The search for Population III stars

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Abstract. Population III stars, the first generation of stars formed from primordial Big Bang material with a top–heavy IMF, should contribute substantially to the Universe reionization and they are crucial for understanding the early metal enrichment of galaxies. Therefore it is very important that these objects, foreseen by theories, are detected by observations. However PopIII stars, searched through the HeII 1640Å line signature, have remained elusive. We report about the search for the HeII line in a galaxy at z = 6.5, which is a very promising candidate. Unfortunately we are not yet able to show the results of this search. However we call attention to the possible detection of PopIII stars in a lensed HII dwarf galaxy at z = 3.4, which appeared in the literature some years ago, but has been overlooked.

Keywords. cosmology: observation, galaxies: formation, stars: chemically peculiar

1. Introduction

Theoretical models foresee that the first generation of stars, forming from primordial Big Bang material, should have unusually massive stars (a *top–heavy* IMF), with masses up to about 500 $M_\odot$ (Schneider *et al.* 2002). These stars are called Population III (PopIII) stars, and at least some of them are expected to quickly release metals in the interstellar medium (ISM); therefore later generations would soon be metal enriched. The metallicity threshold in the ISM for producing PopIII stars should be around 10^{-5}–$10^{-4}Z_\odot$. The very massive PopIII stars would then produce a short phase of unusually hard and strong UV radiation ($T_{eff} \sim 100000K$), resulting in a specific line emission signature (Schaerer 2002). The most prominent and unique emission line is expected to be HeII 1640Å, which can become as strong as 1/3 of Lyman α, making it observable with current 8–10m telescopes in the highest redshift galaxies known (Scannapieco *et al.* 2003).

The detection of PopIII stars would be extremely important for understanding the early chemical evolution of galaxies, and because they should be crucial contributors to the reionization of the Universe (Ciardi *et al.* 2003). PopIII stars have however remained elusive: searches for HeII 1640Å through stacking of spectra of Lyman α emitting galaxies (Dawson *et al.* 2004 and Ouchi *et al.* 2008), through deep spectroscopy of an individual galaxy (Nagao *et al.* 2005), or through dual (Lyα and HeII) narrow–band imaging (Nagao *et al.* 2008) have failed. Jimenez & Haiman (2006) have ascribed to PopIII stars the HeII 1640Å line detected in the composite spectrum of ~1000 Lyman break galaxies at $z \sim 3$, but the line is only about 1/10 of Lyman α and is considerably broader: it could therefore be attributed to a stellar wind feature associated with massive WR stars (Shapley *et al.*

2003). The upper limits to the star formation rate (SFR) for PopIII stars, which can be set from these negative results are now quite close to the rates expected from the models of Tornatore *et al.* (2007) (see the contribution by T. Nagao to these Proceedings).

We report about the search for the HeII 1640Å line in a galaxy at z = 6.5 and about the possible detection of PopIII stars in a lensed dwarf HII galaxy at z = 3.4, which has appeared in the literarure (Fosbury *et al.* 2003), but has so far been overlooked.

2. The search for PopIII stars in KCS 1166

KCS 1166 is a Lyman α emitting galaxy at z = 6.518, discovered with slitless spectroscopy in the atmospheric window at $\lambda \sim 9100$Å (Kurk *et al.* 2004). In this object the Lyman α line is clearly asymmetric, being steeper on the blue side, has a very large equivalent width, at least 80Å in the rest frame, and a luminosity of $1.1 \times 10^{43} erg\ s^{-1}$. No continuum is detected at shorter wavelengths, while it is present redward of the line. These characteristics and the fact that the HeII 1640Å line is expected in a region of the J–band relatively free of sky emissions make KCS 1166 a very good candidate for the search of PopIII stars.

