Modeling and Interpretation of the UV, Optical and IR Emission from Galaxies

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Context

★ Interpret the spectral energy distribution of a star-forming galaxy in terms of physical parameters

- Optical spectrum: stellar ages, metallicities, SF history
- Optical emission lines: ISM (metallicity, dust), current SFR
- Ultraviolet emission: current/recent SFR, attenuation by dust
- Infrared emission: dust content, heating, current SFR

→ Should be able to interpret emission from stars, gas, dust in terms of physical parameters (e.g. age, SF history, stellar & interstellar metallicity, dust)
Context

- Interpret the spectral energy distribution of a star-forming galaxy in terms of physical parameters.

- In practice: wide dispersion in the SFRs derived independently from different spectral indicators (UV, Hα and [OII] lines, FIR) for the same galaxies.

- This is mainly because of the uncertainties in the attenuation by dust (e.g., Kennicutt 1998; SC et al. 2001).

A consistent interpretation of the UV, optical and IR emission from galaxies requires a model for the transfer of stellar radiation through the ISM.
Attenuation of stellar radiation by dust

- Much recent progress in this area has come from studies of a UV-selected sample of nearby starburst galaxies with wide variety of data (Meurer et al '99)
  - Unattenuated stellar luminosity known to be dominated by young stars
  - Negligible contribution to dust heating by older stars

$L(dust) =$ total far-IR dust luminosity
$L(1600) =$ UV luminosity at 1600 Å
$H\alpha$ and $H\beta$: lines at 6563 and 4861 Å
$\beta =$ ultraviolet spectral slope ($f_{\lambda} \propto \lambda^{\beta}$)

Note: revised calibration in progress?
The luminosity \( L^\text{obs}_\lambda \) emerging from a galaxy can be expressed in terms of the unattenuated stellar luminosity \( L^\text{stars}_\lambda \) as

\[
L^\text{obs}_\lambda = L^\text{stars}_\lambda \exp(-\hat{\tau}_\lambda)
\]

where the "effective absorption" (or attenuation) curve \( \hat{\tau}_\lambda \) depends on the optical properties (true absorption and scattering) and spatial distribution of dust grains.
Attenuation of stellar radiation by dust

Standard dust models (in which $\hat{\tau}_\lambda$ corresponds to uniform mixtures of stars and dust, or foreground screens of uniform or patchy dust) cannot account simultaneously for all these observations.

Attenuation inferred from the H$\alpha$/H$\beta$ ratio is “twice as high” as that inferred from the UV spectral slope (Calzetti 1997):

$$A_V (\text{cont}) = 0.44 A_V (\text{lines})$$

(scatter? Inclusion in evolutionary models?)

Require more detailed modeling of the effects of dust attenuation
Models of the UV, optical and IR emission

At least 4 categories of models developed to interpret the multi-wavelength properties of galaxies in terms of stars, gas and dust parameters

(1) Monte Carlo radiative transfer models

(2) Radiative transfer models based on analytic approximations

(3) Radiative transfer models with spectral evolution of stellar populations

(4) Models combining dust physics, radiative transfer and spectral evolution
Monte Carlo radiative transfer models

State-of-the-art model of Witt, Gordon, Misselt and collaborators (DIRTY)

- Compute the radiative transfer of photons through arbitrary distributions of dust (typically a 2-phase clumpy medium in a 3D grid)

- Compute dust re-emission self-consistently with absorption and scattering: thermal equilibrium emission from large grains, and emission from small grains (and large PAH molecules) undergoing temperature fluctuations

- Recently applied to investigate the different effects of dust attenuation on the photometric properties of the bulges and disks of late-type spiral galaxies (Pierini et al. 2004) ⇒ importance of scattering and orientation effects
Monte Carlo radiative transfer models

**Example:** spectrum of a young, dusty starburst galaxy

![Spectrum Example](image)

(Gordon et al. 2001)

- These models **instrumental** in assessing the dependence of the integrated spectrum on the **clumpiness, composition, scattering properties and global geometry** of the dust

