DUST AND ELEMENTS IN THE EPOCH OF REIONIZATION

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Epoch of Reionization (EoR)

- The first billion years of the cosmic history.
  - Redshift $z \approx 6-20$.
- The epoch of the first stars and galaxies’ formation.
  - The epoch of the first dust formation.
EoR galaxy observations

• So far, there are about 15 galaxies with a measured spectroscopic redshift \( z > 7 \).
EoR galaxy observations

- So far, there are about 15 galaxies with a measured spectroscopic redshift $z>7$.
- Current record of an emission line is $z=9.1$. 

**Introduction**

- Our ALMA observations
- Temperature estimation
- Summary

**Diagram:**

- **GN-z11** ($z=11.2$, Oesch+16)
- **MACS1149JD1** ($z=9.11$, Hashimoto+18)
- **EGSY8p7** ($z=8.68$, Zitrin+15)
- **GRB 090423** ($z=8.2$, Tanvir+09)
- **ULAS J1342+0928** ($z=7.54$, Banados+18)
[OIII]88 at z=9.1 but no dust

Hashimoto, ..., AKI et al. 2018a, Nature

• MACS1149-JD1
News on May 17, 2018

Oxygen presence in distant galaxy sheds light on early universe

Will Dunham

3 TV news broadcasts in Japan, ~280 web articles in the world on the day!
Dust at z=8.3 and [OIII]88 too


- MACS0416_Y1

Faint K-band → 2175Å bump?
“Big Three Dragons” at $z=7.15$

Hashimoto, AKI et al. 2018b, submitted

- **B14-65666**
- $[\text{OIII}]$, $[\text{CII}]$ and dust

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**Redshift**

- [OIII]88
- [CII]158

**Velocity [km/s]**

- Lyα

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[Dust continuum at 163 μm]

1" = 5.3 kpc

10.6σ

5.3σ

[Dust continuum at 90 μm]

1" = 5.3 kpc

5.8σ

[Dust continuum at 88 μm]

1" = 5.3 kpc

10.6σ
IRX-β diagram at $z>7$

Hashimoto, AKI et al. 2018b, submitted

- Consistent with Calzetti law
- Non-detections possibly favor SMC law
Comparison with a model e.g., Inoue11

• Evolution model of dust content in galaxies

\[ \text{STAR} \quad \frac{dM^*_s}{dt} = S - R \]

\[ \text{ISM} \quad \frac{dM_{\text{ISM}}}{dt} = -S + R + I - O \]

\[ \text{METAL} \quad \frac{dM_Z}{dt} = -ZS + Y_Z + I_Z - O_Z \]

\[ \text{DUST} \quad \frac{dM_d}{dt} = -Z_d S + Y_d - \frac{M_d}{\tau_{\text{SN}}} + \frac{M_d}{\tau_{\text{ac}}} + I_d + O_d \]

Dust mass growth in ISM

Dust supply by stars

Destruction by SN shock
Diversity of dust content in EoR

Black line: $M_z/M_{\text{star}}$ (max dust)
Red line: Efficient destruction
Green line: Inefficient destruction
Blue line: Efficient growth

Cosmic Dust IX (2016, Aug.)

June 15, 2018  CPHDUST2018 12
Diversity of dust content in EoR

\[
\log_{10}\left( \frac{M_{\text{dust}}}{M_{\text{star}}} \right) \sim \text{SF age}
\]

- Black line: \( M_z/M_{\text{star}} \) (max dust)
- Red line: Efficient destruction
- Green line: Inefficient destruction
- Blue line: Efficient growth

CPHDUST2018 (2018, Jun.)
Diversity of dust content in EoR

log10(Mstellar/Mstar) ~ SF age

Black line: $M_z/M_{\text{stellar}}$ (max dust)
Red line: Efficient destruction
Green line: Inefficient destruction
Blue line: Efficient growth

SMGs/mergers

 SXDF-NB1006-2 (z=7.2)
 HFLS3 (z=6.3)
 SPT0311-58W (z=6.9)
 H1689-zD1 (z=7.5)
 B14-65666 (z=7.2)
 A2744_YD4 (z=8.4)
 Himiko (z=6.6)
 SPT0311-58E (z=6.9)
 MACS0416_Y1 (z=8.3)
 MACS1149-JD1 (z=9.1)

June 15, 2018
Dust mass estimation?

- **Need**
  - Complete SED
  - Temperature
  - Dust model (material)
    - Mass emissivity
    - Spectral index

- **A self-consistent temperature estimation with the radiative equilibrium**
  - Assuming a model of dust emissivity.
Formulation

Under the radiative equilibrium,

\[ T_d = \text{function}(M_d, R, L_{\text{UV}}^{\text{obs}}, f_{cl}, \eta_{cl}) \]

\[ T_d = \left( \frac{L_{\text{abs}}}{C M_d} + T_{\text{CMB}}^{\beta+4} \right)^{\frac{1}{\beta+4}} \]

\[ C = \frac{8\pi \kappa_0 k_B^{\beta+4}}{c^2 \nu_0^\beta \hbar^{\beta+3}} \zeta(\beta + 4) \Gamma(\beta + 4) \]

This study

\[ L_{\text{abs}} = L_{\text{UV}}^{\text{obs}} \frac{1 - P_{\text{esc}}(\tau)}{P_{\text{esc}}(\tau)} \]

\[ F_{\nu}^{\text{obs}}(M_d, R, L_{\text{UV}}^{\text{obs}}, f_{cl}, \eta_{cl}) = \frac{1 + z}{d_L^2} M_d \kappa_\nu \left\{ B_\nu(T_d) - B_\nu(T_{\text{CMB}}) \right\} \]

\[ \kappa_\nu = \kappa_0(\nu/\nu_0)^\beta \]

\[ \beta = 1.5, \kappa_0 = 10 \text{ cm}^2/\text{g at 250 micron} \]

