We derive a SFR of 315 \( M_\odot \, \text{yr}^{-1} \), which can be compared with the 270 \( M_\odot \, \text{yr}^{-1} \) obtained by Shioya et al. (2001), 260 \( M_\odot \, \text{yr}^{-1} \) from Tagaki et al. (2003a), and 580 \( M_\odot \, \text{yr}^{-1} \) from Silva et al. (1998).

In connection with this is the total luminosity of Arp 220, which is \( L_\star = 12.16 (L_\odot) \) in our models, close to the value of 12.1 of Tagaki et al. (2003a) and Siebenmorgen & Krügel (2007) and just below the value of 12.4 from Silva et al. (1998). For the total stellar mass of Arp 220 we obtain \( M_\star \sim 10.5 (M_\odot) \), higher than the previous SED model estimates of 10.4 (Silva et al. 1998) and 10 (Tagaki et al. 2003a), but due to the low mass-to-light ratio of our older stellar component (\( \gtrsim 6.2 \)), this value is somewhat uncertain. All these values indicate that both our model and fit to Arp 220 are at least consistent with previous models and suggest the true values for Arp 220.

One well-known detail of Arp 220 is its very high nuclear extinction; \( A_V \sim 30 \) (Shioya et al. 2001; Spoon et al. 2004) has been estimated and even higher estimates from models exist (Siebenmorgen & Krügel 2007). This illustrates a limitation of our fitting procedure. The derived \( A_V \) is determined essentially from fitting the attenuation of the older stellar population, not the nuclear region. When both the 9.7 and 18.0 \( \mu \text{m} \) silicate absorption features are observed along with optical or near-IR stellar continuum, we could then modify our fitting procedure to first fit the \( A_V \) of a foreground screen for the \( \text{H} \, \text{II} \) regions + PDRs implied by the depth of the silicate absorption and then apply a second, more optically thin foreground screen to match the extinction of the older stars seen in the visible-UV part of the spectrum.

In order to test the effect on the fitting parameters, we have made such a model, which we present in Figure 20. This model, with \( A_V = 20 \, \text{mag} \) for the starburst component and \( A_V = 2.2 \) for the older stars certainly fits the region of the silicate absorption features better and allows a much larger fraction of compact \( \text{H} \, \text{II} \) regions; \( f_{\text{UCH}_\alpha} \sim 0.7 \), implying that \( \sim 41\% \) of all stars younger than 1.0 Myr are found in compact \( \text{H} \, \text{II} \) regions.

The fact that we derive a lower \( A_V \) for the starburst than other authors is not surprising, since the attenuation law that we use provides greater attenuation in the IR and less in the UV than a standard extinction law, thanks to the patchy nature of the foreground screen. What is surprising is the reduction in the strength of the emission lines in the visible and UV regions of the spectrum. This is caused by the much larger nuclear attenuation, and shows that the equivalent widths of the IR emission lines compared with the visible or near IR emission lines may be used as a sensitive diagnostic of nuclear extinction.

It should be noted that, while Arp 220 is one of the predominantly used starburst templates, there is increasing evidence that this object is not a good representative for high-\( z \) star-forming galaxies (see, e.g., Menéndez-Delmestre et al. 2007). Rather, less extreme objects such as M82 or NGC 6240 are better local analogs of the high-\( z \) actively star-forming objects such as submillimeter galaxies.

### 8.3. Fitting Spitzer IRS Spectra

As a final example of the fitting process, we compare our fit with the detailed Spitzer Space Observatory IRS low-resolution spectra of NGC 7714 from Brandl et al. (2006). The fit is shown in Figure 21. Note that this object has a much lower SFR (\( 8.0 \, M_\odot \, \text{yr}^{-1} \)) than the previous two examples. The SFR is very well constrained by the normalization process and can be determined to an accuracy of better than 5\%, assuming that the IRS aperture integrates the full extent of the star-forming region.

For this object, the older stellar component is not well constrained, as the IRS spectra do not quite extend to short enough wavelengths to measure it. In addition, because the attenuation is not enough to produce appreciable 9.7 \( \mu \text{m} \) silicate absorption...
(AV < 5 mag.), we cannot measure AV from these spectra, so it has been set equal to zero. Note that the line-emission spectrum is quite well fitted by the model, except for the strength of both the [S iv] and the [Ar iii] lines in the vicinity of the 9.7 μm silicate absorption band. Again, this may indicate a rather higher obscuration of the young H II regions than in the model.