- **Weakness:** no spectral evolution, rudimentary treatment of stellar population input spectrum (single age) ⇒ difficult to combine with evolutionary population synthesis
Analytic radiative transfer models

Illustrated in a series of recent papers by Popescu, Misiriotis, Tuffs, Kylafis

- Solve the radiative transfer equation throughout a bulge+disk (de Vaucouleurs + exponential) system (simplifying approximation for > 2-order scattering; Kylafis & Bahcall 1987) ⇒ Compute local 3D radiation field at any point in model galaxy

- Compute everywhere re-emission at $\lambda>40$ $\mu$m (no PAHs) of the dust heated by the local radiation field: thermal equilibrium emission from large grains, and emission from small grains undergoing temperature fluctuations

- The best fits to observed FIR spectra obtained by invoking 3 components:
  - Diffuse old stellar population (bulge+disk) and associated dust (disk)
  - Diffuse young stellar population and associated dust (thin disk) ⇒ spiral arms
  - Clumpy dust component around HII regions ⇒ molecular clouds
Analytic radiative transfer models

**Example:** fit of the far-IR emission of the edge-on spiral galaxy NGC 891

(Popescu et al. 2000)

- These models have brought **new insight** into the different contributions to the far-IR emission from late-type spiral galaxies

- **Weakness:** no spectral evolution, rudimentary treatment of stellar population input spectrum (templates) ⇒ difficult to combine with evolutionary population synthesis
Radiative transfer and spectral evolution

First model coupling realistic treatment of dust with spectral evolution of stellar populations is that of Silva, Granato and collaborators (GRASIL)

- Optically thick molecular clouds around young stars
- Older stars freely immersed in a diffuse ISM (cirrus)
- Dust emission from AGB star envelopes (minor)
- Includes chemical evolution (gas infall/consumption)

- Simplified treatment of radiative transfer (effective optical depth) to compute local radiation field. Compute thermal equilibrium emission from large grains, and emission from small grains (+ large PAH molecules) with temperature fluctuations

- Recently combined in a simplified way with photoionization code CLOUDY (no absorption of ionizing photons by dust; Panuzzo et al. 2004) ⇒ nebular emission
Radiative transfer and spectral evolution

Example: fit of the UV-IR spectrum of the prototypical starburst galaxy M82

- These models have represented an important step forward in the consistent modeling of the production of stellar radiation and its transfer through the ISM in galaxies

- Weakness: many adjustable parameters (although many observational constraints can be used) ⇒ difficult to apply to interpretation of large samples of galaxies
Radiative transfer, dust physics, and evolution

Recent model of Dopita, Groves & collaborators (MAPPINGS/STARBURST99)

- Include the effects of the dynamical expansion of HII regions (as driven by winds & supernovae) on the spectra of young (<100 Myr) starburst galaxies
  - HII regions surrounded by opaque molecular shells with finite lifetimes
  - The entire starburst region bade in a warm, dusty, diffuse ISM
  - Expansion of an HII region set by the pressure (density) of the diffuse ISM

- Compute emission by dust in a self-consistent way (MAPPINGS), including PAH emission from the inner regions of molecular shells (photodissociation regions; the PAHs are photodestructed in the ionized gas)

- Note: does not (yet) include emission by dust in the diffuse ISM
**Result:** two main ISM parameters control the shape of the spectrum:

- **Pressure of diffuse ISM**
- **Lifetimes of molecular clouds**

(Dopita et al. 2004)

- **These models are providing deep insight** into the effects of dust physics (and of the geometry of gas/dust relative to hot stars) on the global spectral properties of galaxies.

- **Weakness:** so far limited to young starburst galaxies (ages < 100 Myr; no emission from diffuse dust) ⇒ not easily applicable to the interpretation of large galaxy samples.
The above models have greatly improved our understanding of the effects of dust on the UV-IR spectral energy distributions of star-forming galaxies.

