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LETTER TO THE EDITOR

A Lyman-α blob in the GOODS South field: evidence for cold accretion onto a dark matter halo[*]

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ABSTRACT

We report on the discovery of a $z = 3.16$ Lyman-α emitting blob in the Great Observatories Origins Deep Survey (GOODS) South field. The discovery was made with the VLT, through narrow-band imaging. The blob has a total Lyα luminosity of $\sim 10^{43}$ erg s^{-1} and a diameter larger than 60 kpc. The available multi-wavelength data in the GOODS field consists of 13 bands from X-rays (Chandra) to infrared (Spitzer). Unlike other known Lyα blobs, this blob shows no obvious continuum counter-parts in any of the broad-bands. In particular, no optical counter-parts are found in deep HST/ACS imaging. For previously published blobs, AGN (Active Galactic Nuclei) or "superwind" models have been found to provide the best match to the data. We here argue that the most probable origin of the extended Lyα emission from this blob is cold accretion onto a dark matter halo.

Key words. cosmology: observations – galaxies: high redshift – galaxies: halos

1. Introduction

Narrow-band surveys for Lyman-α (Lyα) emitting galaxies at high redshift have recently revealed a number of luminous (up to 5×10^{43} erg s^{-1}), very extended (from a few times ten kpc to more than 150 kpc) Lyα-emitting objects, so-called Lyα "blobs" (Fynbo et al. 1999; Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Matsuda et al. 2004; Palunas et al. 2004; Dey et al. 2005; Villar-Martin et al. 2005). At least three mechanisms have been suggested as energy sources for Lyα blobs. These are: *i)* hidden QSOs (Haiman & Rees 2001; Weidinger et al. 2004, 2005); *ii)* star formation and superwinds from (possibly obscured) starburst galaxies (Taniguchi et al. 2001; Ohyama et al. 2003; Mori et al. 2004; Wilman et al. 2005); and *iii)* so-called cold accretion (Haiman et al. 2000; Fardal et al. 2001; Keres et al. 2004; Maller & Bullock 2004; Birnboim & Dekel 2003; Sommer-Larsen 2005; Dijkstra et al. 2006a,b; Dekel & Birnboim 2006). Cooling flows are phenomena observed in galaxy clusters for more than a decade (Fabian 1994). These are explained by gas which is cooling much faster than the Hubble time through X-ray emission in the centres of the clusters. However, cooling emission from a galaxy, or a group sized halo can be dominated by Lyα emission (e.g. Haiman et al. 2000; Dijkstra et al. 2006a,b). In this letter we present the discovery of a Lyα blob at redshift $z \approx 3.16$ located in the GOODS South field, which we argue is the first piece of evidence for cold gas accretion onto a dark matter halo.

Throughout this paper, we assume a cosmology with $H_0 = 72$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. All magnitudes are in the AB system.

2. Observations and data reduction

A 400×400 arcsec^2 section, centred on RA $= 03^h32^m21.8^s$, Dec $= -27°45'52''$ (J2000), of the GOODS South field was observed with FORS1 on the VLT 8.2 m telescope Antu during two visitor mode nights on December 1–3, 2002. A total of 16 dithered exposures were obtained over the two nights for a combined exposure time of 30 ks, all with the narrow band filter OIII/3000+51 and using the standard resolution collimator (0.2×0.2 arcsec^2 pixels). For this setup the central wavelength of the filter is 5055 Å with a *FWHM* of 59 Å, corresponding to the redshift range $z = 3.126$–3.174 for Lyα.

The observing conditions were unstable during the two nights with the seeing *FWHM* varying between $0.''66$ and $1.''25$ on the first night and $1.''4$ and $3.''3$ on the second night. The images were reduced (de-biased, and corrected for CCD pixel-to-pixel variations using twilight flats) using standard techniques. The individual reduced images were combined using a modified version of our code that optimizes the Signal-to-Noise (S/N) ratio for faint, sky-dominated sources (see Møller & Warren 1993, for details on this code). The modification of the code was necessitated by the highly variable seeing. The sky background was assumed to be constant. The *FWHM* of the PSF of the final combined narrow-band image is $0.''8$.

For object detection, we used the software package SExtractor (Bertin & Arnouts 1996). A full description of our selection of Lyα emitters in the GOODS field will be given in a subsequent paper. In this *Letter* we discuss the nature of an extended, low surface brightness blob with a centroid (of the Lyα emission) of RA $= 03^h32^m14.6^s$ and Dec $= -27°43'02''.4$ (J2000) detected in the combined narrow-band image.

