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LOOKING FOR THE FIRST GALAXIES WITH GTC + EMIR

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RESUMEN

Los nuevos modelos de estrellas de Población III de Schaerer (2002) se han utilizado para derivar las propiedades observacionales de las primeras galaxias en términos de magnitudes y colores esperados para estas fuentes. Hemos estudiado la influencia de la función inicial de masas y de la masa límite superior para la formación estelar en las propiedades de los objetos. Los espectros sintéticos así obtenidos se han utilizado para discutir la posible observación de dichas fuentes. Hemos comprobado que es posible detectar ciertas líneas de emisión intensas, tales como Ly α o He II λ1640, con buena relación señal/ruido, utilizando un espectrógrafo de resolución intermedia en el dominio próximo-infrarrojo tal como EMIR en el GTC. Nuestras simulaciones tienen como objetivo explorar las posibles restricciones observacionales que podrán imponerse en un futuro sobre la época de formación de las primeras estrellas en galaxias.

ABSTRACT

The new Population III models by Schaerer (2002) have been used to derive the observed properties of the first galaxies in terms of the expected magnitudes and colors. The dependence of their properties on the initial mass function and upper mass limit for star formation are studied. The emerging synthetic spectra are used to discuss the implications on different observational features. Strong emission lines, such as Lyα and He II λ1640, could easily be detected with a good S/N with near-infrared medium resolution spectrographs, such as EMIR on the GTC. Our simulations aim at exploring possible observational constraints on the formation epoch of the first stars in galaxies.

Key Words: **COSMOLOGY: EARLY UNIVERSE — GALAXIES: EVOLUTION — GALAXIES: HIGH-REDSHIFT — INFRARED: GALAXIES**

1. INTRODUCTION

In recent years, important advances have been made in the modeling of the first stars and galaxies forming from primordial matter in the early Universe, the so-called Population III objects (for a review see Loeb & Barkana 2001; for conference proceedings see Weiss et al. 2000; Umemura & Susa 2001). The detection of such sources, which constitute the first building blocks of galaxies, remains one of the major challenges of present-day observational cosmology. Recent modeling efforts have been motivated by the future space facilities such as *NGST*, which should be able to observe these objects at redshifts up to $z \sim 30$. Nevertheless, the detection and first studies of the physical properties of Population III objects could probably be started earlier using ground-based 10 m class telescopes. Near-infrared (NIR) multiobject spectrographs, with intermediate resolution capabilities, such as EMIR on the GTC ($\sim$2005) and the future KMOS on the VLT ($\sim$2008), will allow observations of Population III objects up to redshifts of $z \sim 18$.

Among the expected direct observational signatures of Pop III stars or galaxies (i.e., ensembles/clusters of Pop III stars) we may mention:

- Strong UV emission and characteristic recombination lines of hydrogen and He II, especially Lyα and He II (Tumlinson & Shull 2000; Bromm et al. 2001b; Schaerer 2002).
- Mid-IR molecular hydrogen lines at 2.12 μm and longer wavelengths formed in cooling shells (Ciardi & Ferrara 2001).
- Individual supernovae whose visibility in the rest-frame optical and NIR could be enhanced time because of dilatation (Miralda-Escude & Rees 1997; Heger et al. 2001).
- High energy neutrinos from Pop III gamma-ray bursts eventually associated with fast X-ray transients (Schneider et al. 2002).

Rest-frame UV stellar and nebular continuous and recombination line emission represent the largest

