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Cooking with X-rays:

Can X-ray binaries heat the early Universe?

THEMATIC SCIENCE AREAS (RANKED BY RELEVANCE):
7. Cosmology and Fundamental Physics
4. Formation and evolution of compact objects
5. Galaxy Evolution # 8. Multimessenger Astronomy and Astrophysics

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Abstract

X-rays from high mass X-ray binaries (HMXBs) within the first primordial galaxies likely played a significant role in heating the early Universe at $z \gtrsim 10$. While X-ray observations of distant $z \gtrsim 2$ galaxies may be prohibitively expensive, studying a sample of relatively nearby ($z < 0.05$) low metallicity galaxies is within reach and offers several advantages: (1) a complete and unbiased survey of the stochasticity in X-ray scaling relations and (2) measurements of the shape of their X-ray spectra. Combining observations from next generation X-ray telescopes with upcoming measurements of the cosmic 21-cm signal will have the power to reveal the interstellar medium (ISM) structure of the first primordial galaxies and their X-ray emission properties.

1 Science Motivation

Over the past decades, significant effort in cosmology has been dedicated towards finding increasingly distant objects in the early Universe. This is set to culminate with the upcoming James Webb Space Telescope (*JWST*), which will enable detailed studies, including remarkable spectroscopy, of galaxies well into the epoch of reionization (EoR), when the combined radiation from primordial galaxies ionized virtually every baryon in the Universe. However, the steepness of the faint end of the galaxy luminosity function, and the lack of a detected faint-end turnover, makes it likely that the bulk of the early galaxy population will be faint dwarfs and remain unseen, even with *JWST* (e.g. O'Shea et al. 2015).

Upcoming 21-cm interferometers, the Hydrogen Epoch of Reionization Array (HERA; DeBoer et al. 2017) and eventually the Square Kilometre Array (SKA; Mellema et al. 2013), will see the combined imprint of all galaxies in the large-scale distribution of neutral hydrogen (Greig & Mesinger 2018). The 21-cm signal is sensitive to the thermal and ionization state of the intergalactic medium (IGM), and its timing and spatial patterns encode the ultraviolet (UV) and X-ray properties of the first galaxies. If these galaxies behave similarly to local star-forming ones, it is likely that X-ray binaries (XRBs) dominated the heating of the neutral IGM prior to reionization at $z \gtrsim 10$ (Fragos et al. 2013a). This Epoch of Heating (EoH) is expected to result in the strongest cosmic 21-cm signal, over an order of magnitude greater than that during the Epoch of Reionization (EoR). Easily detectable with HERA and the SKA (*e.g.,* Mesinger et al. 2016; Cohen et al. 2018; Park et al. 2018), this signal will allow us to study high-energy processes inside the first, unseen galaxies of our Universe.

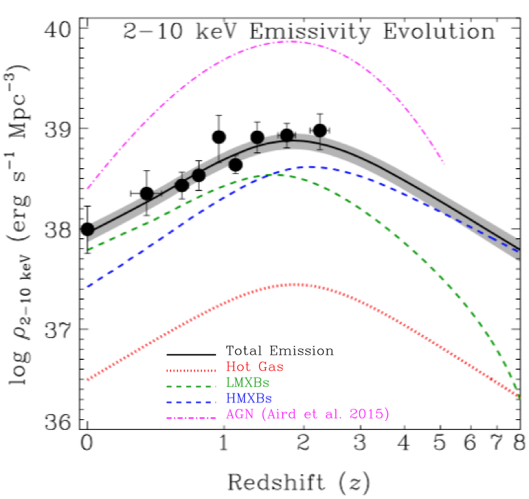

Figure 1: **X-ray binaries dominate the X-ray emission at $z > 6$, during the EoH, which is inaccessible to current X-ray telescopes.** Lehmer et al. (2016) show how the volume-averaged 2–10 keV X-ray luminosity, (*i.e.,* X-ray emissivity), from different X-ray sources evolves over cosmic time. The AGN curve, shown in magenta, precipitously decreases at $z \sim 6$, while the total emission from galaxies (shown by the black solid line and gray shaded region) dominates at higher z. The high mass X-ray binaries (blue dashed line) are the main contributors within galaxies.