Follow-up MOS spectroscopy was obtained in service mode using FORS1/VLT UT2 over the time period

Table 1. Specifications of deep, multi-wavelength data available in the GOODS South field and the narrow-band image. The last column gives the 3σ limit as detected in a $2''$ radius aperture and the narrow-band value gives the blob flux in this aperture.

Filter/Channel	λ_c	Filter FWHM	3σ limit ($2''$ aperture) (erg cm^{-2} s^{-1} Hz^{-1})
X-rays (*Chandra*)	4.15 keV	3.85 keV	9.90×10^{-34}
U (*ESO* 2.2-m)	3630 Å	760 Å	8.62×10^{-31}
B (*HST*)	4297 Å	1038 Å	9.25×10^{-30}
Narrow (*VLT*)	5055 Å	60 Å	6.68×10^{-30}
V (*HST*)	5907 Å	2342 Å	4.66×10^{-30}
i (*HST*)	7764 Å	1528 Å	1.50×10^{-29}
z (*HST*)	9445 Å	1230 Å	3.00×10^{-29}
J (*VLT*)	1.25 μm	0.6 μm	5.31×10^{-30}
H (*VLT*)	1.65 μm	0.6 μm	1.86×10^{-29}
*K*s (*VLT*)	2.16 μm	0.6 μm	1.56×10^{-29}
Ch1 (*Spitzer/IRAC*)	3.58 μm	0.75 μm	2.51×10^{-31}
Ch2 (*Spitzer/IRAC*)	4.50 μm	1.02 μm	6.43×10^{-32}
Ch3 (*Spitzer/IRAC*)	5.80 μm	1.43 μm	5.01×10^{-29}
Ch4 (*Spitzer/IRAC*)	8.00 μm	2.91 μm	4.65×10^{-30}

December 2004–February 2005. The total observing time was 6 hours. We used a $1''.4$ slitlet and grism 600V resulting in a wavelength range of 4650 Å to 7100 Å and a spectral resolution *FWHM* of approximately 700. The seeing varied between $0''.77$ and $1''.2$ during the spectroscopic observations.

The GOODS archival data used here and their detection limits are listed in Table 1.

3. Results

The spectrum of the part of the Lyα blob covered by the slit-let can be seen in the left-most panel of Fig. 1. The line has the asymmetric profile expected for a high redshift Lyα emitter. We detect no other emission lines in the spectrum. The most likely interloper is [OII] at redshift 0.36, but no emission is observed in the spectrum where e.g. Hβ or [OIII] are expected at this redshift, see Fig. 1. This leads us to the conclusion that we are observing a Lyα-emitting object at $z = 3.157$. The observed *FWHM* velocity width of the emission line is 505 km s^{-1}. The instrument *FWHM* of the set-up is 290 km s^{-1}, hence the Lyα intrinsic velocity width is marginally resolved. The intrinsic width is less than 500 km s^{-1}. This is of the order or smaller than for other published blobs, with velocity widths of 500−2000 km s^{-1} (Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Ohyama et al. 2003; Bower et al. 2004; Dey et al. 2005).

A contour-plot of the blob superimposed on the HST/ACS *V*-band image is shown in the middle panel of Fig. 1 and a plot of the surface brightness of the blob is seen in the right panel of the same figure. The full set of thumb-nail images of the blob in all 14 bands can be found in Fig. 2. No obvious continuum counterpart is detected in any band. The radial size is at least 30 kpc (60 kpc diameter) with fainter emission extending out to 40 kpc radius. This can be seen as the extension to the SW in the contour-plot in Fig. 1. The significance of the lowest contour levels is of the order of 2σ per pixel. The total Lyα luminosity, in a 30 kpc radius aperture, is $L_{\text{Ly}\alpha} = (1.09 \pm 0.07) \times 10^{43}$ erg s^{-1}. This coincides, after correction for the smaller area sampled in the spectrum, to the Lyα flux detected in the spectrum within errors. A conservative lower limit to the restframe equivalent width (*EW*) of the emission line can be calculated from upper limits on the broad-band fluxes in the HST *B* and *V* filters in the

Table 2. Photometric redshifts of objects surrounding the blob. Numbering refers to those given in Fig. 1. Errors given are 1σ.

