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THESEUS and the high redshift universe

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Abstract. Long-duration gamma-ray bursts (long-GRBs) can be detected throughout cosmic history and provide several unique insights into star-formation and galaxy evolution back to the era of reionization. They can be used to map star formation, identify galaxies across the luminosity function, determine detailed abundances even for the faintest of galaxies, quantify the escape fraction of ionizing radiation and track the progress of reionization. Fully exploiting these techniques requires a significant increase in the number of long-GRBs identified and characterised at $z \gtrsim 6$, which can be achieved through a discovery mission with the capabilities of *THESEUS*, in combination with the powerful follow-up facilities that will be available in the 2030s.

Key words. Galaxies: abundances – Cosmology: observations

1. Introduction

Understanding the evolution of the early generations of stars and galaxies in the universe, and the accompanying reionization of the intergalactic medium, are primary objectives of contemporary astrophysics. In particular, whether extreme ultra-violet radiation from those early stars was the predominant driver of reionization is a crucial question, since if not then some other substantial source of ionizing radiation must be found (e.g. Robertson et al. 2010).

Determination of the electron scattering optical depth from microwave background observations indicate a peak era of reionization around $z \sim 7$–10 (Planck Collaboration et al. 2016). Considerable progress has been made in recent years in unveiling the galaxy populations at these redshifts, particularly thanks to the various deep field campaigns undertaken with the *Hubble Space Telescope* (e.g. Koekemoer et al. 2013), most recently the Frontier Fields initiative employing gravitational lensing to probe to fainter levels than would otherwise be possible (e.g. Ishigaki et al. 2015).

This has suggested that a major proportion of star formation is occurring in very faint galaxies (e.g. Atek et al. 2015), for which direct constraints on their number and properties are very limited.

Several *Swift*-discovered long-duration gamma-ray bursts (long-GRBs) have been found approaching and within the era of reionization (e.g. Tanvir et al. 2009; Salvaterra et al. 2009; Cucchiara et al. 2011; Tanvir et al. 2017).

As outlined in this brief contribution, these high redshift long-GRBs have already produced unique insights into high-z star formation, and have paved the way for the key high-z science theme of the *THESEUS* mission (Amati et al. 2018).

2. The astronomical landscape of the late 2020s

Gamma-ray bursts are quintessential multi-wavelength, and indeed multi-messenger, phenomena, and so the scientific return obtained from GRB missions is enhanced greatly by the facilities available for complementary observations and follow-up. By the time *THESEUS* is operational, if selected by ESA for an M5 launch, the landscape of astrophysical hardware is likely to be significantly different from today. Supplementing the current generations of 8 m class optical telescopes, ground-based radio, submm, and gravitational wave detectors, together with the X-ray, gamma-ray and optical observatories in space, we expect a new generation of 30 m class ground-based optical/IR telescopes, the Square Kilometre Array, potentially third-generation gravitational wave detectors, the Large Synoptic Survey Telescope, and *ATHENA* in space.

The *THESEUS* mission will provide the essential link to exploit the synergies between these facilities for transient science generally, and in the exploration of the early universe in particular.

3. The role of GRBs

Long-duration GRBs are found over a large span of cosmic history; they are born in massive star core-collapse, and lie at the star-forming hearts of galaxies. Thus they provide a range of unique probes high redshift galaxy evolution, which will be exploited by the *THESEUS* mission together with follow-up observations.

3.1. Evolution of the global star formation rate density

Since long-GRBs are core-collapse phenomena, they trace massive star formation (e.g. Blain & Natarajan 2000). Thus the observed GRB redshift distribution, providing the sample is redshift complete, can in principle be inverted to estimate the global star formation evolution without regard to whether the host galaxies are detected or not. Early attempts already showed that the long-GRB rate was surprisingly high at $z > 4$, given the fairly rapid decrease in star formation being found by galaxy surveys (e.g. Kistler et al. 2009). In practice, it is known that long-GRBs are preferentially created in lower metallicity environments, and suitable accounting for this effect, combined with a realisation that a greater proportion of high-z star formation is likely happening in very faint galaxies, has brought estimates into better agreement (Perley et al. 2016). However, this remains a critical question for reionization.

