What's important at z>5? X-ray Emission from Starbursts.
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How do we know about what is creating X-ray emission in high-z galaxies?

By studying local galaxies, we know that X-ray emission from binaries correlates strongly with galaxy properties (so if we measure galaxy properties like mass and Star Formation Rate [SFR], we have some sense of X-ray emission from binaries vs AGN).

![Diagram showing the relationship between SFR and X-ray emission.](Credit: http://chandra.harvard.edu)

Accretion timescales: ~10^10 yrs & ~10^7 yrs

$L_x = L_x(L_{\text{XRBs}}) + L_x(L_{\text{HMXBs}})$

$\alpha = (0.05 \pm 0.27) \times 10^{39} \text{ erg s}^{-1} \text{ M}_\odot^{-1} \text{yr}^{-1}$

$\beta = (1.62 \pm 0.22) \times 10^{39} \text{ erg s}^{-1} \text{ M}_\odot^{-1} \text{yr}^{-1}$

Similarly, by studying local galaxies, we know that hot Interstellar Medium (ISM) properties also scale with galaxy properties like SFR.

![Diagram showing the relationship between SFR and X-ray emission.](Minero et al. 2012)

- Two components to hot ISM (hot gas):
  - Cool: $kT \approx 0.24$ keV.
  - Warmer: $kT \approx 0.7$ keV (not always required)

- The diffuse gas is heated by e.g. supernova explosions. By studying it we learn about mechanical energy input from supernovae into the ISM.

And, at least up to z=4, we seem to have a good theoretical and observational picture of X-ray emission from galaxies.

![Diagram showing the relationship between SFR and X-ray emission.](Basu-Zych et al. 2013a)

![Diagram showing the relationship between SFR and X-ray emission.](Basu-Zych et al. 2013b)

(LEFT): By studying Lyman Break galaxies (LBGs) up to z=4, we can see that $L_x$/SFR evolves only mildly with redshift

(RIGHT): By looking at local LBG analogs we can see that metallicity appears to drive the evolution in $L_x$/SFR that we observe.

Are there any implications of these scaling relations, etc. for the amount of X-ray emission from high-z galaxies?

At cosmic dawn (z~10-20), when the first galaxies appeared, the X-ray output from star-forming galaxies (gas and binaries) may rival and/or exceed that of AGN. This means X-ray emission from star-forming galaxies may play an important role in heating the Intergalactic Medium (IGM) at cosmic dawn.

![Diagram showing the expected emission from X-ray binary populations in the 2-10 keV band.](Credit: http://chandra.harvard.edu)

This line shows the expected emission from X-ray binary populations in the 2-10 keV band where we have the best constraints (we can’t observe in the rest-frame 0.5-2 keV at high-z). Note, however, that we know that hot gas and binaries have a comparable contribution in the 0.5-2 keV band, which is very important for heating the IGM:

$L(\text{HMXBs})_{0.5-2 \text{ keV}} \sim 8 \times 10^{38} \text{ erg s}^{-1} \text{ M}_\odot^{-1} \text{yr}^{-1}$

(Mineo+ 2012a)

$L(\text{hot ISM})_{0.5-2 \text{ keV}} \sim 5 \times 10^{38} \text{ erg s}^{-1} \text{ M}_\odot^{-1} \text{yr}^{-1}$

(Mineo+ 2012b)

The signature of the X-ray emission from early star-forming galaxies will be observable via the impact on the heating of the IGM. There are implications for high-z 21 cm line measurements with new low-frequency radio facilities/instruments.

Slices of a 21 cm brightness temperature model at the X-ray heating peak at large scales (detectable by next-generation facilities like MWA, HERA and SKA, see Pacucci et al. 2014):

![Diagram showing X-ray SED.](Pacucci et al. 2014)

This SED has a spectrum typical of X-ray binaries ($\Gamma = 1.8$), resulting in a more uniform brightness temperature map, due to longer distance traveled by more energetic photons.

![Diagram showing X-ray SED.](Pacucci et al. 2014)

This SED has a softer spectrum representative of hot gas ($kT \approx 0.3$ keV, $\Gamma = 3$) resulting in a broader and more patchy temperature distribution.

In the meantime, we are using X-ray observations to better constrain the 0.5-40 keV emission from cosmologically relevant populations of star-forming galaxies.

The Chandra Deep Field South (CDF-S) 7 Ms survey will push to higher redshift and lower $L_x$ (finishing Dec 2014). We also continue our X-ray studies of the local cosmologically-relevant Lyman Break Analog population (Basu-Zych et al. 2014, in prep.).