X-ray binaries as heating sources of the early Universe

Compared to UV radiation from young stars and galaxies, X-ray photons from XRBs have longer mean free paths, penetrating deeper into the IGM. X-ray photons ionize hydrogen and helium; in turn free electrons can distribute their large kinetic energy into the IGM through secondary ionizations and free-free heating (Furlanetto 2006; Pritchard & Furlanetto 2007; Mirabel et al. 2011). Beyond ionization fractions of a few percent, most of the X-ray photon energy goes into heating. Depending on the X-ray emissivity of the first galaxies, the EoH can precede the EoR. Indeed this must be the case if the recent claimed detection of the sky-averaged 21-cm signal by the Experiment to Detect the Global EoR Signature (EDGES; Monsalve et al. 2017; Bowman et al. 2018) at $z \sim 17$ is genuinely of cosmic origin.

XRBs are expected to dominate the X-ray emissivity at $z \gtrsim 5-8$, surpassing the contributions from AGN and hot gas, as shown in Figure 1 (Lehmer et al. 2016; Madau & Fragos 2017). This implies that HMXBs, those XRBs with young massive donors, are likely the main source of heating of the neutral IGM prior to the EoR (*e.g.,* Mirabel et al. 2011; Mesinger et al. 2013; Fialkov et al.

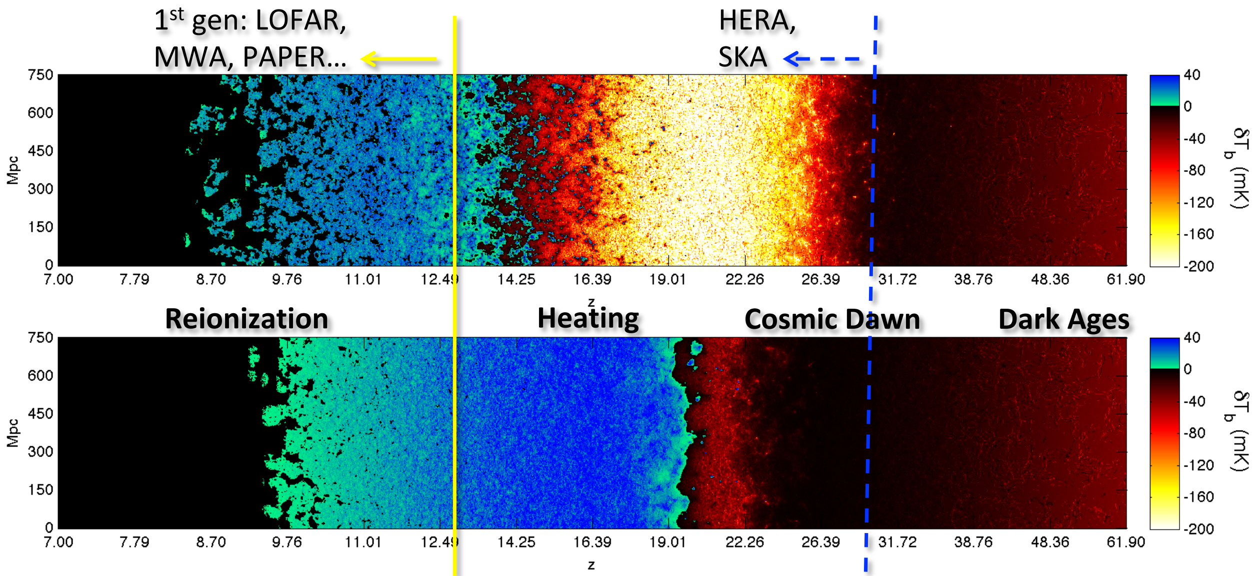

Figure 2: **X-rays can have a dramatic impact on the IGM in the early Universe, as should be seen with upcoming 21-cm interferometers.** This figure shows simulated light-cone maps of the 21-cm brightness temperature offset from the CMB. The horizontal axis shows evolution along the line of sight, from $z \sim 62$ to $z \sim 7$. From right to left we see the expected major milestones in the signal: (i) collisional decoupling (red→black); (ii) Wouthuysen-Field coupling (black→yellow); (iii) X-ray heating (i.e. the EoH; yellow→blue); (iv) reionization (blue→black). The vertical lines show the reach into cosmic history that the 21-cm interferometers probe for the first generation experiments (*e.g.,* LOFAR, MWA, PAPER in yellow) compared to next generation ones (*e.g.,* HERA and SKA in dashed blue). The top panel corresponds to the "fiducial" model of Mesinger et al. (2013) in which L_X/SFR is calibrated to local starburst galaxies (though recent studies using high-z galaxy observations suggest lower SFRs, thus implying that EoH should occur later; see Mirocha & Furlanetto 2018; Park et al. 2018). The lower panel corresponds to an "extreme X-ray" model in which primordial galaxies are much more luminous, with harder X-ray spectra. The astrophysical milestones are very different in the two X-ray models.