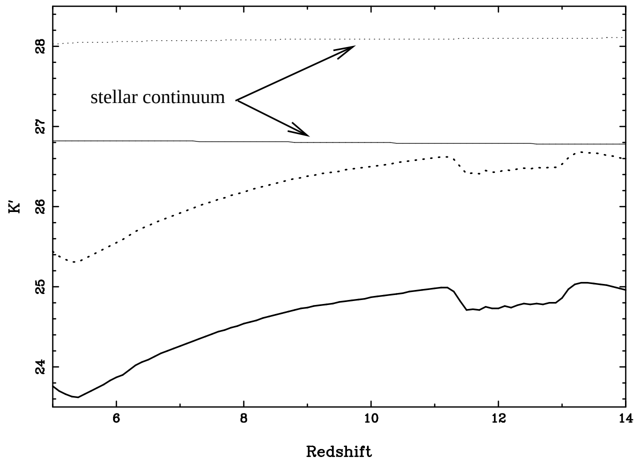

Fig. 1. K' magnitude (Vega system) as a function of redshift over the interval $z \sim 5$ to 14, for a starburst model of 10^7 $M_\odot$ and age 10^4 yr, with a Salpeter IMF, and stellar masses ranging from 1 to 500 $M_\odot$ (dotted lines) and 50 to 500 $M_\odot$ (solid lines). Pure stellar continuum predictions correspond to the upper thin dotted and solid lines, for the two IMFs respectively. The lower thick lines display the predictions for the total spectrum, including lines and nebular continuous emission. The two brightness enhancements at $z \sim 5.5$ and $z \sim 11.5$–13 correspond to the He II $\lambda 3203$ and He II $\lambda 1640$ emission lines entering and crossing this filter. A typical total magnitude of $K' \sim 24$–25.5 is expected for a stellar halo of 10^7 $M_\odot$.

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fraction of the energy emitted by Population III objects, which are generally thought to be predominantly massive or very massive stars (e.g., Abel et al. 1998; Bromm et al. 2001a; Nakamura & Umemura 2001). The predicted rest-frame UV to optical spectra of Pop III galaxies including the strongest emission lines (Lyα, He II, etc.) have recently been computed by Schaerer (2002). In this paper, we use these synthetic spectra to simulate the expected properties of Pop III galaxies, in terms of their colors and magnitudes, and to study the detectability of the strongest emission lines. According to our results, efficient photometric and spectroscopic observations of these features will be possible in the NIR domain, thanks to future imaging and spectroscopic facilities, for a large number of sources, thus allowing us to derive statistically significant conclusions about their formation epoch and physical properties.

2. SIMULATIONS OF POP III STELLAR SYSTEMS

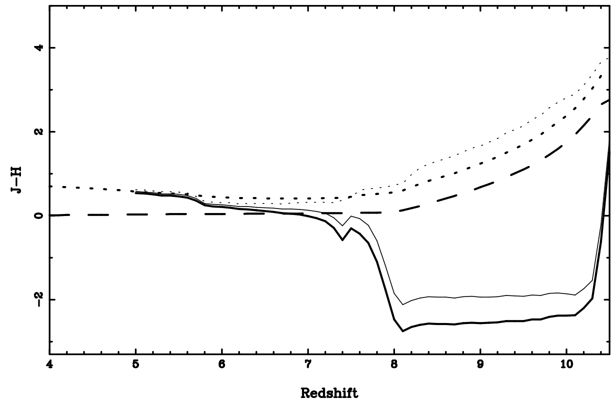
Simulations have been done to support this scientific case, in view of future NIR facilities, such as EMIR on the GTC and the future KMOS on the VLT (preliminary version: Schaerer & Pelló 2001). A popular cosmology is adopted: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.05$, $H_0 = 75$ km s^{-1} Mpc^{-1}). The reionization redshift is assumed to be $\sim$6, but a small change in this value does not modify the conclusions of this paper. Lyman series troughs (Haiman & Loeb 1999), and a Lyman forest following the prescription of Madau (1995) are included. We consider a fiducial stellar mass halo of 10^7 $M_\odot$, corresponding to a collapsing dark matter (DM) halo of 2×10^8 $M_\odot$, thus typically to $\sim$1.5–2 σ fluctuations between $z = 5$ and 10 (e.g., Loeb & Barkana 2001). Magnitudes and S/N ratios are to be rescaled according to this value for other mass haloes. The virial radius is of the order of a few kpc, and thus we consider that sources are unresolved on a $0.3''$ scale, with spherical symmetry. Simulations accounting for an extended Lyα halo (cf. Loeb & Rybicki 1999) have also been performed (Pelló & Schaerer 2002).

