AGN - Dust-Obscured Galaxies at z~2-3 in the COSMOS field revealed by near-to-far infrared SED-fitting

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Modeling Galaxies through Cosmic Times, Cambridge, UK 09/17/2015
Studying the star formation in the universe

FUV + IR rest-frame measurements

Black hole accretion history from IR

Black hole accretion history from X-ray

Madau & Dickinson (2014)
The Main Sequence of star-forming galaxies

Whitaker et al. (2011) demonstrated that there is a clear delineation between star-forming and quiescent galaxies with the NMBS data set. Quiescent galaxies are characterized by strong Balmer/4000 Å breaks, with red U–V colors and bluer V–J colors relative to dusty star-forming galaxies at the same U–V color.
dict an even smaller scatter (0.17 dex) to the intrinsic scatter to be 0.17 dex. Semi-analytic models provide a star formation sequence, from which we estimate the intrinsic scatter to be 0.18 dex. However, we note that this value is quite uncertain (e.g., Wuyts et al. 2011a). In total, we estimate that random uncertainties in the conversion from 24 μm fluxes to star formation rates introduce 0.08 dex scatter. Additionally, about 0.08 dex scatter is introduced due to the evolution of the mass-completeness limits with redshift. Furthermore, uncertainties in the conversion from 24 μm fluxes to star formation rates introduce linearly into scatter in the SFRs, this may reconcile the discrepancies between theoretical predictions and observations. To bolster the cartoon view presented in Figure 4, we introduce a thorough understanding of the selection techniques and the gradual evolution we measure of the star formation sequence will depend critically on the sample selection. The gradual evolution we measure of the star formation sequence will depend critically on the sample selection.

An in-depth analysis of the physical properties of these galaxies and comparisons between the observations and theoretical predictions will help constrain the physical mechanism driving star formation. The gradual evolution we measure of the star formation sequence will depend critically on the sample selection. The gradual evolution we measure of the star formation sequence will depend critically on the sample selection.

While 28% of galaxies with log(M/M⊙) > 10 have already quenched their star formation at 1 < z < 1.5, we find that 11% may be in the process of shutting down star formation.

Adding this potential curvature and the outliers from the star formation sequence out to redshift 0, we note that some models predict slopes that are too steep compared to the observations (e.g., Bouché et al. 2010; Dutton et al. 2010); it is possible that discrepancies at high-mass star formation in rapidly star-forming galaxies are mainly starbursts, as very few appear to be in the process of shutting down star formation. Moreover, we note that the spectral shapes of these galaxies are all very similar, irrespective of stellar mass (upper right panel in Figure 5). These galaxies have red colors and low L_IR/L_UV ratios, occupying the lower envelope of the star formation sequence. We compare the composite SEDs of these galaxies to that of quiescent star-forming galaxies and may soon migrate to the red sequence. Additionally, we consider the composite SEDs of normal star-forming galaxies in bins of stellar mass. Due to the increasing levels of dust attenuation, we see a clear evolution of the composite SEDs in Figure 5. On average, the most massive star-forming galaxies have characteristic dustily spectral shapes, with a 2175 Å break between the blue dust-free and red, low-dust star-forming galaxies. We note that we see a steep compared to the observations (e.g., Bouché et al. 2010; Dutton et al. 2010); it is possible that discrepancies at high-mass star formation in rapidly star-forming galaxies are mainly starbursts, as very few appear to be in the process of shutting down star formation.
1) how can we explain the starbursts and the luminosities of these galaxies?
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2) how the galaxies from the Main Sequence evolve into quiescent galaxies?
Possible evolutionary paths for massive galaxies at $z \sim 2$

![Diagram of possible evolutionary paths for massive galaxies at $z \sim 2$](image)

- **Major Merger**
  - Gas-rich
  - Gas-rich

- **Smooth Accretion**
  - (1)
  - (2)
  - (3)

Bussmann+11 (see also Dey+09, Sanders+88)

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Importance of the Infra-red (IR) - I

LIRGs = Luminous IR Galaxies:

ULIRGS = Ultra-Luminous IR Galaxies:

Magnelli+13, + work from LeFloc’h+05, Magnelli+11, Burgarella+13, etc.
Optical selection to select star-forming galaxies at \(1.5<z<3\)

(Original criteria: **BM/BX** Adelberger+04,
Uvi: Grazian+07
Adaptation to the COSMOS filters: Riguccini+11)

50% of the **MIR-selected** sources (with \(1.5<z<3\)) are missed!!!!