The models however cannot yet be easily applied to derive the physical parameters (SF history, metallicity, dust content) of large galaxy samples.

Alternative, more efficient approach: rather than to interpret all at once the UV-IR spectrum, constrain the different physical parameters in different steps:

- **Optical continuum spectrum**: stellar ages, metallicities, SF history
- **Optical emission lines**: ISM (metallicity, dust), current SFR
- **Ultraviolet + infrared emission**: current/recent SFR, dust
Optical spectrum: SFH & stellar metallicity

Example: optical spectrum of a normal star-forming galaxy (Bruzual & SC '03)

The spectrum is sensitive to the ages and metallicities of the stars, attenuation by dust, and also the spectro-photometric accuracy.
In reality, dust and the spectrophotometric accuracy affect primarily the spectral shape (broad-band colors), while stellar absorption lines remain primarily sensitive to the ages and metallicities of the stars.
Optical spectrum: SFH & stellar metallicity

*Example:* optical spectrum of a normal star-forming galaxy (Bruzual & SC '03)

The "high-pass" spectrum can be used to constrain the formation history and metallicity of the stars, almost independently of dust and the spectro-photometric accuracy (e.g., Baldry et al. 2002)
**SF histories from high-pass galaxy spectra**

**Example:** reconstructed SF histories for model galaxies with different SF timescales (likelihood of fractions of total mass formed in 6 age bins) using MOPED algorithm (Heavens et al. 2000)

- Intermediate-age stars (~1 Gyr) are the most difficult to constrain, especially for smoothly declining SFHs (light dominated by younger and older stars)

- Fundamental limitation of the interpretation of galaxy spectra (not only high-pass)

- High S/N ratio is required: decreasing the median S/N ratio from 30 to 10 (per pixel) significantly degrades the results

Mathis, SC & Brinchmann (2005)
Difficult to derive precise constraints on metallicity from full high-pass spectra, because models (unlike observations) have fixed $\alpha$/Fe element ratio. Focus on a set of spectral features which do not depend strongly on element abundance ratios (e.g., $H\beta$, $H\gamma A$, $H\delta A$, $[\text{MgFe}]'$, $[\text{Mg}_1\text{Fe}]$, $[\text{Mg}_2\text{Fe}]$, D4000).
**Optical spectrum: stellar metallicity**

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- To fit these features in galaxy spectra, use a large library of Monte Carlo star formation histories (underlying continuous model + superimposed random bursts).

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**Observations**

**SDSS**

**Model library**

metallicity range: $0.2 \leq Z/Z_\odot \leq 2$
**Optical spectrum: stellar metallicity**

Starburst diagnostic diagram \([D4000-H\delta_A]\) binned and color-coded to reflect the average physical parameters of the galaxies falling into each bin.

- Metallicity
- light-weighted age
- stellar mass

![Graphs showing metallicity, age, and stellar mass](image)

(Gallazzi et al. 2004)

- Stellar metallicity, age, and stellar mass all increase with D4000
- At fixed D4000, stronger H\(\delta_A\) absorption appears to be associated to the presence of younger and more metal-rich stars
Nebular emission: SFR & gas parameters

* The accurate fitting of the stellar continuum allows precise measurements of emission line fluxes.

Relative strengths of emission lines provide valuable information about the physical parameters of the star-forming gas (e.g. metallicity, ionization, dust)
Interpret emission lines using simple but physically consistent model of the nebular emission from star-forming galaxies (SC & Longhetti 2001)

Examples of constraints derived from the simultaneous fits of [OII], [OIII], Hα, Hβ, [NII], and [SII] (Brinchmann et al. 2004)

Note: new calibrations of standard emission line diagnostics (e.g. Hα, R23) (see SC et al. 2002; Brinchmann et al. 2004; Tremonti et al. 2004)
Ultraviolet & infrared emission: dust

- Attenuation by dust affects negligibly constraints on SF history and stellar metallicity that can be derived from high-pass galaxy spectra.
- Also, attenuation of optical emission-line fluxes well constrained by Balmer-line ratios (caution: dependence on $T_e$ and $n_e$; absorption of ionizing photons!)
- The attenuation of continuum emission by dust must also be evaluated to infer galaxy stellar masses from SFH-constrained (dust-free) M/L ratios.
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Need to account for the different attenuation of young and old stars in galaxies (e.g., simple angle-averaged model of SC & Fall '00)

- Giant molecular clouds have lifetimes $\sim 10^7$ yr.