We have therefore carried out near IR spectroscopy in the J–band of KCS 1166, using SINFONI, an Integral Field Spectrograph at the VLT (Bonnet *et al.* 2004), with a total on–source exposure time of 9 hours, equally spread over 3 consecutive nights (Fig. 1). Thanks to the excellent efficiency in the J–band and the lack of OH Suppressor and of slit losses of SINFONI, we estimate that our observations of KCS 1166 should be a factor of about 1.5 more efficient in detecting the eventual presence of the HeII 1640Å line than those of SDF J132440.6+273607 at z = 6.3 by Nagao *et al.* (2005), although we had a slightly shorter exposure time.

However at the time of this Conference we are yet unable to report about the results of our observations, since the data reduction, which is rather complicated for an Integral Field Spectrograph like SINFONI, is not yet finished.
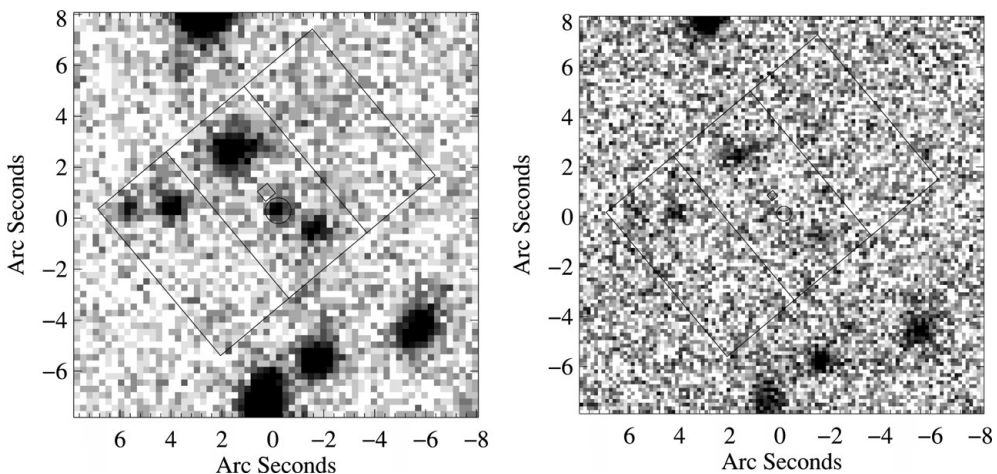

Figure 1. FORS z–band (left) and ISAAC J–band (right) images of the field of KCS 1166. The large boxes mark the two squared areas covered by the Integral Field of view of SINFONI in the two observing positions, shifted by half of the field size to improve the sky subtraction and to leave KCS 1166 in the overlapping area observed for the whole observing time. The galaxy is marked by a small circle and is clearly visible only in the z–band, which contains the Lyman α line.

3. The possible detection of PopIII stars in the Lynx arc

We take this opportunity to draw the attention of the Conference participants and of those interested in PopIII stars to the results obtained by Fosbury *et al.* (2003) on the Lynx arc, since these could well mark the first detection of PopIII stars, and are completely overlooked by the relevant literature. Although we recommend the interested reader to read the paper by Fosbury *et al.* directly, we give here a summary of their work.

The Lynx arc is a dwarf HII galaxy at z = 3.357, lensed by the z = 0.570 cluster RX J0848+4456, and it has been discovered serendipitously by Holden *et al.* (2001) during spectroscopic follow–up of the cluster. The HII galaxy is magnified by a factor of about 10, as evaluated by a detailed analysis of the complex cluster environment from HST WFPC2 images. The unusual emission line spectrum has been thoroughly studied with the LRIS, ESI and NIRSPEC at the Keck telescopes, covering the rest–frame ranges 900–2500 and 3300–5700Å. It shows strong and self–absorbed Lyman α line and CIV 1548,1551Å doublet, strong intercombination lines of NIV] 1483,1487Å, CIII] 1907,1909Å, and OIII] 1661,1666Å, moderate HeII 1640Å, absent [OII] 3727,3729Å. The doublet SiIII] 1883,1892Å is clearly detected in the ESI spectrum, and is 40 times brighter, relative to Hβ, than foreseen by models with scaled solar abundances. The intercombination lines have a very narrow width ($\sigma \sim 30 - 35 km s^{-1}$), indicating a small gravitating mass of about $10^9 M_\odot$, typical of a dwarf galaxy. The absence of NV 1240Å and the weakness of NIII] 1750Å indicate that the ionizing source is a blackbody, rather than a power law, as it would be expected in case of ionization by an AGN.