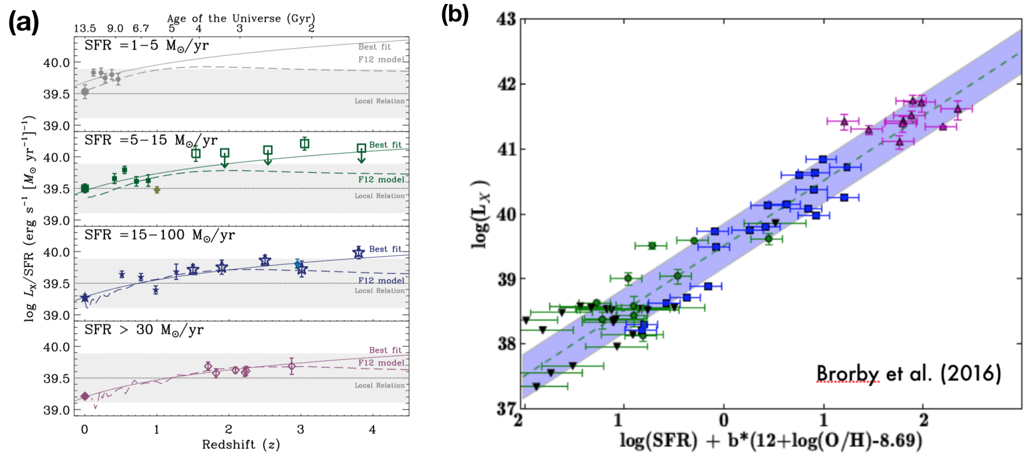

Figure 3: **The relationship between X-ray luminosity and SFR also depends on metallicity, in both the distant and nearby Universe.** *Left (a):* Basu-Zych et al. (2013b) find that the X-ray–SFR ratio evolves mildly with redshift, closely matching the theoretical prediction (shown with dashed lines) which is driven by the metallicity evolution of the Universe. *Right (b):* Using only local galaxies, including extremely low-metallicity galaxies, Brorby et al. (2016) measure the L_X-SFR-Z relationship. However, the scatter is high at the low-SFR end and the result may be biased towards detected sources. Therefore, application to high redshifts requires further study and properly measuring the scatter and stochasticity in this relationship.

2013; Kaaret 2014; Pacucci et al. 2014).

Predictions about the expected X-ray output from XRBs within early galaxies rest upon scaling relations between the star formation rate (SFR) and X-ray luminosity (L_X) in local, "normal" galaxies (*i.e.,* not active galactic nuclei), as well as their associated spectral energy distributions (SEDs). Because the cross-section of hydrogen and helium is a strong function of the photon energy, soft X-rays are much more relevant for the EoH, with photons more energetic than 1.5–2 keV having mean free paths longer than the Hubble length (*e.g.,* McQuinn 2012). Different SEDs and X-ray luminosities can result in markedly different 21-cm signals, as illustrated in Fig. 2.

Based on X-ray binary population synthesis models, the L_X/SFR scaling is expected to be significantly enhanced at $z = 8 - 20$ (by a factor of ≈ 10) due to the low metallicity of the Universe, which is predicted to be $\approx 5 - 30\%$ solar at these redshifts (see, *e.g.,* Guo et al. 2011 and Fig. 1 in Fragos et al. 2013a). Since the distant Universe poses significant observational challenges, several studies have focused on nearby metal-poor galaxies and find evidence that L_X/SFR is indeed enhanced for low-metallicity galaxies (*e.g.,* Prestwich et al. 2013; Basu-Zych et al. 2013a; Douna et al. 2015; Basu-Zych et al. 2016; Brorby et al. 2016).

