A Wide-Field Search for Massive PopIII Stars in High-z Universe in the Subaru Deep Field

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History of the Universe

Big Bang

Recombination

z = \infty

First Stars

Reionization

z = 1000

Big Bang Nucleosynthesis

~ H, He (and D, Li, Be...)

z = 11

First-Metal Creation from BBNS gas cloud

z = 3

Metal Enrichment

Metal-enriched Universe

z = 0

Current Universe

Galaxy Evolution

0.3billion

13.7billion (year)

0.38million

2billion

Zero-age

0.38 million

Chemical Evolution of the Universe
What is PopIII? ...Massive Stars.

PopIII: First-Generation Stars
   — Created from BBNS (or “Zero-Metal”) Gas Clouds

Formation of Very Massive PopIII
   — Insufficient Cooling $\rightarrow$ Suppressed Fragmentation

$\sim$ Up to a few $10^2-10^3 \, M_{\odot}$
$\sim$ Significant contribution to chemical enrichment in the early universe

Nakamura & Umemura (2001)
What is PopIII? ...Hot Stars.

Very High Effective Temperature
— No Metals in Atmosphere → Low Opacity

\( T_{\text{eff}} \sim 10^5 \text{K} \)

Tumlinson et al. (2003)

~ SED: characterized by very high \( T_{\text{eff}} \)
~ Emitting huge number of UV photons
~ Significant contribution to cosmic re-ionization in the early universe

~ Strong Ly alpha and He\( \text{II} \) emission lines
Spectrum of HII Regions around PopIII Galaxies

Characterized by strong H I and He II emission lines at the earliest phase (~ a few Myr) of the galaxy evolution

Schaerer (2002)
Where (When) do PopIII Stars Exist?

Tornatore et al. (2007)

Scannapieco et al. (2003)

PopIII possibly existed even at $z \sim 4-7$ ✈ currently accessible !!
Let's search for "Ly$\alpha$-HeII dual emitters" as PopIII candidates
~ requiring "well-matched" combination of filters
~ requiring very wide FOV to find "rare" objects
Why not use Subaru/Suprime-Cam + Custom Filter Set !!
Observations

- $z=4.0$
  - $\sim$ HeII@8200Å: “NB816”
  - $\sim$ Lya@6080Å: “IA598”

- $z=4.6$
  - $\sim$ HeII@9180Å: “NB921”
  - $\sim$ Lya@6810Å: “IA679”

- NB816 & NB921: Existing deep data@Subaru Deep Field (SDF)
  - $\sim$ originally for Lya emitters at $z = 5.7, 6.5$ (Taniguchi+05, Kashikawa+06)

- IA598 & IA679: Additionally obtained in April 2007 @ SDF
  - $m_{\text{lim}}$(IA598) = 26.52 ($111\text{min}$), $m_{\text{lim}}$(IA679) = 27.07 ($231\text{min}$)
  - $\sim$ wider bandwidth ($\Delta\lambda \sim 300\text{Å}$): sensitive only to large-EW
  - ... no problem for us, because our targets are PopIII !!
Selection of Ly\(\alpha\)-HeII Dual Emitters

- for z=4.0
  ~ using IA598 & NB816
  ~ Cont – IA598 > 0.3 mag
  ~ \(EW_{\text{obs}} > 114\,\text{A}\)
  ~ 113 guys show IA excess
  ~ 4 guys show NB excess

- for z=4.6
  ~ using IA679 & NB921
  ~ Cont – IA679 > 0.3 mag
  ~ \(EW_{\text{obs}} > 143\,\text{A}\)
  ~ 234 guys show IA excess
  ~ 6 guys show NB excess
Results: Discovery of “Dual Emitters” !?

Nagao et al. (2008)

4 IA598-NB816 dual emitters
6 IA679-NB921 dual emitters

... candidates for PopIII !?
All of IA-NB dual emitters show “blue” B-V colors (B-V < 1.0)

Galaxies at z > 4 should show “red” B-V colors (B-V > 1.5)

IA-NB dual emitters: consistent to

[OII] & [OIII] at z=0.6 or z=0.8
Hβ & Hα+[NII] at z=0.2 or z=0.4

⇒ No “Lya-HeII dual emitters” found...
Upper Limit on the PopIII SFR Density (SFRD)

- Our survey sensitivity on $SFR_{\text{PopIII}}$
  \[ L(\text{HeII}) = f_{1640} \times SFR_{\text{PopIII}} \]
  \[ \sim f_{1640} : \text{depends on model parameters, e.g., IMF} \]
  \[ \sim \text{adopting } f_{1640} \text{ reported by Schaerer (2003)} \]
  \[ \text{[ assuming Salpeter IMF with } 50 < M_{\text{PopIII}}/M_{\odot} < 500] \]
  \[ [SFR_{\text{PopIII}}]_{\text{lim}} \sim 2 \ M_{\odot}/\text{yr} \]

- Upper limit on the PopIII SFR density ($SFRD_{\text{PopIII}}$)
  \[ V_{\text{survey}} = 4.03 \times 10^5 \text{ Mpc}^3 \ (3.93 < z < 4.01 \text{ & } 4.57 < z < 4.65) \]
  \[ \sim \text{no galaxies with } SFR_{\text{PopIII}} > 2 \ M_{\odot}/\text{yr} \text{ were found} \]
  \[ \sim \text{assuming no PopIII formation with low } SFR_{\text{PopIII}} \]
  \[ \sim [SFRD_{\text{PopIII}}]_{\text{lim}} = [SFR_{\text{PopIII}}]_{\text{lim}} / V_{\text{survey}} \]
  \[ SFRD_{\text{PopIII}} < 5 \times 10^{-6} \ M_{\odot}/\text{yr/Mpc}^3 \]
SFRD(PopIII): Comparison with a Theoretical Work

- Expected PopIII fraction is lower at lower redshift.
- Expected $SFRD_{\text{PopIII}}$ shows a "peak" at rather low-z (~6).
- Our upper limit on $SFRD_{\text{PopIII}}$ is higher than model prediction, but not so discrepant!!
- Further observational limits will give interesting constraints on PopIII theoretical works!!

SFRD model:
Tornatore et al. (2007)

Observational limit:
Nagao et al. (2008)
Summary

- Our new survey for “Lya-HeII dual emitters”
  - a new strategy to search for PopIII in high-z galaxies
  - selecting PopIII candidates by combining NB filters

- No candidates found
  - [OII]-[OIII] dual emitters are detected
  - sensitivity: \( SFR_{PopIII}^{lim} = 2 \, M_{\text{sun}}/\text{yr} \)
  - \( SFRD_{PopIII}^{lim} = 5 \times 10^{-6} \, M_{\text{sun}}/\text{yr}/\text{Mpc}^3 \)
  - very close to theoretical predictions

- Our future plan
  - “Hyper S-Cam”: FOV = 1.5 deg\(^2\)
    - (Subaru next-generation camera [2011-?])
  - \( x10 \) deeper limits on \( SFRD_{PopIII} \)
    - at 4 < z < 5 \( \rightarrow \) constraints on models