(Hildebrand 83)
Spherical shell

• Optical depth of the shell:

\[ \tau_{\text{she}} = \frac{3QM_d}{16\pi asR^2} \]

• UV escape probability from the shell:

\[ P_{\text{esc}}^\text{she}(\tau) = e^{-\tau} \]
Homogeneous sphere

• Optical depth of the sphere:

\[ \tau_{\text{hom}} = \frac{9QM_d}{16\pi as R^2} \]

- \( Q \): Q-parameter
- \( a \): grain size
- \( s \): grain material density

• UV escape probability from the sphere (Osterbrock 89):

\[ P_{\text{esc}}^{\text{hom}}(\tau) = \frac{3}{4\tau} \left\{ 1 - \frac{1}{2\tau^2} + \left( \frac{1}{\tau} + \frac{1}{2\tau^2} \right) e^{-2\tau} \right\} \]
Clumpy sphere

- Optical depth of each clump:

\[ \tau_{cl} = n_{d,cl} \sigma r_{cl} = \tau_{\text{hom}} \left( \frac{\eta_{cl}}{f_{cl}} \right) \]

- Optical depth from the sphere using the Mega-Grain (MG) approximation (e.g., Varosi & Dwek 99; Inoue 05):

\[ \tau_{MG} = \tau_{\text{hom}} P_{\text{esc}}^{\text{hom}}(\tau_{cl}) \]

\[ P_{\text{esc}}^{\text{hom}}(\tau) = \frac{3}{4\tau} \left\{ 1 - \frac{1}{2\tau^2} + \left( \frac{1}{\tau} + \frac{1}{2\tau^2} \right) e^{-2\tau} \right\} \]

- UV escape probability from the sphere:

\[ P_{\text{esc}}^{MG} = P_{\text{esc}}^{\text{hom}}(\tau_{MG}) \]

\[ \eta_{cl}/f_{cl} \to 0, \tau_{cl} \to 0, P_{\text{esc}}^{\text{hom}}(\tau_{cl}) \to 1, \tau_{MG} \to \tau_{\text{hom}}, P_{\text{esc}}^{MG} \to P_{\text{esc}}^{\text{hom}} \]
Example object: A1689zD1

- **ALMA detections**
  - Band6: 0.56±0.1 mJy (Watson+15)
  - Band7: 1.33±0.14 mJy (Knudsen+17)
  - Band8: 1.77±0.44 mJy (2016.1.00954.S; PI: AKI)
Example object: A1689zD1

- **ALMA detections**
  - Band6: $0.56 \pm 0.1$ mJy (Watson+15)
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Band 8 (0.\"5 tapered)

Size measurement:

FWHM

$\frac{1.\"3 \pm 0.\"3}{(0.\"59 \pm 0.\"16)}$

$R = \sqrt{ab}/2 = 0.\"44 \pm 0.\"08$
Modified Black-Body fit

\[ \beta = 1.5, \kappa_0 = 10 \text{ cm}^2/\text{g at 250 micron} \text{(Hildebrand 83)} \]

MC 1,000 trials for three bands fit

A1689zD1
68% range

B7 flux density regression line

(GL magnification \( \mu = 9 \); Watson+15)
Shell model fit

$\beta = 1.5, \kappa_0 = 10 \text{ cm}^2/\text{g}$ at 250 micron (Hildebrand 83)

MC 1,000 trials for three bands fit

Radiative equilibrium for B7 flux density

We can get this solution only with B7.
Homogeneous model fit

\[ \beta = 1.5, \kappa_0 = 10 \text{ cm}^2/\text{g at 250 micron} \text{(Hildebrand 83)} \]

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We can get this solution only with B7.
Clumpy model fit

$\beta = 1.5, \kappa_0 = 10 \text{ cm}^2/\text{g at 250 micron (Hildebrand 83)}$

$MC \ 1,000 \ trials \ for \ three \ bands \ fit$

Radiative equilibrium for B7 and $\eta_{cl}/f_{cl} = 0.04$

We can get this solution only with B7.
All models

\[ \beta = 1.5, \kappa_0 = 10 \text{ cm}^2/\text{g at 250 micron}(\text{Hildebrand 83}) \]

\[ \begin{align*}
T_d & \approx 40 \text{ K} \\
M_\text{d} & \approx 6 \text{ M}_\odot
\end{align*} \]

(GL magnification \( \mu=9 \); Watson+15)
Discussion: Clumpy model

- Two solutions:
  - $\eta_{cl}/f_{cl} \sim 0$: Homogeneous
  - $\eta_{cl}/f_{cl} \sim 0.1$
    - $\sim 10\%$ density contrast
    - Is consistent with the suggested merger event? (Knudsen+17)
A preliminary demographic result

• Homogeneous sphere/spherical shell cases

$\beta = 1.5, \kappa_0 = 10\ \text{cm}^2/\text{g}$ at 250 micron (Hildebrand 83)
Summary

- ALMA observations for high-z galaxies rapidly progresses.
- IRX-β diagram: 4 dust detected galaxies at $z>7$ follow the Calzetti law.
- Diversity of dust mass/stellar mass ratio.
- Radiative equilibrium gives dust temperature and mass simultaneously.
- ISM clumpiness may be discussed with the multi-band IR SED.
IAU Symposium #341: PanModel2018
Everything related to galaxy SEDs is welcome!!

November 12—16, 2018
Osaka University Hall, Japan

Deadlines on June 30
Abstract submission
Travel support application
Early registration (25,000 JPY)