X-ray studies of normal galaxies

Theory predicts that L_X/SFR would increase with decreasing metallicity since low metallicity stars drive weaker stellar winds, allowing both the compact object and donor star to retain more mass over their lifetimes; therefore, lower metallicity environments produce more numerous and luminous HMXBs and potentially host more accreting black hole binary systems (Linden et al. 2010; Fragos et al. 2013b). X-ray stacking of deep *Chandra* observations have yielded important constraints on the L_X/SFR relation (Basu-Zych et al. 2013b; Lehmer et al. 2016, see Figure 3a), including revealing an enhancement at higher z due to metallicity evolution, consistent with X-ray binary population synthesis models. Therefore, we might expect that primordial galaxies, which likely contribute to heating the IGM, have higher X-ray emission given their SFR.

However, accessing the X-ray photons from these great distances (*i.e.,* $z > 2$), requires effective (total stacked) *Chandra* exposure times of months (to years!), currently making this an expensive endeavor. A successful alternative has been to study nearby ($z < 0.1$) analogs of high redshift galaxies, metal-poor starbursts. Such studies of local metal-poor galaxies have also demonstrated elevated L_X/SFR (Basu-Zych et al. 2013a; Prestwich et al. 2013; Brorby et al. 2014, 2016; Douna et al. 2015; Tzanavaris et al. 2016) consistent with the theoretical predictions, suggesting that a metallicity-dependent scaling relation (henceforth, the L_X-SFR-Z relation, see Figure 3b) may be a more accurate way to characterize their emission (Brorby et al. 2016). The challenge is that these analogs are extremely rare because the majority of low metallicity galaxies in the local Universe either do not reach the low metallicities expected of $z \gtrsim 10$ galaxies ($\lesssim 0.3\ Z_\odot$) or have very low SFRs ($< 0.1\ M_\odot\ \mathrm{yr}^{-1}$) and a correspondingly small number of HMXBs, resulting in highly stochastic X-ray emission. A large number of such sources would be required to statistically characterize their distribution of L_X-SFR-Z. **Thus, current observations are not sufficient to predict the X-ray emissivity in the early Universe. This challenge can only be met by obtaining large samples, of order $\sim$ 100s of nearby high-z analogs (extremely low-metallicity galaxies), with a next generation X-ray telescope that is able to perform a complete and unbiased survey and quantify the level of scatter and stochasticity in the L_X-SFR-Z relation.**

Another critical ingredient to the theoretical 21-cm predictions is the shape of the X-ray SED in the soft band. The SED which emerges from the galaxy to heat the IGM is a product of (i) the intrinsic SED of the accreting objects, and (ii) the absorption by the interstellar medium of the host galaxy. Both can soften/harden the X-ray SED which drives the EoH. They are highly degenerate in terms of their impact on the 21-cm signal (see red curves in Figure 4a). We currently do not have constraints on either (i) or (ii); in particular, the structure of the first galaxies is likely very different from the Milky Way, with their metal-poor ISM likely resulting in less X-ray absorption (Das et al. 2017). Luckily, X-ray observations should aid in constraining the intrinsic SED expected from HMXBs in metal poor environments. **Specifically, with the next generation of X-ray telescopes we would be able to constrain the intrinsic SED locally, as demonstrated in Figure 4b. Together, 21-cm and X-ray observations of metal-poor HMXBs will teach us about the ISM properties in the first, primordial galaxies and their X-ray emission properties (blue curves in 4a).**

2 Programmatic Recommendations

While progress continues with theoretical predictions of the 21-cm line, additional input from X-ray observations of galaxies, particularly *local* low metallicity, high-z analogs is essential to further the efforts. In particular, the following key properties must be constrained via observations:

1. **The X-ray radiation field during the EoH**. X-ray observations of local low-metallicity galaxies with a range of SFRs are required to measure the scatter and stochasticity in the current L_X-SFR-Z relation. For meaningful constraints, the next generation of X-ray telescopes needs to be able to target $\sim$ 100s of extremely low-metallicity, nearby ($z < 0.03$) galaxies efficiently (within exposure times of $\sim$ 100 ks) down to fluxes $S(0.5-10\mathrm{keV}) \lesssim$

few $\times 10^{-16}$ erg s^{-1} cm^{-2}.