Attenuation affecting stars older than $\sim 10^7$ yr is typically only $\sim 30\%$ of that affecting younger stars.
The slope of the observed relation for starburst galaxies in the “IRX-UV” diagram tightly constrains the slope of attenuation curve in the diffuse ISM. Writing: \( \exp(-\hat{\tau}_\lambda^{\text{ISM}}) = \int d\tau\lambda \, p(\tau\lambda) \exp(-\tau\lambda) \), this can be reproduced for example by a Milky Way-type distribution of thin clouds for standard dust properties.
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Reminder: easy to account for galaxies with large \( L(\text{dust})/L(\text{UV}) \) at fixed ultraviolet spectral slope (need more stars at high UV optical depths)
Remarkably, at fixed UV slope $\beta$, quiescent star-forming galaxies have lower $L_{\text{dust}}/L_{\text{UV}}$ ratio than starburst galaxies (Bell 2002).

...raises the question of how SF history and attenuation by dust respectively drive the positions of galaxies in the IRX-UV diagram?
Ultraviolet & infrared emission: dust

- Explore with large library of Monte Carlo SF histories (continuous model + random bursts) and dust contents (total attenuation + fraction in GMCs)

(Kong et al. 2004)
**Ultraviolet & infrared emission: dust**

- Explore with large library of **Monte Carlo SF histories** (continuous model + random bursts) and **dust contents** (total attenuation + fraction in GMCs) (**Kong et al. 2004**)

![Graph showing color-coded data points]

- Color-coded to reflect **average ratio**
  \[ b = \frac{\text{SFR(\text{present})}}{\langle \text{SFR} \rangle} \] in each bin

- **Broadening of the relation** is due to **SF history**

**Note:** Seibert et al. (2005) do not detect this trend but plot \( \frac{L(\text{FIR})}{L(\text{UV})} \) and not \( \frac{L(\text{dust})}{L(\text{UV})} \)

\[ \Rightarrow L(\text{dust})L(\text{FIR}) \text{ expected to correlated with } b \]

**Also:** large scatter expected for small samples
Explore with large library of Monte Carlo SF histories (continuous model + random bursts) and dust contents (total attenuation + fraction in GMCs)

(Kong et al. 2004)

Color-coded to reflect average ratio
\[ b = \frac{\text{SFR}(\text{present})}{\langle \text{SFR} \rangle} \] in each bin

Broadening of the relation is due to SF history

Color-coded to reflect average ultraviolet attenuation \( A_{\text{UV}} \) in each bin

\( \frac{L(\text{dust})}{L(\text{UV})} \) much better estimator of \( A_{\text{UV}} \) than \( \beta \) in galaxies with different SF histories

Constraints on dust attenuation from \( \beta \) can be improved if some constraints are available on the ratio of present to past-averaged SFR (D4000, NUV-r)
**Conclusions**

- Simple but physically motivated models available to derive physical parameters from integrated UV-IR spectra of large statistical galaxy samples.

- More detailed models of the production of stellar radiation and its transfer through the ISM have allowed important progress in understanding influence of geometry, orientation and dust physics on the global properties of galaxies.

- These various models also instrumental in understanding the connection between star formation and AGN (Groves et al. 2004; Heckman et al. 2004).

- Unprecedented new constraints from spatially resolved UV-optical-IR observations of galaxies (Gordon et al. 2005, Popescu et al. 2005; C. Martin).

Toward better understanding of the parameters that control galaxy evolution.