位於低紅移(z<1)之新類型極高恆星生成率星系

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摘要

找出宇宙中第一代星系是目前天文學研究中非常熱門的課題，這些星系被認爲在生成其第一代恆星時會發出強烈的紫外輻射(萊曼-α)並游離周邊的氣體。至今的天文觀測已經讓我們可偵側到宇宙極早期(紅移2至紅移8)的紫外發射線源，但仍未有直接證據證明這些紫外輻射可對應至第一代星系。然而，根據目前宇宙學的概念，我們的宇宙持續在產生新星系，因此我們應該能在個別宇宙年齡階段找到剛誕生的星系。

這邊我會利用由目前最新的寬譜段濾鏡巡天觀測，找出宇宙近期中(紅移1以內)具有高恆星生成率並低質量的星系樣本來進行我們的研究。這些被稱作爲豆狀星系的奇異天體，是如同宇宙早期的年輕星系般正在誕生恆星組建其恆星質量，除此之外我們也認爲有許多物理性質會和早期宇宙的極年輕星系多所類似。感謝我們的研究技術，我們可以大量並有效率的選擇出這些年輕星系樣本而不見得需要特定的窄波段觀測或是極耗時間光譜巡天計畫來幫忙完成。

A new class of extremely star-forming galaxies at z<1.0

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Abstract

The detection of candidates for the first generation of galaxies in the distant Universe is hot topic in Astronomy. Young galaxies, forming their first stars, are an important contributor to the ionization of the gas between galaxies, as a result of their strong Lyman-α emission. A large number of these Lyman Alpha Emitters have been detected, at z=2 to z=8, but so far none of these correspond to the first generations of galaxies. However, the current paradigm of galaxy formation suggests that new galaxies are formed continuously. Therefore we should detect very young galaxies at any epoch.

I will introduce a population of extremely star-forming and low mass galaxies at *z*<1.0, that we have identified using the latest generation of broad-band surveys. These objects, called ‘Peas’, appear to be in the act of building up their stellar mass and share many properties with young galaxies observed in the early Universe. The Peas may be the last remnants of a mode of star-formation common in the early Universe. Thanks to our technique, a large number of very young galaxies will be efficiently selectable at different epochs of the Universe, without the need for highly specialized imaging (e.g. narrow-band) or expensive spectroscopic surveys.

關鍵字 (Keywords)：星系（galaxy）、高紅移天體（galaxies: high-redshift）、星系演化（galaxies: evolution）

1. Introduction

The search for the first generation of galaxies have driven studies of galaxies as distant as z~8. Young galaxies forming their first stars produce copious ionizing radiation, and hence strong Lyman-α emission (Partridge & Peebles, 1967). Selected using narrow-band filters, Lyα emitters (LAEs) are galaxies at z=2-7 with a faint ultra-violet (UV) continuum but a prominent Lyα emi-ssion line (e.g. Ouchi et al., 2009). LAEs are mainly young galaxies in a state of formation, cha-racterized by a substantial star-formation rate and a low mass (e.g. Gawiser et al., 2006). However the faint and unresolved distant LAEs (z>2) are challenging to study in detail, therefore selecting galaxies with comparable properties at lower redshifts is critical to conduct detail studies.

We have identified a population of rare, compact objects, which display extremely strong emission lines, indicating that they are forming stars at extremely high rates given their modest stellar masses. These objects were initially noticed as part of the Galaxy Zoo project (Lintott et al., 2008), due to their strong green and compact appearance in the Sloan Digital Sky Survey (SDSS) colour images, which resulted in them being named 'Peas' (Cardamone et al., 2009). The SDSS Peas' apparent green colour is a result of strong [OIII] and Hβ lines, redshifted to z=0.1-0.35, and therefore falling in the SDSS r-band. The Peas appear to have properties that are very similar to objects typically found at z>3 which are often suspected of being galaxies early in the process of formation (e.g., Pentericci et al. 2009). Further-more, LAEs can also be strong [OIII] emitters (Maschietto et al. 2008). The Peas present a possibility of studying the early stages of galaxy formation at an accessible redshift.

The link between the SDSS Peas and LAEs at very high redshift is circumstantial. In order to establish a more compelling link, we require a sample of Peas at higher redshifts (z>0.3).