We have considered different initial mass functions (IMFs) and ages for the stellar population, as well as two different star formation regimes (starburst and continuous star formation), following the prescriptions given by Schaerer (2002). Magnitudes and colors were derived for these sources in the visible and NIR. A complete set of results will be presented in Pelló & Schaerer (2002). We have also computed the expected S/N ratios for the main emission lines. In this case, telescope parameters correspond to the GTC. The characteristics of the NIR spectrograph are set similar to the expectations for EMIR (Balcells et al. 2000), with $0.2''$/pixel, $1''$ slit width, $0.8''$ seeing, and a mean total efficiency of 40%. All simulations shown subsequently were calculated for a young population, with a Salpeter IMF from 1 to 500 $M_\odot$ (somewhat more "favorable" than a constant star formation case). Spectral resolutions from $R = 1000$ to 5000 were considered.

3. SUMMARY OF RESULTS

3.1. *Photometric properties*

The importance of the nebular continuous emission, neglected in earlier studies (Tumlinson & Shull 2000; Bromm et al. 2001b), is shown in Figure 1. The predicted magnitude in the K' band is typically $\sim$24 to 25 for the reference halo mass. Similar effects are seen in the J and H bands (see also Schaerer & Pelló 2001). Examples of broad band colors are given in Figure 2. Broad band colors do not allow us to constrain physical properties such as the IMF (i.e., the mass range of Pop III stars), ages, etc., but could be useful in identifying the sources on ultra-deep photometric surveys (cf. below). Spectroscopy is needed to study the physics of these objects.



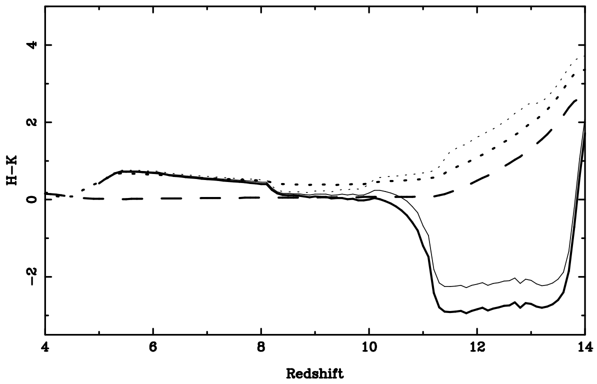


Fig. 2. $J-H$ (top) and $J-K'$ (bottom) versus redshift, for different fractions of Lyα emission entering the integration aperture: 100% (thick solid lines), 50% (thin solid lines), and 0% (thin dotted lines). The expected colors obtained within an integration aperture corresponding to the core (unresolved) source, with Lyα emission coming from an extended halo (Loeb & Rybicki 1999), are displayed by thick dotted lines. The colors expected for a pure stellar population are given for comparison as dashed thick lines. In all cases, a Salpeter IMF has been used to derive the synthetic spectra.

3.2. *Spectroscopic properties*

The expected S/N for the He II λ1640 and Lyα lines versus the redshift of the source (observed in the JHK bands), for a spectral resolution $R = 1000$ and a nominal exposure time of 10^5 s, are shown in Figure 3. The simulations illustrate the following.

Lyα can easily be detected with a good S/N over the redshift intervals $z \sim 8$ to 18, with some gaps, depending on the spectral resolution (OH subtraction) and atmospheric transmission. A joint detection with He II λ1640, the strongest He II line, is possible for $z \sim 5.5$–7.5 (Lyα in optical domain), $z \sim 8$–14 with both lines in the NIR, again with some gaps. The typical line fluxes for the He II λ1640 line range between 10^{-17} and a few 10^{-18} erg s $^{-1}$cm^{-2}. The detection of both He II λ1640 and Lyα allows one, for example, to obtain a measure of the hardness of the ionizing flux, which constrains the upper end of the IMF and the age of Pop III systems. Measuring the continuum, when possible, will provide additional information on the stellar populations, extinction, etc.

Higher spectral resolution ($R \sim 5000$) considerably increases the chances of detection between the sky lines. For unresolved lines (such as expected for He II the resulting decrease in S/N is modest. The medium spectral resolution is also favored to attempt to measure the emission line profiles, in order to distinguish Pop III sources from potential very high z AGN (cf. Tumlinson et al. 2001). Once this is obtained, the data can be rebinned to increase the S/N.