Obj #	Dist. from blob (arcsec)	z_{phot}	χ^2/d.o.f.	Type	A_V rest
1	4.6	$1.1^{+0.40}_{-0.30}$	1.3	Burst	0.20
2	4.6	$1.1^{+0.34}_{-0.41}$	8.6	Burst	1.20
3	6.8	$2.9^{+1.41}_{-0.59}$	4.8	Spiral	1.20
4	8.4	$0.6^{+1.97}_{-0.63}$	8.1	Burst	0.40
5	8.7	$0.9^{+2.46}_{-0.89}$	2.0	Burst	0.20
6	3.0	$4.5^{+4.29}_{-1.54}$	0.9	Spiral	1.20
7	6.3	$1.1^{+1.24}_{-0.81}$	1.9	Burst	1.20
8	4.5	$3.5^{+1.27}_{-3.48}$	0.6	Spiral	0.00

same aperture. This limit is $EW \gtrsim 220$ Å in the restframe. This is in the range of previously published Lyα blobs, that have a Lyα flux to *B*-band flux density range between 50–1500 Å in the restframe (but typically these values are derived measuring the continuum flux in a smaller aperture than the emission line flux).

There are seven objects detected in a wide range (≥ 8) of energy bands, within a $10''$ radius surrounding the blob. 8 other objects are detected within the *V*-band and one further detected in the *Spitzer/IRAC* bands. The photometric redshift of these objects was calculated using the public *Hyperz*[1] code by Bolzonella et al. (2000). The resulting photometric redshifts for the eight objects with most data points (≥ 8) can be found in Table 2. The other eight objects detected in the *V*-band have only a few detections across the spectrum and hence their photometric redshifts are unreliable. The redshift of object #3 is similar to the blob redshift and indicates that this galaxy may be near to the blob. Object #6 is an intriguing object, undetected in the deep optical and near-IR imaging but bright in the *Spitzer/IRAC* bands. Its photometric redshift is consistent with the redshift of the blob, but with a large uncertainty. The object is also detected in the *Spitzer/MIPS* 24 μm band. Based on the Spitzer magnitudes, and on the diagnostic colour-colour diagram of Ivison et al. (2004), object #6 is best fit by a star-burst at high redshift ($z \sim 5.5$, consistent with the photometric redshift estimate), hence unrelated to the blob.

4. Discussion

We first consider that the Lyα emission of the blob may be due to recombination of gas, photo-ionized by an AGN or a star-burst galaxy. If the blob is a "passive" gas cloud illuminated and photo-ionized by a nearby AGN, then, following Cantalupo et al. (2005), one can show that for an AGN with luminosity $L_\nu = L_{\text{LL}}(\nu/\nu_{\text{LL}})^{-\alpha}$, and in order to result in a peak blob Lyα surface brightness of $\Sigma_{\text{Ly}\alpha}$, the AGN has to be located at a distance of no more than

$$270 \text{ kpc} \left(\frac{\Sigma_{\text{Ly}\alpha}}{10^{-3} \text{ erg s}^{-1}\text{cm}^{-2}} \right)^{-1} \sqrt{\frac{L_{\text{LL}}}{10^{30} \text{ erg s}^{-1}\text{Hz}^{-1}}} \sqrt{\frac{0.7}{\alpha}},$$

where equality applies to the case where the blob gas is optically thick at the Lyman limit. No AGN has been detected in the deep *Chandra* image available within this distance. Worsley et al. (2005) argue that a significant fraction of the unresolved X-ray background in hard bands consists of highly obscured AGN. However, Worsley et al. (2005) also predict that the AGN responsible for this background are situated at $z \sim 0.5{-}1.0$.
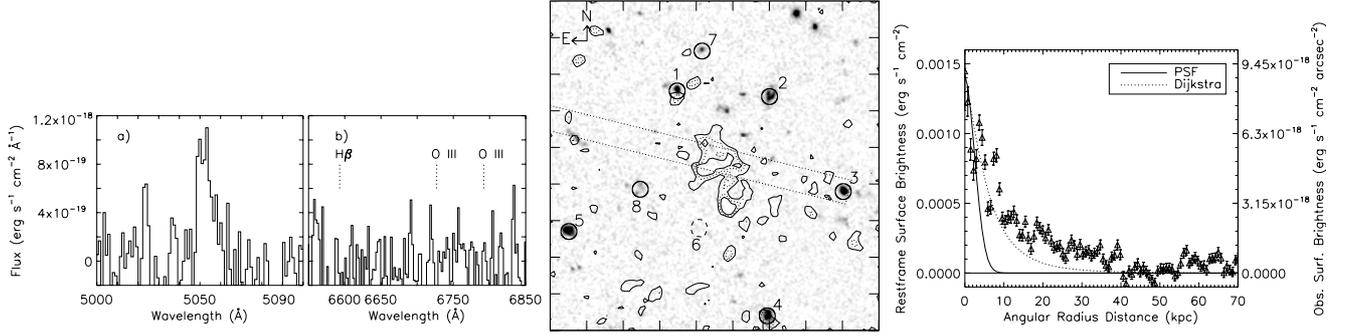
[1] http://webast.ast.obs-mip.fr/hyperz/

