"Normal" and "extreme" stellar populations and galaxies in the early Universe

Daniel Schaerer (Geneva Observatory & CNRS)
« Normal » and « extreme » stellar populations and galaxies in the early Universe

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• Introduction

• Hard ionizing spectra: a solution to the long-standing HeII problem

• Spectral diagnostics for sources of cosmic reionization (Lyman continuum emitters)

• Conclusions
Our current census of high-redshift galaxies

Large number of photometrically selected galaxies in the epoch of reionization
Spectroscopy is lagging severely behind imaging
→ Limit of current facilities reached
ELTs: Enormous sensitivity gain

- Lya and UV metal line detections down to $H\sim28$ in 10h exposures: complete spectroscopic samples
- Surface density of such targets: $\sim1$ arcmin$^{-2}$, efficient use of multiplex
- Absorption lines: $z\sim7$ will be the new $z\sim2$
High-redshift galaxies: some open questions

Galaxies - physical properties
• What ISM properties? Metallicity?
• Stellar content? Age? Radiation field?
• Pop III clusters?

• Rotation curves, dark matter content
• Dust and gas content

Formation of Globular Clusters

Cosmic reionization
• When does reionization occur?
• Which sources responsible?
• How does Lyman continuum radiation escape?
Consistent galaxy SFR and mass build-up

Rapid evolution in the early Universe
Strong evolution of galaxy properties

- Increase of specific SFR(z)
- Increase of emission lines

With increasing redshift we also expect - TBC:
- Decrease of metallicity
- Increased intensity of the radiation field
- Increased hardness of the radiation field !?
- Higher ISM pressure / density
- Increase Lyman continuum escape

Khostovan et al. 2016
Strong evolution of galaxy properties

Increased H ionizing photon production!?
Strong evolution of galaxy properties

Higher excitation?  
$\text{[OIII]}/\text{[OII]}$

Lyman continuum escape more frequent and higher?  

Nakajima & Ouchi 2014  
Jaskot & Oey 2014,  
Faisst et al. 2016,  
Izotov et al. 2016, 2018  
Tang et al. 2019
UV spectra of galaxies in the epoch of reionization

CIII] emission in strong at \( z > 7 \)
EW more than 10x larger than \( \text{EW(CIII]} \) in \( z \sim 3 \) LBG stacks

\[ \text{Stark+17} \]
\[ \text{z=7.73} \]
\[ \text{Stark+15a} \]
\[ \text{Ly-\( \alpha \)} \]
\[ \text{z=6.02} \]

\[ \text{1216\( \AA \)} \]
\[ \text{CIII]} \]
\[ \text{1909\( \AA \)} \]

\text{e.g. Stark+2015, 2017, Mainali+2017, 2018, Schmidt+ 2017, Laporte+ 2017} \]
UV spectra of galaxies in the epoch of reionization

High ionization emission lines - common? 
Requires hard ionizing spectrum capable of triply ionizing carbon

UV spectra of galaxies in the epoch of reionization

Observationally vast uncharted territory
Theory/models many open questions

• Statistics of CIII], CIV, HeII … detections
• Do we understand CIII] and CIV detections?
• Need for (exceptionally) hard ionizing spectra?
• UV line diagnostics: SF/AGN, radiation field, metallicity,…
  Lyman continuum escape?!

Nakajima+2018
UV spectra of galaxies in the epoch of reionization

Observationally *vast uncharted territory*
Theory/models *many open questions*

• Need for (exceptionally) **hard ionizing spectra**?
  → nebular HeII emission unexplained (>54 eV)

Berg+2018
Xiao, Stanway, Elridge+2018

Uncertainties/diffs in SEDs
(single/binary stars, rotation, …)
The HeII problem

**ARTICLES**

**Detection of an X-ray-ionized nebula around the black hole candidate binary LMC X-1**

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Optical spectra of the black hole candidate X-ray binary LMC X-1 show a highly ionized He II region, N159F, which appears to be a strongly ionized nebula. The spatially resolved temperatures and intensities of the nebulae are determined with high accuracy. The spatially resolved temperatures and intensities of the nebulae are determined with high accuracy.

**Strongly star forming galaxies in the local Universe with nebular He II**

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**ABSTRACT**

We present a sample of 356 emission-line galaxies with strong nebular He II λ4686 emission. We determine the star-formation escape fraction by fitting the observed emission-line spectra to the templates predicted by the star-formation dependence of the young stellar population. We find that the escape fraction is strongly dependent on the star-formation rate and is consistent with the predictions of the star-formation dependence of the young stellar population.