4. DISCUSSION AND FUTURE PROSPECTS

The expected number of Pop III objects and primordial QSOs has been derived by several authors. For example, in a comprehensive study Ciardi et al. (2000) show that at $z > 8$ naked stellar clusters, i.e., objects which have completely blown out their ISM, and thus avoid local chemical enrichment, dominate the population of luminous objects. Although pilot studies have recently started to explore the possible formation of dust in Pop III objects (Todini & Ferrara 2001), the effect is generally neglected. Based on such assumptions, Oh et al. (2001) have calculated the predicted number of Pop III objects detectable in He II lines with the *NGST* for a one-day integration time. Their estimate yields between ~60 and 4500 sources in a $10' \times 10'$ field of view, depending on the model parameters. The expected density of primordial quasars could be similar to that of Pop III galaxies (Oh et al. 2001). Thus, multiplexing is needed to allow highly efficient observations of relevant samples of Pop III objects.

An important issue for spectroscopic studies is the strategy for source selection. Given their peculiar SED (strong nebular continuous emission + lines), young Pop III bursts, or Pop III objects with ongoing massive star formation, show distinct characteristics in their NIR colors compared to "normal" galaxies at any redshift (Pelló & Schaerer 2002). Such objects could be detected from deep NIR photometry based on the measurement of two colors with accuracies of the order of ~0.2 mag. Ideal fields for the first studies are lensing galaxy clusters with areas of strong gravitational amplification, and other very deep fields with NIR photometry. Also IFU NIR observations could allow us to detect the strong He II emission lines. Because the observational signatures of primordial quasars are expected to be similar to

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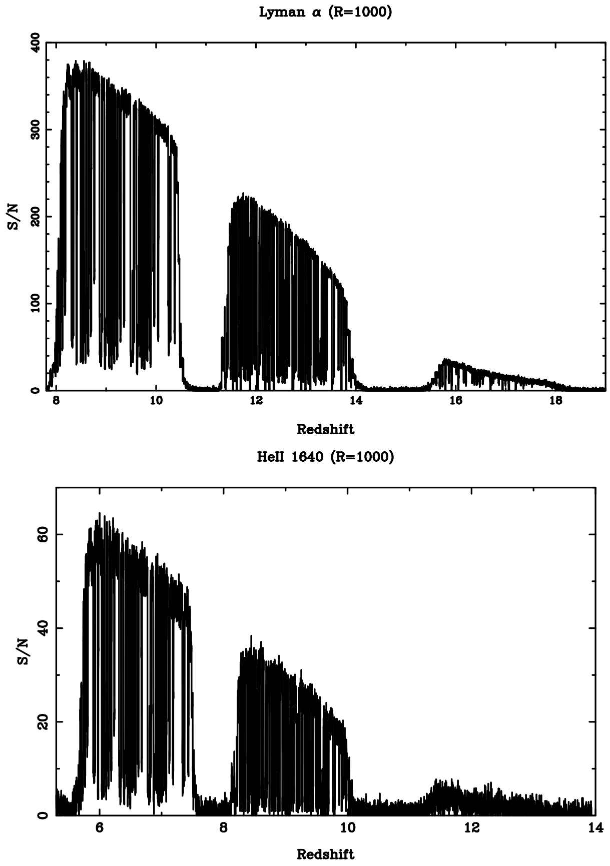

Fig. 3. S/N ratio versus redshift for Lyα (top) and He II λ1640 (bottom) emission lines, as seen in the JHK bands, for a 10^7 $M_\odot$ Pop III stellar halo. The exposure time is 10^5 s, using a 10 m telescope and an EMIR-like spectrograph, with an equivalent spectral resolution of $R = 1000$ (rebinned mode). In the case of Lyα, the S/N corresponds to 100% of the energy entering the slit and is thus the maximum value expected for a compact Lyα halo. Depending on the extent of such a halo, the S/N could typically be lowered by as much as 5–10% with respect to the value shown in this figure.

those of genuine Pop III stars, a relatively high resolution is needed to obtain line profiles.

Thanks to its multiplexing, spectral resolution, and wide field-of-view capabilities, GTC + EMIR is the ideal instrument to start exploring the formation epoch of the first stars in galaxies.

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