Exploring Chemical Evolution from the Cosmic Dawn

Context:

Until the Cosmic Dawn, the Universe was chemically quiescent. Complex chemical evolution began when elements heavier than lithium (i.e. metals) formed within the cores of the first generation of stars. However, despite the integral role that these first (Pop III) stars play in chemical evolution, little is known about their properties. Though surveys have spanned over four decades, we are yet to detect a Pop III star in the local Universe. In lieu of studying these stars directly, we can search for the chemical fingerprint that they leave behind in chemically near-pristine environments. This indirect method is yet to conclusively pin down their properties. To further our knowledge of early chemical enrichment and structure formation, it is imperative that we overcome this hurdle. Fortuitously, we are entering into a new ear of discovery with the recently launched James Webb Space Telescope (JWST). This telescope has been heralded as the key to investigating both the first elusive stellar population and the first galaxies. In this statement, I describe my previous experience investigating chemically near-pristine systems. I go on to outline multiple ongoing and future projects designed to decipher the properties of Pop III stars from both an observational and computational perspective. Taken together, these projects have the potential to trace chemical evolution of near-pristine systems from the birth of the first stars.

Previous Research:

Modelling the Cosmic Dawn

One of the key mysteries surrounding Pop III star formation is their underlying mass distribution. Simulations suggest that these stars predominantly formed with masses between $10 - 100$ $M_{\odot}$ [1, 2]. Thus, their Initial Mass Function (IMF) is thought to be distinct from that of later stellar populations. Furthermore, the latest generation of simulations [3, 4, 5] suggest that the first stars form in binaries or small multiples. Until now, when comparing the chemistry of near-pristine objects to the yield calculations of the first stars (e.g. [6]), it has been assumed that the most metal-poor environments were enriched by a single Pop III star, or by an IMF-weighted abundance of elements. The true case is somewhere in between. To make headway on this problem, I have developed the first stochastic chemical enrichment model that takes into account the number of Pop III stars enriching a given environment [7]. I have used this model to investigate the enrichment history of both the most metal-poor reservoirs of gas in the early Universe [7, 8] and a sample of metal-poor Milky Way halo stars [9]. Together, these works suggest that some of the lowest mass structures at $z \sim 3$ contain the chemical products from < 13 (2σ) Pop III enriched minihaloes.

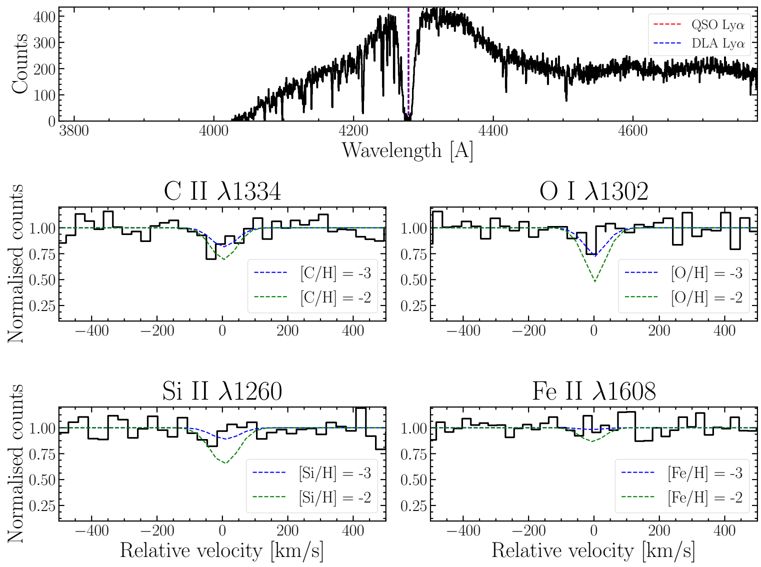

Figure 1: *Example spectrum of a candidate EMP DLA found during WHT programme (7 nights; PI). The top panel illustrates the H I line profile that is characteristic of a DLA. The bottom four panels show a selection of wavelength regions where the strongest DLA metal absorption lines should appear.*

Current Research:

While most of the data analysed came from existing literature. The work presented in [8] contains SV data secured by the authors using a new instrument known as ESPRESSO mounted on the four ESO Very Large Telescopes

(VLT). The key science of this paper will be discussed with my current research in the following sections. The progression from using literature data to using data secured by myself as PI is one of the key differences between my earlier and more recent work. The focus of current research can be summarised in three main projects:

Deciphering the Pop III chemical fingerprint

Large reservoirs of neutral gas, mentioned above, are known as Damped Lyman-α systems (DLAs) when their column density of neutral hydrogen exceeds $\log_{10} N(\mathrm{H\,I})/\mathrm{cm}^{-2} > 20.3$; they are identified via the distinctive H I absorption features (see Fig. 1) that they imprint onto the spectra of unrelated, background quasars. The *most* metal-poor DLAs allow us to study the chemical composition, and evolution, of near-pristine gas in the Universe. Indeed, these near-pristine DLAs may have been exclusively enriched by the first generation of stars [7]. There is mounting evidence to suggest that all DLAs with an iron abundance below [Fe/H] < -3.0 exhibit an elevated [O/Fe] abundance relative to their higher metallicity counterparts (see Fig. 2; adapted from [10]). Since oxygen is predominantly sourced from the supernovae of massive stars, this apparent up-turn observed at the lowest metallicities could be indicative of enrichment by a generation of metal-free stars. I am the PI of multiple VLT/UVES programmes that will determine this ratio within one of the most metal-poor DLAs currently known (green star, Fig. 2) with a precision ~ 0.05 dex as well as secure the first high precision measurements in newly discovered systems. With these data we will reveal whether these most metal-poor DLAs are enriched by the first stars.

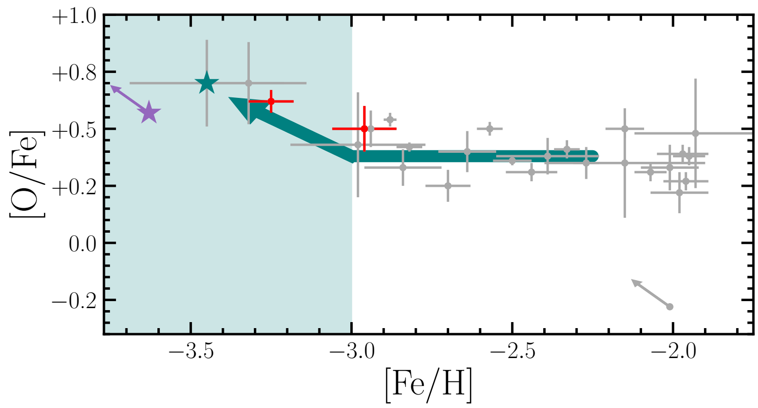

Figure 2: *The [O/Fe] ratio of all confidently measured metal-poor DLAs and sub-DLAs (grey). The upturn of the [O/Fe] ratio when [Fe/H] < -3.0 might be a signpost of enrichment by the first stars. New high precision measurements reported in [10] are shown in red. A target of an upcoming VLT/UVES (PI) programme is marked by a green stars. The purple star indicates the most metal-poor DLA currently known [11].*

Isotopic chemical evolution of DLAs

Another mystery surrounding Pop III stars is whether the formation of low mass metal-free stars is, in fact, possible. I have proposed an observational programme to assess the existence or absence of low-mass Pop III stars using the carbon isotope ratio. Simulations of stellar evolution have shown that most stellar populations predominantly produce ^{12}C. Only low-mass metal-free stars, or metal-poor intermediate mass stars are capable of producing low values of ^{12}C/^{13}C [12, 13] By measuring this isotope ratio of a near-pristine gas cloud, we can test if low-mass Pop III stars might have contributed to the enrichment. I have placed the first bound on the carbon isotope ratio ^{12}C/^{13}C of a near-pristine gas cloud, J0035−0918, using Science Verification VLT/ESPRESSO data [8]. With further data in hand (17 hours; PI), I will improve the current bound on the initial target and investigate the evolution of this isotope ratio across a subset of the DLA population whose metallicities span $\sim 1/1000$ solar to $\sim 1/6$ solar. Given the recent detection of molecular carbon associated with a high redshift DLA [14], an ambitious extension of this exploration may involve the use of ALMA to detect the ^{12}CO $(3-2)$ and ^{13}CO $(3-2)$ transitions of $z \sim 2$ DLAs. This would first require pilot study using IRAM that is currently in preparation.

