The Infrared Glow of the First Galaxies

Andrea Ferrara*

Scuola Normale Superiore, Pisa, Italy &
Kavli IPMU, Tokyo, Japan

*Tinsley Centennial Professor @ UT Austin
A PUZZLING EXCESS

Best fit model to NIR data

\[ z_{\text{end}} = 8.8 \]

\[ f_{\star} \approx 30\% \]

Massive Pop III stars can explain NIRB excess

BUT..
TOO MANY HIGH-Z GALAXY COUNTS

“Minimal” NIRB model:
IRTS data + Wright ZL
PopIII stars with $\delta$-fct IMF, $M = 300 M_\odot$

Expected galaxy counts

$z \approx 10$

$f_{\text{NIRB}}(\text{PopIII}) \leq 1\%$
NEAR INFRARED BACKGROUND

Aharonian+05, Dwek+05

GAMMA-RAY CONSTRAINTS

- Galaxy counts
- Direct measurements

See also Mapelli+05
Modern Approaches
CHEMICAL FEEDBACK

MASS OF EARLY STARS

Schneider, AF+02, 06, 12

~ 100 Msun
~ 1 Msun
~ 0.1 Msun

Fraction of metals depleted onto grains

Metallicity \([Z_\odot]\)

High mass
Dust dominated
Low mass

Metallicity scale from \(-\infty\) to 1

\(Z_{\text{crit}}\)
COSMIC POPIII/POP II TRANSITION

Total Metallicity

Fraction of PopIII forming sites
CHEMICAL FEEDBACK

STAR FORMATION RATES

Tornatore, AF & Schneider 2007
\[
\dot{\rho}_{\text{crit}} = (0.018 \ M_\odot \ \text{yr}^{-1} \ \text{Mpc}^{-3}) \left[ \frac{(1 + z)}{8} \right]^3 \left[ \frac{C_H/3}{f_{\text{esc}}/0.2} \right] \left[ \frac{0.004}{Q_{\text{LyC}}} \right] T_4^{-0.845}
\]

Dwarf (fainter) galaxies required?

\[\frac{C_H}{f_{\text{esc}}} = \text{const}\]
Searching for the reionization sources

T. Roy Choudhury* and A. Ferrara†

*Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
†SISSA/ISAS, via Beirut 2-4, 34014 Trieste, Italy

ABSTRACT
Using a reionization model simultaneously accounting for a number of experimental data sets, we investigate the nature and properties of reionization sources. Such model predicts that hydrogen reionization starts at $z \approx 15$, is initially driven by metal-free (PopIII) stars, and is 90% complete by $z \approx 8$. We find that a fraction $f_\gamma > 80\%$ of the ionizing power at $z \geq 7$ comes from haloes of mass $M < 10^9 M_\odot$ predominantly harboring PopIII stars; a turnover to a PopII-dominated phase occurs shortly after, with this population, residing in $M > 10^9 M_\odot$ haloes, yielding $f_\gamma \approx 60\%$ at $z = 6$. Using Lyman-break broadband dropout techniques, $f$-band detection of sources contributing to 50% (90%) of the ionizing power at $z \sim 7.5$ requires to reach a magnitude $I_{110} = 31.2 (31.7)$, where $\sim 15 (30)$ (PopIII) sources/arcmin$^2$ are predicted. We conclude that $z > 7$ sources tentatively identified in broadband surveys are relatively massive ($M \approx 10^9 M_\odot$) and rare objects which are only marginally ($\sim 1\%$) adding to the reionization photon budget.
REIONIZATION SOURCES

Choudhury & AF 2007

IONIZING PHOTON BUDGET

$f_\gamma > 80\%$ of the ionizing power from $M < 10^9 \, M_\odot$ halos
HIGH-Z LUMINOSITY FUNCTIONS

Fraction of ionizing photons sampled

Steep faint-end $\alpha \approx -2$
IONIZING EMISSIVITY

Ionizing phot. emissivity

Fraction produced by visible galaxies

HIGH-Z GALAXIES

Salvaterra+11
MODEL SUMMARY

(a) Chemical feedback regulated PopIII/Pop II transition
(b) Radiative feedback: H$_2$ minihalo suppression + photoevaporation
(c) Population spectral synthesis according to age, metallicity and (Salpeter) IMF for PopIII and PopII stars in each galaxy to get emissivity
(d) Reproduces high-z dropout galaxy LFs AND reionization bounds (G-P and CMB)
(e) Angular correlation of intensity fluctuations $C(\theta)$ from Peacock & Dodds formalism

\[
C(\theta) = \left( \frac{1}{4\pi} \right)^2 \int_{z_0}^{\infty} dz \frac{e^2 e_v(z)}{(1+z)^2} e^{-2\tau_{eff}} \left( \frac{dx}{dz} \right) \int_{-\infty}^{\infty} du \xi_g(r, z)
\]

\[
\xi_g(r, z) = \xi(r, z) b_{\text{eff}}^2(z)
\]

From: simulations Ly$\alpha$ model

Non linear galaxy 2P C.F.

Mass 2P C.F. \times (BIAS)$^2$

\[
b_{\text{eff}}(z) = \frac{\int_{M_{\text{min}}(z)}^{M_{\text{max}}(z)} dM_h \ b(M_h, z) \ \frac{dn}{dM_h}(M_h, z) \ f(M_h, z)}{\int_{M_{\text{min}}(z)}^{M_{\text{max}}(z)} dM_h \ \frac{dn}{dM_h}(M_h, z) \ f(M_h, z)}
\]
FLUCTUATIONS

\[ P(q) = 2\pi \int_0^\infty C(\theta) J_0(\theta, q) \theta d\theta \]

Clustering $z > 5$ galaxies

Shot noise
$z < 5$ galaxies

POPII

POPIII

Spitzer/IRAC data
Kashlinsky+ 2005, 2007

Salvaterra+06

Salvaterra, Cooray+06, Sullivan+06, Thompson+07, Fernandez+06,10,12
INTENSITY

\[ 5 \leq z \leq 9 \text{ galaxies} \]

\[ \nu J_{\nu} \text{ [nW m}^{-2} \text{ sr}^{-1}] \]

\[ \nu J_{\nu} \text{ [erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}] \]

\[ \lambda^{-3} \]
Pop III stars disappear very rapidly: transition to normal stars at $Z_{\text{crit}} \approx 10^{-5\pm1} Z_\odot$

Reionization sources populate the (steep) faint-end of LF ($M_{\text{UV}} > -18$)

NIRB fluctuations at 3.6 and 4.5 $\mu$m consistent with clustering of reionization sources

Pop III contribution always subdominant

Expected intensity (1-2 nW m$^{-2}$ sr$^{-1}$) consistent with $\gamma$-ray opacity studies

Problem I: Predicted spectral colors are relatively red.

Problem II: IRTS/AKARI intensity in J-band inconsistent with $\gamma$-ray experiments.