2. **The shape of the galaxy X-ray spectrum at the EoH**. 21-cm measurements will not be able to reveal the full picture regarding the structure of the ISM within the first primordial galaxies without X-ray observations (Fig. 4). Via X-ray stacking techniques and $\sim 50ks$ observations of $\sim$ tens of galaxies, we expect future X-ray telescopes can independently constrain the intrinsic shape of the X-ray SED to break degeneracies faced by the 21cm observations alone (*e.g.,* Fig. 4).

Therefore, we recommend X-ray telescopes offering a wide field of view (FOV ~ 0.5 deg^2) and sensitivity $S \lesssim$ few $\times 10^{-16}$ erg s^{-1} cm^{-2} in $\sim$ 100ks, to efficiently survey a complete and unbiased sample of $\sim$ 100 low-metallicity galaxies in the nearby Universe. For these studies, angular resolution of $\theta < 5''$ is sufficient for avoiding source confusion, as demonstrated by other multi-wavelength datasets (*e.g., GALEX*, *WISE*, *Spitzer*, SDSS spectroscopic data), since the goal is to study the global (*i.e.,* galaxy-wide) X-ray emission from the galaxies.

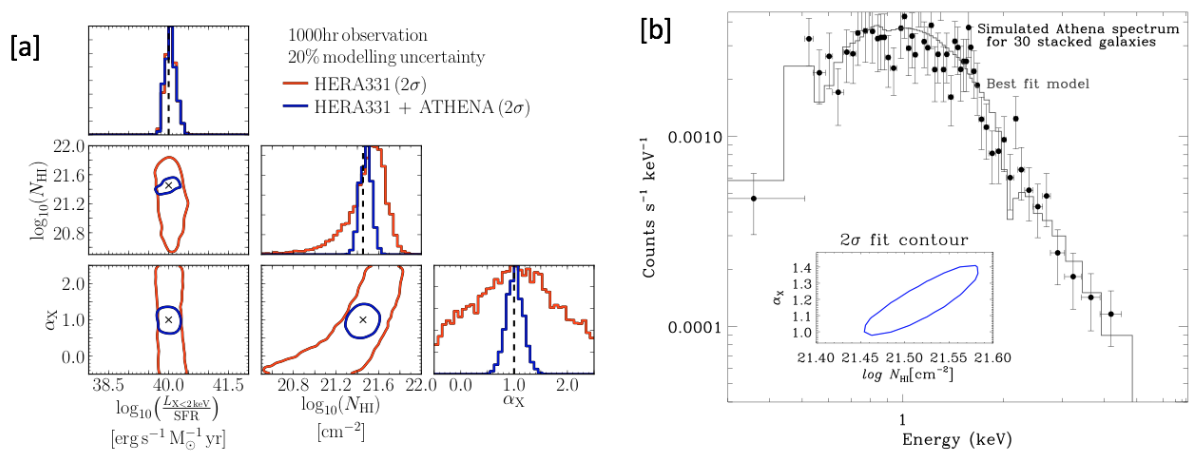

Figure 4: **Only a complementary approach that combines upcoming 21-cm measurements with next generation X-ray observations of the intrinsic X-ray SED of star-forming galaxies will allow us to learn about the conditions of the early Universe, *i.e., both* the ISM properties of the first, primordial galaxies *and* heating by their X-ray source populations.** *Left:* [a] This panel shows the posterior probability from a mock, 1000 hr measurement of the 21-cm power spectrum with HERA (Greig & Mesinger 2018). For clarity we only show parameters regulating the EoH: the integrated soft-band X-ray luminosity per unit SFR escaping primordial galaxies ($L_{X<2keV}$/SFR), the typical intrinsic X-ray spectral energy index in the soft-band (α_x), and the typical HI column density of primordial galaxies which attenuates the X-rays (N_{HI}). 21-cm measurements alone (*red curves*) show a strong degeneracy between N_{HI} and α_X, both acting to soften the X-ray spectrum which escapes the galaxy to heat the IGM. *Right:* [b] The simulated spectrum based on X-ray stacking of $\sim$ 30 galaxies (effective exposure of $\sim$ 150 ks) with *e.g., Athena* illustrates that observations of low metallicity galaxies can provide meaningful constraints on N_{HI} and α_X. The inset shows the 2σ fit contours on these two parameters. Using these constraints as priors on α_X and N_{HI} (*blue curves in panel a*) significantly mitigates the degeneracy shown in panel a, based on using only the 21cm observations. Combined, the two observations result in constraints much tighter than each can achieve individually.

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