**Ultraviolet spectra of extreme nearby star-forming regions -- approaching a local reference sample for JWST**

Peter Sheth,* Daniel P. Stark, Alina Vidal-Grisa, Jacob Chevalier, and Sibylle Bachtler

SERC, Theoretical Astrophysics, Princeton University, Princeton, NJ 08544

**ABSTRACT**

Nearby star-forming regions provide a unique laboratory in which to test stellar population models below Z=2. Such objects are particularly difficult to model because they are typically young, massive, and highly ionized, and their stellar populations have a wide range of ages from a few million years to a few hundred million years. We present new measurements of UV spectra of 90 nearby star-forming regions obtained in the optical regime. These measurements are used to constrain the properties of young stellar populations and to test models of stellar populations.

**HE II EMISSION IN EXTRAGALACTIC H II REGIONS**

Donald W. Goudey, Robert C. Smith, and John C. H. Yih

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

**ABSTRACT**

We present new ultraviolet observations of the He II λ4686 emission line in a sample of extragalactic H II regions. We find that the He II λ4686 emission line is stronger than the He I λ4686 emission line in most cases, but that the He II λ4686 emission line is weaker than the He I λ4686 emission line in some cases. We also find that the He II λ4686 emission line is stronger in galaxies with higher star-formation rates.
The HeII problem

Nebular HeII 4686 and HeII 1640

z~0 dwarf galaxies and HII regions

The HeII problem

→ Nebular HeII/Hβ intensity increases at low metallicity

SDSS, DR7: Shirazi & Brinchmann
2002

SDSS DR14+:
~1463 SF galaxies with HeII measurements
Schaerer, Izotov, Fragkos 2019
The HeII problem

Star-forming galaxies, NOT AGN

Possible sources:

• Very hot stars (Teff>~80-10 kK)
  → Hot Wolf-Rayet stars
  → Rapidly rotating stars
  → Binaries
  → PopIII
  → post-AGB

• Shocks
• X-ray binaries

→ no consistent quantitative explanation so far

Shirazi & Brinchmann (2002)
A fresh look at the HeII problem - (I) X-rays

X-ray emission in SFGs dominated by point-like sources (HMXB, ULX)

Total $L_X$ correlates with SFR

e.g. Mineo et al. 2012, 2014
A fresh look at the HeII problem - (I) X-rays

Excess of X-ray emission $L_X/SFR$ at low metallicities
(cf. Linden et al. 2010, Basu-Zych et al. 2016…)

Scatter in X-rays due to stochasticity of HMXBs

I Zw 18

Brorby et al. 2016, Douna et al. 2015
A fresh look at the HeII problem - (II) I Zw 18

Empirically:
point-line X-ray source coincides with HeII region

$L_X=(0.3-1.4)10^{40}$ erg/s
$F(\text{HeII}4686) \Rightarrow Q(\text{He}+) = 1.3\times 10^{50}$ photon/s
$\Rightarrow Q(\text{He}+)/L_X \sim 2\times 10^{10}$ photon/erg

Thuan+ 2004
Kaaret & Feng 2013
Leboutellier+ 2017
A fresh look at the HeII problem – putting it together

\[ \frac{L_X}{SFR} \sim \frac{Q(He^+)}{SFR} \]

\[ \sim \frac{Q(He^+)}{Q(H)} \sim \text{HeII4686}/\text{Hb} \]

Assumes:
- SFR=const
- \( Q(He^+)/L_X \) from I Zw 18

Schaerer et al. (2019)

Brorby et al. 2016

Observed \( \frac{L_X}{SFR} \) reproduces naturally observed metallicity dependence of HeII intensity
A fresh look at the HeII problem – (III) HMXB population models

- **Strong age-dependence of L_X**
- **Strong increase of L_X at low metallicity**: lower stellar mass loss →
  More massive + numerous BH population
  Less binary angular momentum loss → tighter orbits → more overflow → more numerous and more luminous X-ray binaries

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Fragos et al. 2013
Madau & Fragos 2017
Schaerer et al. (2019)
Assume $SFR = \text{const}$

HMXB population models + assumed $Q(\text{He}+)/L_X$ from I Zw 18

→ Predicts observed HeII line intensities and their metallicity dependence

Schaerer et al. (2019)
Schaerer et al. (2019)

HMXB population models + assumed Q(He+)/L_X from I Zw 18

→ Predicts observed HeII line intensities and their metallicity dependence

~1/3 of sources at 12+log(O/H)<8.4 show non-detection of HeII

Can be explained by:
- « Stochastic » effects (absence or variability of HMXB)
- Variations of HMXB SED
- Low ionization parameter
Next steps, improvements

- **HeII 1640 predictions (Schaerer+ 2019)**
- **Impact on UV diagnostics**

- More individual studies of X-ray + HeII ?!
- Systematic study of known HMXB/ULX

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**On the contribution of ULXs to stellar feedback: an intermediate mass black hole candidate and the population of ULXs in the low-metallicity starburst galaxy ESO 338-4**

Lidia M. Oskinova¹,², Arjan Bik³, J. Miguel Mas-Hesse⁴, Matthew Hayes³, Angela Adamo³, Göran Östlin³, Felix Fürst⁵, Héctor Otf–Floranes⁴

**Kaaret & Corbel, 2009**
The quest for the sources of cosmic reionisation

- Faint, low mass galaxies thought to be main contributors to cosmic reionization

- Numerous searches for « Lyman continuum leakage » from star-forming galaxies at low and high-z → sources elusive, so far!