Fig. 1. *Left*: **a)** flux calibrated spectrum of the blob emission line. The line has the characteristic blue side absorption, indicating high redshift. **b)** The part of the spectrum (binned with a binsize equal to half the resolution (1.1 Å)) where Hβ and [OIII] should have been observed if the emission line was [OII] at a redshift of $z \approx 0.36$. These lines are not observed and therefore we conclude the observed line is due to Lyα at $z = 3.16$. *Middle*: contour-plot of narrow-band emission from the Lyα blob overlaid the HST *V*-band image. The narrow-band image has been continuum subtracted by subtracting the re-binned, smoothed and scaled HST/*V*-band image. Contour levels are 2×10^{-4}, 4×10^{-4} and 6×10^{-4} erg s^{-1} cm^{-2} in restframe flux (corresponding to 1.2×10^{-18}, 2.5×10^{-18} and 3.7×10^{-18} in observed flux). The image is $18''\times18''$ ($18''$ corresponds to a physical size of $\sim$133 kpc). Numbers refer to those used in Sect. 3. The dotted lines indicate the slitlet position for our follow-up spectroscopy. *Right*: plot of surface brightness as function of radius. The flux is the sky subtracted narrow-band flux. The PSF of the image is illustrated by the solid line, and the dotted line is the best fit model of Dijkstra et al. (2006). The deficit at $\sim$45 kpc is due to the asymmetric appearance of the blob.
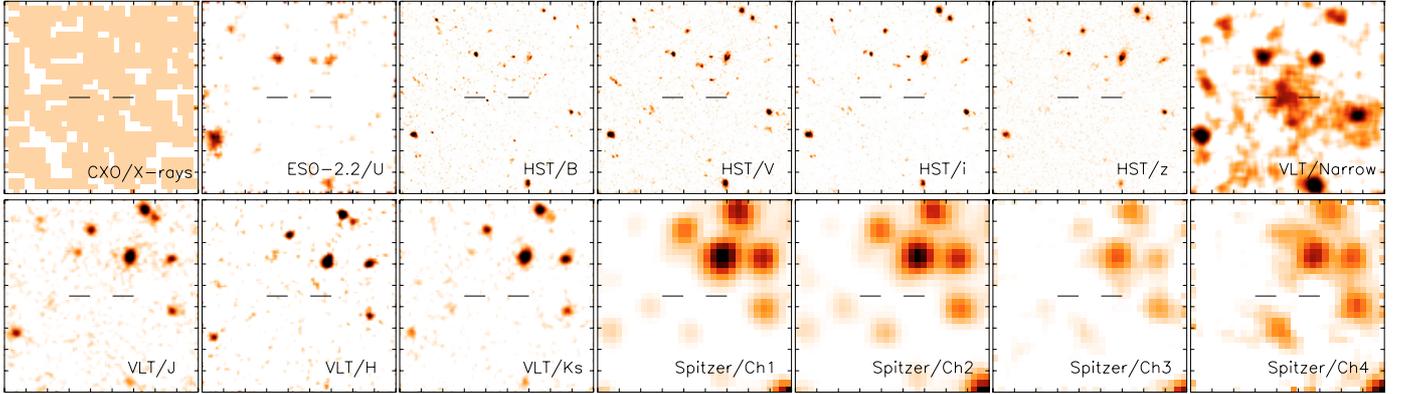

Fig. 2. Thumbnail images of all available multi-wavelength data in the GOODS South field, centred on the Lyα blob. All images are $18''\times18''$.