The intensity of the continuum observed longward of Lyman α is completely explained by the nebular continuum, as accurately predicted from the observed strength of Hβ. The continuum produced by an instantaneous burst of $10^7 M_\odot$, Salpeter IMF, Z = $0.05 \times Z_\odot$, age of 1 to 5 Myr would be seen in the data, if it were present, but would produce an ionizing flux 20 times lower than the one necessary to produce the observed emission lines: this type of continuum, therefore, cannot be the source of ionization.

The photoionization model reproducing all the observed features has a black–body ionizing source with: a) a black–body temperature of 80000K, much higher than the effective temperature of Galactic compact HII regions, which does not exceed 40000K; b) an ionization parameter U = 0.1, also higher than in local HII regions; c) a low *nebular* metallicity Z = $0.05 \times Z_\odot$. The lack of stellar continuum longward of Lyman α, the strong necessary ionizing flux, and the small stellar mass all indicate that the ionizing flux should be produced by fewer than 10^6 hot stars, formed with a top–heavy IMF, and most likely with a metallicity still lower than the nebular one. The substantial overabundance of silicon in the nebula indicate enrichment by past pair instability supernovae, as those resulting from the total disruption of stars with 140–260 $M_\odot$ (Hegel & Woosley 2002).

All these characteristics point strongly to the presence of PopIII stars, some of which might have already exploded to partially enrich the ISM. However in a dwarf galaxy like the Lynx arc, the formation of PopII stars could have been delayed long enough to make the uncontaminated UV signature of PopIII stars detectable at intermediate redshift. In fact this uncontaminated signature of PopIII stars might have a much shorter duration in the massive galaxies, which are the only observable galaxies at high redshift. This might be the reason why PopIII stars have not yet been detected at high redshift, where they have been searched so far, following the obvious paradigm that primordial material is more abundant in the very young Universe.

In a contribution to a conference Schaerer (2004) finds it unlikely that the Lynx arc contains an extremely metal poor cluster, because the ISM metallicity is 1/20 solar and there are no known cases of the stellar metallicity lower than the nebular one, and the

alternative explanation of an obscured AGN (Binette *et al.* 2003) seems to be capable of reproducing the observed spectrum. However, it should not be surprising that new phenomena are observed when dealing with a new class of objects, like PopIII stars, and Binette *et al.* (2003) find it plausible that the stellar metallicity might be lower than the nebular one. Furthermore, of the 5 models presented by Binette *et al.* (2003) the one that best fits the observed line ratios of the Lynx arc is the hot star (80000 K) model, which is relevant for PopIII and which has only one inconsistent line, Si III] 1883,1892Å, whose discrepancy could in any case be due to the nucleosynthetic signature of pair instability supernovae, as explained above. The other 4 models also have discrepant Si III] 1883,1892Å, but in addition have at least two more lines inconsistent with the observations. Therefore the most likely explanations for the observed spectrum of the Lynx arc remains the very hot star model expected for PopIII stars.

4. Final remarks

Although we are yet unable to report on the results of our observations of the HeII 1640Å line in KCS 1166, which is a good candidate for PopIII search at z = 6.518, it is well possible that PopIII stars have already been detected by Fosbury *et al.* (2003) in a dwarf star–forming galaxy at z = 3.357, thanks to the fortunate combination of the longer uncontaminated PopIII phase in dwarf galaxies and of the opportunity given by the lensing magnification to identify PopIII stars, even if not at their peak activity.

Clearly further detections of PopIII stars, or stringent upper limits, would be extremely important to understand the connection between reionization and metal production, since PopIII stars should be major players on both scenes, and could spoil the simple proportionality between ionizing photons and metals, claimed by some (see e.g. the contribution by A. Ferrara to these Proceedings).

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