In this spectrum the abundance is fairly well constrained by the strength of the PAH features and the equivalent width of the emission lines, while the 20–35 μm slope constrains the values of log C and fUCH. The rather steep slope in the continuum spectrum at about 16 μm is a characteristic signature of the presence of compact H II regions.

9. DISCUSSION AND CONCLUSIONS

In this paper we have described an extensive library of panspectral SED models applicable to starburst galaxies and demonstrated the promise of these in deriving the physical parameters of starbursts. These models rely on a local, rather than a global solution to the radiative transfer. Such an approach works because of the fact that, in starburst galaxies, the vast majority of the far-IR emission arises from absorption of the UV radiation field in a relatively thin dust layer, the classical photodissociation region (PDR). This region has a typical optical depth corresponding to AV ~ 3 and a thickness ΔR ~ 300/nH pc. In the molecular regions surrounding normal galactic H II regions, hydrogen densities are typically 100–1000 cm⁻³, implying that much of the far-IR they produce comes from a layer of parsec or sub parsec dimensions. In starburst galaxies, interstellar pressures may range up to a factor of 100 higher than this, producing correspondingly thinner PDR zones. In addition, the Strömgren volume, the volume of the ionized gas in the H II region surrounding the exciting star or cluster, scales as nH², making H II regions much more compact as the pressure in the ISM is increased.

By simplifying the radiative transfer problem to a local one connected with individual clusters and their H II regions and PDRs, we can compute the SED as the sum of a set of effectively independent components. Our library of models provides the following ingredients to the panspectral SED of starbursts:

1. An ensemble of H II regions surrounding young clusters with ages <10 Myr.
2. A set of PDRs surrounding these H II regions.
3. A population of young (<1.0 Myr) ultracompact H II regions and their PDRs surrounding individual massive stars.
4. An older stellar population with ages 10 ≤ t ≤ 100 Myr.
5. A foreground turbulent attenuating dust screen. Separate screens may be used for the younger <10 Myr population and the older stellar population.
6. A reemission component from the diffuse ISM.

We have shown that the position of the far-IR dust reemission peak is primarily controlled by compactness parameter C defined in § 3, although the position and shape of this feature is also influenced by the mean covering fraction of the PDRs surrounding the individual H II regions, fPDR, investigated in § 4, and by the metallicity discussed in § 7. In addition we have investigated the effect of the column density in the PDRs surrounding the H II regions, provided a global spectrum of an ensemble of compact H II regions derived from our earlier work, and have investigated the effect of metallicity on the SED of the older stars with ages 10 ≤ t ≤ 100 Myr.

Finally, we have provided the attenuation properties of a turbulent absorbing dusty screen and have computed simple onedimensional models of the thermal emission from the diffuse dust illuminated by the SED of the older (>10 Myr) population. These models are characterized by the local diffuse radiation field intensity, expressed in units of the Habing field intensity, G₀, where G₀ = 1.0 corresponds to the intensity of the diffuse radiation field in the vicinity of the Sun.

We have demonstrated how the far-IR to submillimeter SED is controlled by the compactness parameter log C and by the metallicity. This is of particular application to the high-redshift submillimeter galaxies. As shown by Blain et al. (2004), a modified blackbody fit can be made to the long-wavelength side of the far-IR peak in starburst galaxies to derive a “dust temperature.” Although the concept of such a dust temperature is physically meaningless in the light of our models, which contain a wide distribution in dust temperatures, it is a useful way to characterize the slope and the position of the submillimeter SED and may well be related to the minimum dust temperature in the starburst.

Blain et al. (2004) showed that, in ULIRGs, the dust temperature derived in this way is observed to correlate with the absolute luminosity (or, equivalently, to the SFR). In our interpretation we would conclude that for ULIRGs, the compactness parameter increases with increasing luminosity. This would be consistent with more luminous galaxies having greater surface densities of star formation and greater gas pressures and densities. This in turn is in accord with the empirical Kennicutt (1998) law of star formation, \( \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4 \pm 0.1} \).

However, the Blain et al. (2004) work also showed that the high-redshift submillimeter-selected galaxies (SMGs) provide a similar correlation, but shifted to higher luminosity. At a given luminosity, the dust temperature in SMGs is about 20 K cooler than in ULIRGs in the local universe, and at a given dust temperature, the SMGs are typically 30 times as luminous as their ULIRG counterparts. Given that we have no reason to suspect lower dust temperatures in submillimeter galaxies, we must conclude that the starbursts in these galaxies have compactness similar to local starbursts, but are typically 30 times more luminous and spatially extended than local ULIRGs.