Riguccini+11
Importance of the IR - III

IR and submillimeter detections

• Submillimeter (SCUBA): Galaxies detected at submillimeter wavelength (850μm) with really faint optical counterparts.
  (Hughes+ 98)

• Infrared (Spitzer): large population of luminous galaxies at z~2 detected at 24μm but really faint at optical wavelength
  (‘Dust-Obscured Galaxies’, DOGs, Dey+ 08)
Our sample of DOGs

• 95 DOGs in the COSMOS field
  – Selected at 24 μm: $f_\nu(24\mu m)/f_\nu(R) > 982$
  – $1.5 < z < 3$
  – Detected in the Herschel bands

• Seeking for their AGN contribution to their IR luminosity
Particularities of the Dust-Obscured sources (DOGs)

- Contribute for 25% to the $\rho_{\text{IR}}$ at $z\sim2$
- Present LIRG and ULIRG luminosities (ie luminous and Ultra-luminous IR Galaxies with $L_{\text{IR}}>10^{11} \, L_\odot$)
- Important step in the evolution of galaxies
  (e.g., Bussmann+ 11)
Some evidences of AGN activity among the DOGs

Power-Law DOGs
= power-law SED in the near-IR

versus

Bump- DOGs

Dey+08
Increase of the contribution of the QSO

Flux (normalized at 1.6 μm)

Rest Wavelength (μm)

95% QSO

No QSO

A_v(QSO) = 0

Donley+12

PAHs
Evolution of SED along $z$

Spectral Energy Distribution (SED) of an ultra-luminous galaxy ($L_{IR}=10^{12}L_\odot$) obtained from the Rieke et al. (2009) library.

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composite spectra with decompIR

They provide 5 average host galaxy templates:

And an average AGN Template:

We add 2 ULIRGs templates (Chary & Elbaz, 2001) + 1 z~2 dusty galaxy template (Magdis+12)
AGN-DOGs

- 95 Herschel DOGs
- 15 are fitted by « composite spectra » and then considered as AGN-DOGs
- More than 60% of the AGN-DOGs are inside the NIR-AGN selection box
AGN-DOGs

Riguccini+15,
Check also Elbaz+11
AGN-DOGs

Riguccini+15,
Check also Elbaz+11
Dust temperatures and Masses: Far-IR Fit

• A two-temperatures fit

\[ L(\nu) \propto \alpha B(\nu, T_{d1}^{1})\nu^\beta + (1 - \alpha)B(\nu, T_{d2}^{2})\nu^\beta \]

With \( \beta \) the standard emissivity for big dust grains (\( \beta = 1.5 \) or 2, e.g. Draine & Li 1984, etc.)
And \( B(\nu, T) \) a blackbody spectrum
\( \alpha \) gives the luminosity ratio of the two dust species
\( T_{d1}^{1} \) is constrained between 10 and 45 K
\( T_{d2}^{2} \) is constrained between 45 and 95 K

• A single-temperature fit

\[ L(\nu) \propto B(\nu, T_{d})\nu^\beta \]

\( T_{d} \) is constrained between 10 and 95 K

\( \lambda_{\text{rest-frame}} > 40 \mu m \) to avoid emission from the AGN
Median dust temperature:

\[ T_d \sim (40.6 \pm 9.2) \text{ K} \]

(good agreement with the literature, i.e. Calanog+13)

Dust Mass:

\[ 7 \times 10^7 < M_{\text{dust}} < 10^9 \text{ M}_\odot \]

and a median dust mass of

\[ \sim (3 \pm 3) \times 10^8 \text{ M}_\odot \]

(good agreement with the literature, i.e. Bussmann+09)
Conclusions on the DOGs

- DOGs $(f_{\nu}(24\mu m)/f_{\nu}(R) > 982)$ are a key step in the evolution of galaxies
  
  SMG $\Rightarrow$ DOGs $\Rightarrow$ quasar $\Rightarrow$ elliptical

- 74% of our FIR-sample are fitted by a host galaxy template, 16% show a contribution from an AGN

- AGN-DOGs populate peculiar places on evolution diagram, not starburst anymore
  
  $\Rightarrow$ DOGs = transition phase
Far-IR Fit

• The luminosity is expressed as:

\[ L(\nu) \propto B(\nu, T_d)\nu^\beta \]

• Fluxes are computed in each band by integrating over various instrument filters \( f_i \) which has been normalized so that:

\[ \int f_i(\nu)d\nu = 1 \]

• We normalize fluxes with the total dust luminosity defined as:

\[ L_d = \int L(\nu)d\nu \]
Far-IR Fit

• Fluxes in each band $F_i$ are then defined as:

$$F_i = \frac{L_d}{4\pi D_l^2} \frac{\int L(\nu) f_i(\nu) d\nu}{\int L(\nu) d\nu}$$

• To obtain the mass of the dust, we assume that dust grains are in thermal equilibrium and use Hildebrand (1983) formula:

$$L_d(\lambda) = 4\pi M_d \kappa(\lambda) B(\lambda, T_d)$$

• We use the same hypothesis as Dunne et al. (2000) and take $\kappa$ at 850 $\mu$m and $\kappa(850\mu$m) = 0.077$kg^{-1}$m^{-2}.

We assume the emissivity to follow the relation: $\kappa(\lambda) = \kappa(850 \mu$m)$\lambda/850 \mu$m$^{-\beta}$

The dust mass can be then expressed as:

$$M_d = \frac{L_d}{\int 4\pi \kappa(\lambda) B(\lambda, T)d\lambda \cdot}.$$
Importance of the IR - II

Optical selection to select star-forming galaxies at $\sim 1.5<z<3$
(original criteria: BM/BX Adelberger+04, Uvi Grazian+07)

Selects $\sim 90\%$ of the optical COSMOS catalog with $1.5<z<3$

Seems to be a reliable criteria

Riguccini+11

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Importance of the IR - II

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