→ New strategies needed
  → How to identity and find the sources of reionisation?
  → Study their properties

\[
\dot{n} = \dot{f}_{esc} \xi_{ion} \rho_{SFR}
\]

escape fraction \hspace{1cm} ionizing photons / UV luminosity

UV luminosity density
Signatures of the sources of cosmic reionisation

Direct Lyman continuum (LyC) detection impossible at high redshift
→ Need for *indirect* LyC probes!

- \( f_{esc}(\text{LyC}) = 0.00 \)
- \( f_{esc}(\text{LyC}) = 0.56 \)
- \( f_{esc}(\text{LyC}) = 0.80 \)

\( z \sim 5.7 \)
\( z \sim 5.9 \)
\( z \sim 6.1 \)
\( z \sim 7.1 \)

Inoue+, Siana+
Signatures of the sources of cosmic reionisation

Indirect LyC probes:

- **High \([\text{OIII}]/[\text{OII}]\) ratio**
  Jaskot & Oey 2013, Nakajima+ 2014

- **Lyman-alpha emission**
  Verhamme+ 2015, Djikstra & Gronke 2016

- **UV absorption lines**
  e.g. Heckman+ 2011
The quest for the sources of cosmic reionisation
- a recent breakthrough

COS-HST cycle 22+24 programs: measure Lyman continuum and test indirect indicators (Izotov, Schaerer, Verhamme, Thuan, Orlitova, Guseva)

Object selection (from Sloan):
- High [OIII]/[OII] ratio
- Compact SF galaxy – « Green Pea » like
- z~0.3 and UV-bright for « easy »
  Lyman-continuum detection with COS
→ 5 galaxies selected

G140M, G160M grism observations to cover:
• Lyman continuum
• Lyman alpha
• UV absorption lines
The quest for the sources of cosmic reionisation

Cycle 22 COS-HST program: *measure Lyman continuum and test indirect indicators* (Thuan, Izotov, Orlitova, Verhamme, Schaerer, Guseva)
Strong Lyman continuum leakers at z=0.3


✔ Lyman continuum leakage
- 11.8 sigma detection \((3.43 \pm 0.29) \times 10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\)
- Absolute fesc\(=7.8 \pm 1.1\) % (highest so far at low redshift)
- ~model-independent fesc determination (from H recombination lines + LyC)
Strong Lyman continuum leakers at $z=0.3$

**Cycle 25 observations:**
6 new sources with $O32 > 10$
→ Total 11 $z \sim 0.3-0.4$ galaxies

- **100% LyC detection → efficient selection criteria** ($O32 />4$, compact, strong EL)
- **3 sources with $f_{esc} > 40\%$**
- **Wide range of $f_{esc}$**

Izotov et al. (2016b)

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Izotov et al. (2018ab)
Lyman-alpha properties of Lyman continuum leakers


- Strong Lyα emission (EW>70 Ang)
- Double-peaked profiles
- Small peak separation as predicted by Verhamme et al. (2015)
  → Intense star formation, low dust content
  → Low HI column density

Izotov et al. (2018)
Neutral gas properties of LyC emitting galaxies

Analys of UV absorption lines (Lyman series, and metal lines) of known LyC leakers and comparison sources:

- 9 known LyC leakers (COS spectra, z~0-0.3)
- 6 other star-forming galaxies with COS Lyman-series coverage (z~0.1-0.3)
- High-res (R~3000-4000) rest–UV spectra of lensed galaxies at z~2-3 including ‘Cosmic Horseshoe’ (MEGASURA, Rigby+ 2017)

==> Determination of ISM covering fraction, HI and OI column densities

→ Gazagnes et al. (2018), Chisholm et al. (2018)
Neutral gas properties of LyC emitting galaxies

UV spectral fitting of:
- stellar continuum + lines (theoretical Starburst99)
- UV attenuation (Reddy+ 2017 + other laws)
- ISM absorption lines (HI, OI, OVI, CII, CIII, SiII)

Gazagnes et al. (2018)
Neutral gas properties of LyC emitting galaxies

confirmed leaker J1503+3644 (Izotov+ 2016)

GP 1244+0216 (Henry+ 2015)

Gazagnes et al. (2018)
Neutral gas properties of LyC emitting galaxies

**Main results** (Gazagnes et al. 2018):

- **HI lines are saturated** (but mostly not damped; \(N_{\text{HI}} \sim 10^{16} \text{ to } 10^{20} \text{ cm}^{-2}\))

  \(N(\text{HI})\) values from unsaturated OI lines (using known metallicity O/H)

- LyC leakers have covering fraction < 1

  \(\rightarrow\) **escape of photons through holes**

- SiII 1190, 1260 Å covering fraction is lower than HI \(C_f\)

  \(\rightarrow\) empirical relation between SiII and HI
Predicting ionizing photon escape from UV absorption lines (+UV modeling!)