Tagaki et al. (2003a, 2003b) had previously found that most ULIRGS have a constant surface brightness of order 10^{12} L_☉ kpc⁻². These parameters probably characterize “maximal” star formation, above which gas is blown out into the halo of the galaxy and star formation quenched. In order to scale the star formation up to the...
rates inferred for SMGs (~1000–5000 M⊙ yr⁻¹), we must involve a greater area of the galaxy in star formation, rather than trying to cram more star formation into the same volume. For a typical value of 10¹³ L⊙ kpc⁻², we require “maximal” star formation over an area of ~10 kpc², and the most luminous SMGs require star formation to be extended over an area of order ~100 kpc².

From our library of models, we have constructed synthetic pan-spectral SEDs composed of only the following components:

1. The young H II regions with ages < 10 Myr characterized by a mean compactness, C, and metallicity.
2. The PDRs surrounding these H II regions with a mean geometrical covering factor f_{PDR}.
3. A population of young (< 1.0 Myr) ultracompact H II regions and their PDRs surrounding individual massive stars, characterized by a fraction f_{UCHII}, where f_{UCHII} = 1.0 would imply that 50% of massive stars younger than 1.0 Myr were surrounded by ultracompact H II regions.
4. The older stellar population with ages 10 ≤ t ≤ 100 Myr, scaled by a factor f_{old}, where f_{old} = 1 corresponds to continuous star formation over the period of 10 ≤ t ≤ 100 Myr.
5. A one- or two-component foreground turbulent attenuating dust screen.

Together, these components allow us to construct theoretical pan-spectral SEDs which encompass the full richness and variety observed in the SEDs of real starburst galaxies. We note that different parts of the SED are sensitive in different ways to these various theoretical components. Therefore, given a sufficient spectral range in the observations, we can create fits to observed SEDs which are unique, and which allow us to extract each of the various physical parameters listed above for the individual starburst galaxies. Finally, the scaling of the bolometric flux of the theoretical SED to the observed bolometric flux of the starburst provides us with an accurate estimate of the total SFR ∙ Mₜ, measured in M⊙ yr⁻¹.

We have demonstrated the utility of this method by fitting theoretical SEDs to a few famous template starbursts such as Arp 220 and NGC 6240. These fits have been “handcrafted,” and it remains to automate the process to a multivariate least-squares fitting procedure, which we hope to present in a future paper.

Although this paper has dealt exclusively with starbursts, we note that many ultraluminous infrared galaxies (ULIRGs) are known to contain an active galactic nucleus (AGN). To deal with these cases, we need to add a further five components to the mix:

1. The UV-IR continuum emission of the AGN itself.
2. Hot dust from the accretion disk around the AGN, emitting mostly in the 5–50 μm wave band.
3. The global emission from the extended narrow-line region (NLR) surrounding the AGN.
4. A foreground dust screen surrounding the accretion disk, the so-called dusty torus.
5. Nonthermal radio synchrotron emission component or components.

This will be the subject of a future paper in this series, but we note that many of the required components are already fairly well understood. The AGN itself is usually approximated by a power law, or broken power law, and the NLR component has already been computed by Groves et al. (2006). The radiative transfer through a dusty torus around the nucleus is a much more complicated issue that has been dealt with by several authors. Originally pictured and modeled as a smooth distribution (Pier & Krock 1992; Granato & Danese 1994; Efstathiou & Rowan-Robinson 1995), more recent models assume a more clumpy structure to explain the observed distribution of the 10 μm silicate feature and the width of the far-IR peak (Nenkova et al. 2002; Dullemond & van Beekem 2005; Hönig et al. 2006). In any case, treatments of the various components of an AGN SED do exist and must be considered when fitting the SEDs of ULIRGs and high-redshift luminous objects.

The replacement of the semiempirical approach by the new quantitative approach to SED fitting of starbursts presented here should greatly enhance the utility of existing and future surveys by providing detailed estimates of the physical parameters of the starbursts. In this way, it should assist in the derivation of statistical parameters, demography, and cosmic evolution of this class of object and should cast light on the nature of starbursts in the high-redshift universe, including submillimeter galaxies and the high-redshift radio galaxies, when today’s massive “red-and-dead” elliptical galaxies were in the process of assembly, and ULIRGs ruled the SFR density of the universe.

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