Reionisation quenching of gas reservoirs

The metal-poor DLAs observed at $z \sim 3$ are likely hosted by the lowest mass structures capable of retaining gas at that epoch. Current observations suggest a redshift evolution of the [C/O] ratio amongst these *most* metal-poor DLAs (see Fig. 3). This may be expected if star formation in these systems is temporarily halted. In this scenario, the evolving

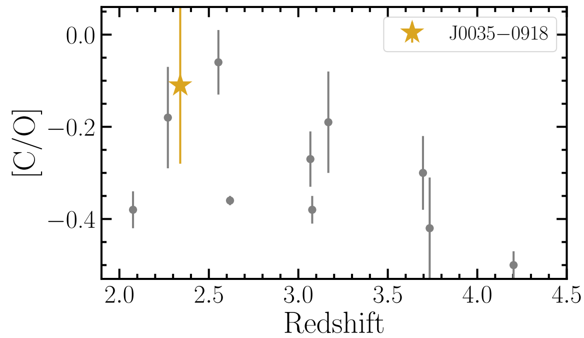

Figure 3: *Redshift evolution of [C/O] ratio observed in the most metal-poor DLAs.*

[C/O] ratio may be due to the onset of chemical enrichment from intermediate mass second generation (Pop II) stars. I have used my stochastic enrichment model to investigate the chemical enrichment history of J0035−0918 (gold star, Fig. 3). The chemistry of this system suggests that it may have experienced a hiatus in star formation following the epoch of reionisation. I am currently extending this investigation to establish whether the *most* metal-poor DLAs are typically affected by reionization quenching; thus, offering a novel environment to study this phenomenon.

FUTURE

A search for *extremely* metal-poor DLAs

There are currently 4 extremely metal-poor (EMP) DLAs whose iron abundance is $< 1/1000$ solar (i.e. [Fe/H] < -3). However, there is yet to be an ultra metal-poor (UMP) DLA, whose iron abundance [Fe/H] < -4 (i.e. 1/10000 solar). The most metal-poor DLA currently known (purple star, Fig. 2) has the potential to breach this limit [15, 11]. To push on the science described above the next main step is to find new EMP systems and build a statiscally significant sample of environments to analyse. Using (low resolution) SDSS spectra, I have compiled a sample of previously unexplored metal-poor DLA candidates in the redshift interval $2 < z < 3$ with the primary goal of identifying EMP and UMP DLAs. Using a 7 night allocation at the William Herschel Telescope (PI) I have acquired intermediate resolution spectra for a subset of this sample. This has revealed 4 systems (including that shown in Fig. 1) that have the potential to be of even lower metallicity. Going forward, I will obtain high resolution spectra of these systems aiming to detect the first UMP (or even chemically pristine) DLA. I will continue my search for these systems using the remaining 30 SDSS identified candidates. Ultimately, this survey will likely reveal $4 - 8$ EMP DLAs, tripling the number currently known. This endeavour will soon be streamlined thanks to surveys like DESI and WEAVE (of which I am a member). These large surveys will negate the need for dedicated follow up with WHT/ISIS — which has, in fact, been decommissioned in favour of WEAVE. The potential to detect these systems will subsequently increase dramatically. Indeed, with the implementation of machine learning techniques in astronomy – the ability of train neural networks to identify promising EMP DLA candidates is on the horizon. Once identified, I will use my stochastic enrichment model to observationally infer the properties of the first stars. I will also use these new data to learn more about the [O/Fe] ratio in these near-pristine environments. Similarly, these new data will provide a strong test of whether the *most* metal-poor DLAs are fossils of reionization.

These is all in preparation fot the ELT BLAH BLAH BLAH
Also take advatange of JWST for light from Pop III :)

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