- Measured HI covering fraction → good agreement with observed LyC escape fraction
- UV attenuation fundamental for accurate f_{esc} prediction (consistent modeling!)

Chisholm et al. (2018)

\[
    f_{esc}^{pre} = 10^{-0.4E_B - V} k_{912} \times (1 - C_f^H)
\]
Predicting ionizing photon escape from UV absorption lines (+UV modeling!)

→ UV absorption lines – Lyman series and SiII 1190, 1260 Å – can be used to infer LyC escape fraction indirectly

The Cosmic Horseshoe (z=2.3812)

Vasei et al. (2016), Quider et al. (2009):

→ Observed $f_{esc,abs} < 0.02$

Chisholm et al. (2018):
SiII covering fraction = 0.77
E(B-V)=0.16
→ Predicted $f_{esc} = 0.009 + 0.003$
Signatures of the sources of cosmic reionisation

Indirect LyC probes:

- High [OIII]/[OII] ratio
  Jaskot & Oey 2013, Nakajima+ 2014

- Lyman-alpha emission
  Verhamme+ 2015, Djikstra & Gronke 2016

- UV absorption lines
  e.g. Heckman+ 2011, Chisholm+ 2018

→ Diagnostics validated for JWST + ELTs!!
Signatures of the sources of cosmic reionisation

- HST Large Program (Jaskot) – LyC exploration
- LyC from very low mass galaxies? Izotov+

Other indicators?

- $f_{\text{esc}(\text{Ly}a)}$ – $f_{\text{esc}(\text{LyC})}$ connection
- MgII 2800 Å (Henry+ 2018, Chisholm+)
- [SII] deficiency (Wang, Heckman+ 2019)
Properties of strong LyC leakers at $z=0.3$

Compact SF galaxies – « Green Pea » like

UV half-light radii $<0.4$ kpc

Kawamata et al. 2018
Properties of strong LyC leakers at z=0.3

J0925+1403

other properties

- UV-optical spectrum dominated by young population (3-5 Myr)
- Low stellar masses (median ~$10^9$ Msun)
- High SFR (~14-40 Msun/yr)

Metallicity $12+\log(O/H)\sim 7.7-8.0$ 
~(0.12-0.25) solar

Low extinction: $A_V\sim 0.18-0.36$
Direct measure of $\xi_{\text{ion}}$:

→ Factor $\sim$2-5 times more ionizing photons produced per unit UV luminosity than commonly assumed

→ Intrinsic $\xi_{\text{ion}}$ – corrected for extinction – is $\sim$(1-2) times « standard » value

Best analogs for sources of cosmic reionisation

Schaerer et al. (2016)
LyC leakers at z=0.3: comparison with high-z galaxies


Best *high*-z Lyman continuum source:
z=3.218 galaxy « Ion2 » in GOODS-S/Candels
UV rest-frame mag_AB~24.5-25
→ Low metallicity (1/6 Z☉), ~low mass (1.6 10⁹ M☉)
→ Strong Lya emission
→ **High ratio [OIII]/[OII]>10, high [OIII]+Hb equivalent width (~1600 Ang)**

Vanzella et al. (2015), de Barros et al. (2016)

EL ratios, equivalent widths, stellar mass of our z~0.3 LyC leakers:
→ Comparable to Ion2
Strong Lyman continuum leakers at $z \sim 0.3$
Comparison with high-\(z\) galaxies

Properties of rare $z \sim 0.3$ leakers are comparable to typical $z \sim 7$ galaxies
→ Best local analogs

EW, stellar mass, size, SFR, SFR/area
...high gas density

Khostovan et al. (2016)
Conclusions

• New insight into the ionizing SED of star-forming galaxies
  
  ➢ Hard ionizing spectra of star-forming galaxies: HMXB/ULX provide a natural solution to the long-standing HeII problem

• Spectral diagnostics for sources of cosmic reionization (Lyman continuum emitters)
  
  ➢ 3 or more indirect diagnostics validated

→ New tools for the interpretation of Big Eyes observations

Key insight from «low-z» galaxies on our understanding of the most distant galaxies