2. Selecting *z*=0.45-0.95 Peas

2.1 Colour selection of *i*-Peas and *z*-Peas

To extend our study of Peas to higher redshifts, we used the DR3 of the UKIDSS-Ultra-Deep Survey (UKIDSS-UDS, Lawrence et al., 2007; Foucaud et al., 2007), which reach depths of K_{AB}=23.4, H_{AB}=23.5 and J_{AB}=23.7, combined with very deep optical data from the

Subaru-XMM Deep Survey (Furusawa et al., 2008), achieving depths of B_{AB}=28.4, V_{AB}=27.8, R_{AB}=27.7, i'_{AB}=27.7 and z'_{AB}=26.7. The co-incident area with the UDS is 0.63 deg^2. The SDSS Peas are selected by being highly luminous in *r* compared to neighbouring bands. By selecting objects luminous in the *i*- or *z*-band, and using custom-designed colour-colour selections, we have identified peas at redshifts of *z*=0.45-0.7 and *z*=0.7-0.95 (see Fig. 1). In addition we imposed our candidates to be selected as "normal" low redshift galaxies (z<1.4), using the well-known BzK selection (Daddi et al. 2004). After a careful visual inspection, we selected 240 *i*-Peas and 231 *z*-Peas candidates to K_{AB}<23. More details on our selection will appear in Bamford et al. (in prep.) and Foucaud et al. (in prep.).

2.2 Spectroscopic follow-up of *i*- and *z*-Peas

In order to confirm the nature of our selected *i*- and *z*-Pea candidates we obtained optical spectroscopy with the EFOSC2 instrument on the European Southern Observatory's New Technology Telescope. Integration times used for our spectra vary between 20 and 45min. Details of our observations and data reduction can be found in Bamford et al. (in prep.).

We acquired 22 spectra of our brightest *i*- and *z*- Peas and 20 of them have been confirmed to be in the expected redshift range 0.45< *z* <0.95 (i.e. ~90% success). Fig. 2 shows an example of our confirmed Pea. All our confirmed Peas display very high emission line luminosities in [OII]λ3727 and [OIII]λ5007, while ~60% present Hβ and [OIII]λ4959. Finally strong [NeIII]λ3868 and Hγ emissions are detected for ~25% of our Peas.

3. Properties of *z*=0.45-0.95 Peas

3.1 Emission line diagnostics

Thanks to the good resolution of our spectra and their high *S/N* ratio we could probe several indices of ionisation or oxygen abundance based on line ratio (O_{32} or R_{23}). These ionisation parameters are very high, indicating a very high star-formation rate and probably a low metallicity. Measurments indicate a metallicity probably half-solar, comparable to the r-Peas.

The star-formation rates inferred for our galaxies are high, and a first estimation gives SFR=1-60$M_{\odot}yr^{-1}$. However, we have to take into account for the extinction by dust that plays a huge role in our evaluation from optical wavebands. Extinction corrections can be estimated roughly by equating the star-formation rates as measured with [OII] and Hβ lines. This method is quite uncertain; a better estimate uses the Balmer decrement, but that would require additional observations of the Hα emission line). However, after correction we estimate the Star-Formation Rates to be: SFRc=20-700$M_{\odot}yr^{-1}$.

3.2 A bit extreme or extremely extreme?

Using a simple conversion of the near-infrared luminosity of our galaxies we estimated their stellar masses to be between 4×10^9 $M_{\odot}$ and 3×10^{10} $M_{\odot}$, which correspond to the lower mass range sampled by LAEs.

While the Peas mainly present SFRs similar to normal LAEs, the most extreme ones have SFRs similar to Ultra-Luminous InfraRed Galaxies (ULIRGs) at any redshift (SFR~200-300$M_{\odot}yr^{-1}$ - e.g. Sanders & Mirabel, 1996; Daddi et al., 2005). The specific star-formation rates and stellar masses of our Peas are shown in Fig. 3. These objects are extreme compared to the normal galaxy population, are more extreme than the *r*-Peas, but share the locus of LAEs at high redshift in this diagram.

This raises some questions regarding the nature of our Peas. With such SFRs, these objects would double their stellar mass on a dynamical time, and thus may be galaxies in the early stages of their formation. However such an extreme star-formation is expected to be limited to a short time scale, as it should lead to very strong winds that could potentially disrupt the galaxies. Finally the mechanisms at the origin of the burst are unknown. Peas are compact, but the HST images of *r*-Peas reveal disturbed morphologies. Our Peas are also frequently in pair or multiple systems, which could indicate a recent or on-going merging history, as is observed for ULIRGs.

4. Conclusions

We have identified a population of very young extremely star-forming galaxies at z<1. Using simple colour-colour techniques a large number of these objects can be selected. Optical spectroscopic follow-up reveals very strong emission lines, inferring a rather low metallicity and a very high star-formation rate (~400$M_{\odot}yr^{-}$). Using photometric estimation, the stellar masses of these objects are rather low (~10^{10} $M_{\odot}$). These galaxies share characteristics with high redshift galaxies, making them probably the last remnants of a mode of star formation common in the early Universe.

However to better constrain their characterristics, near-infrared observations are required to provide measurements of Hα and [NII] emission lines, to determine the fraction of AGN and starburst galaxies amongst these populations, provide robust star-formation rate measurements, extincttion corrections and metallicities for these objects. This will provide us with better insights regarding the age of the galaxy, and definitively prove if these Peas are truly like their high-redshift homologues.