Furthermore, Silverman et al. (2005) present a luminosity function for AGN at higher redshift. To the detection limit of the CDFS ($L_X(z = 3.15) \approx 1.9 \times 10^{43}$ erg s^{-1}) and with our search volume (3×3 Mpc $\times \Delta z = 0.05$) we expect to detect only 0.06 AGN in our entire search volume. We also consider the possibility that galaxy #3 can photo-ionise the blob. However, if we assume a power law for the spectrum and extrapolating from the HST/B and HST/V detections we find that the UV luminosity of galaxy #3 is not sufficient to photo-ionise the blob, unless highly collimated towards the blob. We have no reason to believe that this is the case.

The second possibility is that the blob Lyα emission is somehow related to starburst driven, superwind outflows. A starburst would be expected to be located within the blob to create such a Lyα halo and no central continuum source has been detected. Even though a very massive starburst can be made invisible in the UV/optical range by dust obscuration, it should be visible in the IR, i.e. the *Spitzer/IRAC* bands.

The third option is that the Lyα emission is due to cold accretion of predominantly neutral, filamentary gas onto a massive dark matter halo. For cold accretion, the bulk of the Lyα emission is produced by collisional excitation, rather than recombination. Recently, Dijkstra et al. (2006a,b) presented a theoretical model for Lyα cooling flows, along with predictions of the

emission line profile and the shape of the surface brightness function. The S/N of our spectrum is not high enough to allow a comparison of emission line profiles. However, the surface brightness profile matches well the predictions for a centrally illuminated, collapsing cloud of Dijkstra et al. (2006a), see Fig. 1. Further tests are needed to determine how well their model fits. To test whether this blob can be filamentary gas accreting "cold" onto a companion galaxy, we also conducted the following experiment: we calculated the Lyα surface brightness in a 100×100 kpc (projected) region for a proto-galaxy of "cooling" radiation only (so all contributions from regions with young stars were removed, as well as all emission, in general, from gas closer than 10 kpc to any star-forming region). The calculation was based on a cosmological simulation of the formation and evolution of an M 31-like disk galaxy (Sommer-Larsen 2005; Portinari & Sommer-Larsen 2005).

The results at $z \sim 3$ are presented in Sommer-Larsen (2005), and get to a surface brightness about an order of magnitude lower than the observed level. This is interesting, and may point to a cold accretion origin of the blob Lyα emission on a larger scale, such as filamentary gas accretion onto a galaxy-group sized halo. Another possibility is that the periods with high surface brightness are shorter than 2.5 Myr (the resolution of the simulation). Given that in a search volume of about 40 000 co-moving Mpc^3,

only one such blob has been detected, it is actually comforting, that we could not reproduce the blob characteristics, by cold accretion onto this, randomly selected, M 31-like galaxy. This has to be a rare phenomenon.

A test for the cold accretion model would be to observe the Balmer lines. For collisionally excited hydrogen, neglecting extinction effects, the flux in Hα should only be about 3.5 percent of the Lyα flux, whereas for recombining, photo-ionized gas this ratio is ~11.5% (Brocklehurst 1971). Hence, the relative Hα luminosity is expected to be significantly larger in the latter case. The situation is similar for Hβ, and whereas the Hα line will be very difficult to detect from the ground, Hβ should be observable.

5. Conclusion

We have here reported the results of an extensive multi-wavelength investigation of a redshift $z = 3.16$ Lyα emitting blob discovered in the GOODS South field. The blob has a diameter larger than 60 kpc diameter and a total luminosity of $L_{\mathrm{Ly}\alpha} \sim 10^{43}$ erg s^{-1}. Deep HST imaging show no obvious optical counterpart, and the lack of X-ray or IR emission suggest there are no AGN or dusty starburst components associated with at least the centroid of the blob. Two galaxies within a 10″ radius have photometric redshifts consistent with the redshift of the blob, but follow-up spectroscopy is needed to establish if there is a connection. We have run simulations of Lyα surface brightness arising from cold accretion and found that such extended Lyα emission may be explained by accretion along a filament onto a galaxy group sized dark matter halo. Another possibility is that such emission in very short lived, i.e. significantly shorter than the 2.5 Myr resolution of our simulation. We argue that other previously suggested origins of Lyα blobs (hidden AGN and "super-winds") can be ruled out in this case due to the lack of detected continuum counter-parts. Hence, though our cold accretion simulation cannot perfectly match our data, it is the only explanation that is plausible. Our results combined with the fact that previously studied blobs appear to be caused by superwinds and/or AGN in turn implies that the energy sources for blob Lyα emission are diverse.

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