3.2. Locating star forming galaxies

By virtue of localising GRB afterglows and determining their redshifts, we can sample faint galaxy populations independently of their luminosities (e.g. McGuire et al. 2016). This is in contrast to conventional galaxy surveys, that of course depend on detecting the galaxies in some band(s), and in the large majority of cases rely on photometric redshifts. This is a particular issue at $z \gtrsim 6$, where the galaxy luminosity function becomes increasingly steep and faint-end dominated, and corrections for these missed galaxies difficult and uncertain (e.g. Bouwens et al. 2017). By comparing the number of GRBs in hosts above some given detection threshold to the number below, one can directly estimate the correction factor for the proportion of star formation missed in conventional galaxy surveys (Tanvir et al. 2012; Trenti et al. 2012; Basa et al. 2012).

3.3. Cosmic chemical evolution

GRB afterglows provide bright back-lights against which numerous absorption features created by intervening gas clouds in the host can often be seen. These provide not only gross metallicities, but detailed abundance patterns from which the enrichment by prior generations of stars can be inferred. Once again, this is independent of the host luminosity, unlike crude emission line diagnostics, and can be applied even at high redshifts (Vreeswijk et al. 2004; Thöne et al. 2013; Sparre et al.

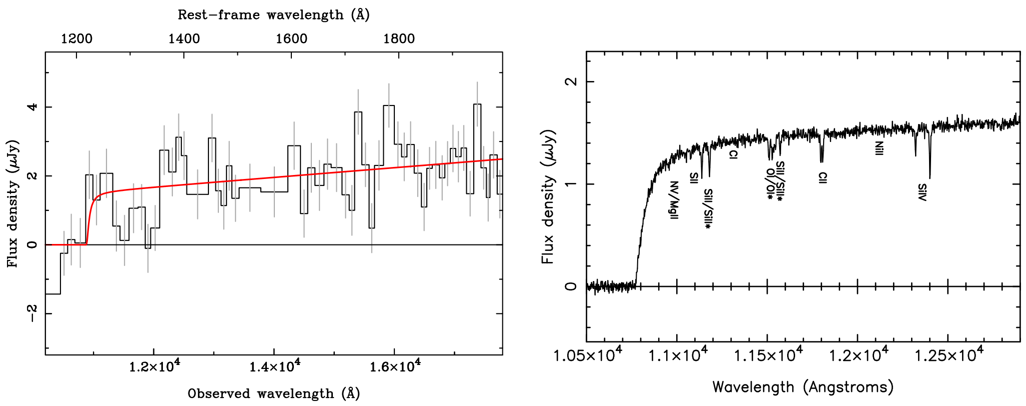

Fig. 1. Left - the observed spectrum of GRB 120923A (Tanvir et al. 2017) which was obtained from a 2 hr VLT X-shooter spectrum. This afterglow was particularly faint and challenging for current technology, and only allowed the redshift, $z \sim 7.8$, to be determined from the Ly-α break. Right - a simulated ELT/HARMONI spectrum of the same afterglow, illustrating the huge improvement in signal-to-noise expected, and consequent detection of metal lines and precise determination of the HI column from the fit to the Ly-α damping wing.