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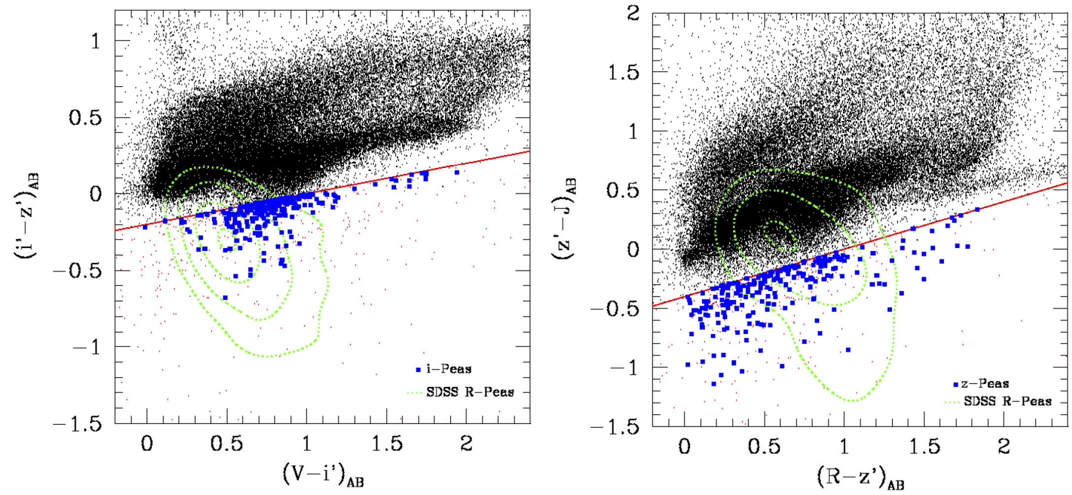

Fig. 1: Colour selections of our i-Peas (left panel) and z-peas (right panel), highlighted in blue. The red line shows our selection criterion. The green dotted lines represent the contours of the distribution of artificially redshifted r-Peas in our colour-colour plot

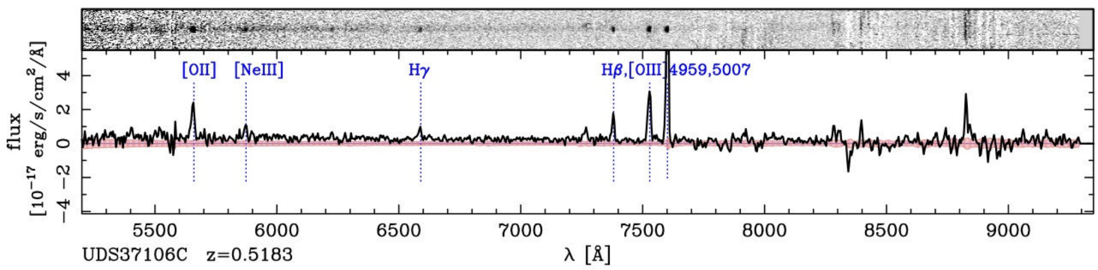

Fig. 2: Exemple of spectrum of our Peas from ESO-NTT EFOSC2, ordered by redshift. The 1D (black line) and 2D (image) spectrum are shown. The red shading indicates the ±1-sigma uncertainty on the 1D spectrum. The expected positions of strong emission lines are indicated by the labelled arrows under each spectrum.

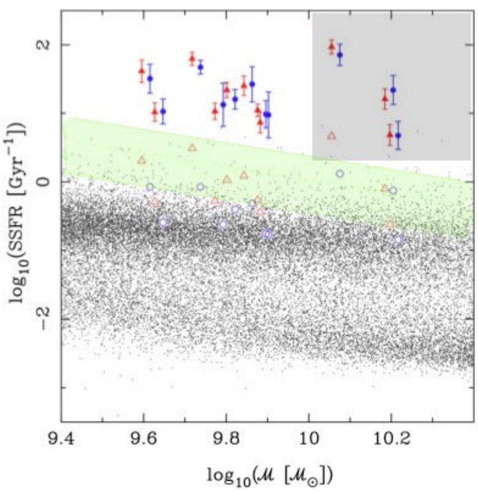

Fig. 3: Specific star formation rate versus stellar mass for our i- and z-Peas (large symbols), compared with a sample of local galaxies from the SDSS catalogue (small, gray points). Red triangles and blue circles indicate SFRs derived from Hβ and [OII], respectively. Open circle and triangles are from the original SFR estimates. Filled symbols have been corrected for extinction. The error bars represent the uncertainty on the emission line luminosity measurement. The light green area corresponds to the locus of r-Peas (Cardamone et al., 2009) and the light grey area (top left corner) highlights the locus of LAEs in such a diagram (Ouchi et al., 2009).