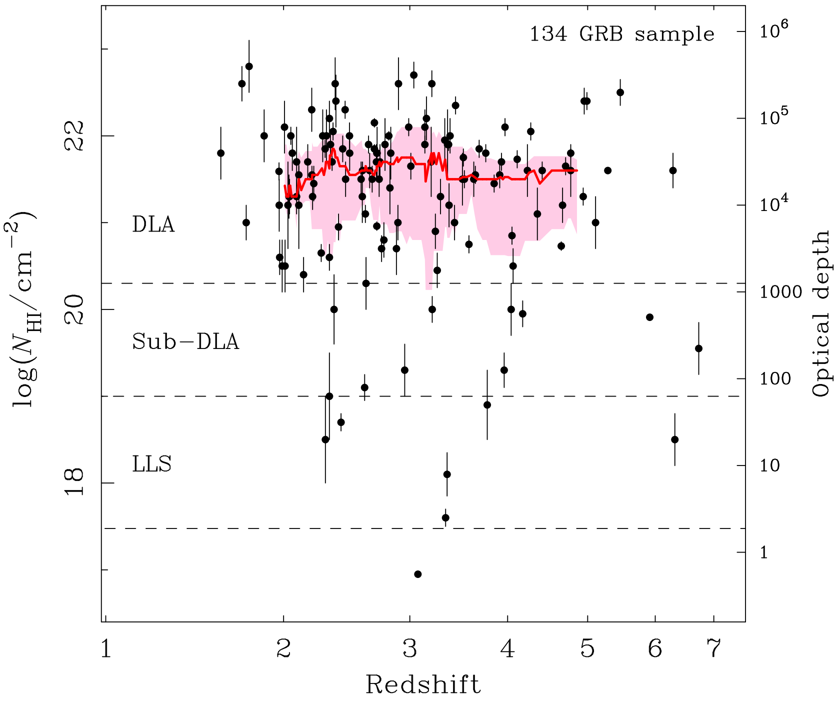

Fig. 2. Neutral hydrogen column density measured from fits to the Lyman-α absorption lines in GRB afterglow spectra. On the right-hand axis is shown the corresponding optical depth to H-ionizing extreme ultra-violet radiation. In nearly all cases the sight-lines are essentially opaque, implying a very low escape fraction. The running median and interquartile range of 20 events (red line and pink band) show little evidence for evolution between $2 \lesssim z \lesssim 5$. (Figure based on data presented in Tanvir et al. submitted.)

2014; Hartoog et al. 2015). The complementarity of *THESEUS* GRB discoveries, and optical/nIR followup with 30-m class telescopes promises a major step forward, which is illustrated by the comparison of the VLT spectrum of GRB 120923A and simulated ELT spectrum of the same afterglow in Figure 1.

3.4. Ionizing radiation escape fraction

Direct observation of escaping Lyman continuum radiation from distant galaxies is challenging at $z \sim 2$–4 (e.g. Japelj et al. 2017), and essentially impossible at higher redshift due to strong IGM absorption. Afterglow spectra of GRBs frequently exhibit strong absorption due to hydrogen Lyman-α, which allows calculation of neutral hydrogen column density, and hence the opacity to ionizing radiation with $\lambda < 912$ Å (Chen et al. 2007; Fynbo et al. 2009). As can be seen from Fig. 2, over a wide range of redshift the large majority of GRB sight-lines are essentially opaque, and thus the bulk of ionizing radiation from the progenitor stars would not escape the host galaxies. Assuming these sight-lines are representative of the sight-lines to massive stars more generally, one can thus infer an average escape fraction of ionizing radiation, which, in a new study by Tanvir et al. (MNRAS submitted) is found to have a 98% upper limit of 1.5%. This is potentially a problem for the hypothesis that reionization was brought about by UV from massive star, since that seems to require escape fractions of at least 10–20%. Although this GRB sample is largely in the range $2 \lesssim z \lesssim 5$, there is little evidence of variation with redshift. From the THESEUS mission we expect to greatly increase the sample of $z > 5$ GRBs with precise $N_{\rm HI}$ measures, thus providing a strong test of whether sufficient stellar ionizaing radiation can escape from the locations of massive stars to drive reionization.

3.5. Topology of reionization

Just as the neutral gas in the host interstellar medium on the lines-of-sight to GRBs can be inferred from the Lyman-α absorption line, so any neutral gas in the intergalactic medium (IGM) proximate to the host also contributes to the absorption. The shape of the damping wing in each case differs slightly, since the IGM absorption is an integrated effect of gas over a path length through the expanding universe. Thus in principle the two columns can be decomposed and hence the neutral fraction of the IGM at that location estimated. In practice, the method is hard for low signal-to-noise spectra, and may be complicated by 'proximity effects' such as inflows or outflows and local ionized regions around the host (McQuinn et al. 2008), although these effects are likely much less significant than in the case of bright quasars. This approach has been attempted in a couple of cases to date (Totani et al. 2006; Hartoog et al. 2015), with results consistent with a low neutral fraction at $z \sim 6$. By obtaining similar results for a larger sample of sight-lines in the *THESEUS* era we will be able to investigate both the overall timeline, but also the variation from place to place (and hence the topology) of reionization.

3.6. Population III stars

Inefficient cooling of metal-free gas tends to produce stars with a top-heavy initial mass function (e.g. Stacy et al. 2016), and if some of these very massive pop III stars end their lives with high specific angular momentum they may produce energetic collapsars. If the jets they produce are sufficiently long-lived then they may produce a distinct class of pop-III GRBs (Mészáros & Rees 2010; Yoon et al. 2015). Even if not detectable directly, the chemical signatures of pop III enrichment may be witnessed in spectroscopy of high-redshift GRBs (Ma et al. 2015).

4. Conclusions

The study of distant galaxy populations, and their role in the reionization of the universe, have been the subject of major efforts, and are a primary science driver for *JWST*. Despite this, some key questions will continue to be very hard to answer, in particular the star formation occurring in faint galaxies, the build up of heavy elements and the escape fraction of ionizing radiation. Long-duration gamma-ray bursts provide unique routes to investigate these issues, which will be fully exploited using the large samples of high-z GRBs found by *THESEUS* together with follow-up by next generation facilities.

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