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PROSPECTS FOR THE COSMOLOGICAL APPLICATION OF POLARIZED LYMAN-ALPHA RADIATION

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Abstract. We discuss the nature of various flavors of Lyman-alpha (Lyα) emitting objects at high redshift. We provide a brief overview of Lyα radiative transport, giving particular consideration to polarization, and discuss the requirements to obtain net polarization on the emitted radiation. We present and discuss the current status of Lyα polarimetric observations, focusing on a single resolved Lyman-alpha blob at a redshift of 3. Finally we discuss some future prospects and further possible application of Lyα polarimetry, and similar methods for different galaxies.

Keywords: galaxies: high-redshift, galaxies: Lyman-alpha emitters, galaxies: specific: LAB1, methods: observational

1 Introduction – Lyman-alpha things at high-redshift

The HI Lyman-alpha (Lyα) emission line is a versatile and intriguing spectral feature, used with high efficiency in the selection of high-redshift (z) galaxies. It has the advantage of enabling us to probe farther down the mass function than effectively any other selection method (E.g. Cantalupo et al. 2007; Rauch et al. 2008; Hayes et al. 2010), while at luminosities ~ 3 dex higher extended (> 100 kpc) Lyα halo emission is also found associated with the most luminous high-z radio galaxies (HzRG; Villar-Martín et al. 2002; van Ojik et al. 1997; Christensen et al. 2006). Furthermore, Lyα selection digs out a more enigmatic population of objects, that appear similar in luminosity and morphology to HzRG haloes, but instead are radio quiet. These objects, usually dubbed Lyα blobs (LAB; Francis et al. 1996; Steidel et al. 2000), show great diversity in their properties, which has fueled debate about how they relate to populations of less luminous compact Lyα-emitters (LAEs) and HzRGs, whether they are a homogeneous population at all, and even about what powers them.

LABs have been studied extensively over the past decade. It is clear that they are rare and highly clustered, suggesting that (like HzRGs) they live at the peaks of the underlying matter distribution (Matsuda et al. 2004; Yang et al. 2009; Francis et al. 1997; Prescott et al. 2008). However, LABs do not present with a common set of counterpart galaxies, with some hosting star forming Lyman break galaxies, some hosting radio quiet AGN, and more curiously, some with no counterpart galaxies detected at any wavelength (Nilsson et al. 2006; Smith & Jarvis 2007). This sets up the framework for the debate upon what drives the luminous Lyα emission, and various mechanisms have been proposed. That the Lyα photons could be produced by photoionization from hot stars and/or AGN (Steidel et al. 2000) is energetically viable for LABs hosting LBG or AGN counterparts, but implies that the UV-luminous systems must be heavily enshrouded by dust for those that do not. The necessary luminosities in most cases are so high that thermal dust emission should cause them to be bright in the IR and sub-mm, which indeed some are but others still are not. Alternatively it has been argued that the extended emission could be caused by shock heating inside an expanding shell driven by the supernova winds produced by an intense bout of star formation (Taniguchi & Shioya 2000; Mori et al. 2004). As with photoionization, this also requires the internal power source to be hidden from view in many cases. Completely circumventing this problem, the energy may not come from within the nebula itself but from without: the Lyα may be the result of intergalactic gas accreting onto a dark matter halo, heating, and subsequently cooling through Lyα (Haiman et al. 2000; Fardal et al. 2001; Yang et al. 2006).

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The last model is of particular interest in light of recent theoretical studies that showed a substantial fraction of the in-falling gas may not shock heat to the virial temperature of the halo, but could possibly arrive at the centre predominantly along cold (10^4 K) filaments in the cosmic web (Kereš et al. 2005; Dekel et al. 2009; Brooks et al. 2009). Results of hydrodynamical simulations coupled with Lyα radiative transfer show that such cold streams are spatially extended Lyα sources with properties similar to those observed in Lyα blobs (Yang et al. 2006; Dijkstra & Loeb 2009). These scenario is also able to reconcile the puzzling fact that while some of the blobs are not associated with any galaxies some others are associated with powerful dust-enshrouded active galaxies (both star-forming and AGN-like activity, e.g., Scarlata et al. 2009). Now we have at least three plausible mechanisms by which LABs could be powered although it is important to remember that (a) not all LABs need to be powered by the same mechanism and (b) just because some counterparts are energetically capable of powering the LABs, does not necessarily imply that they do. Indeed further observational tests are needed. These may come in the form of other emission lines in the UV (Prescott et al. 2009; Scarlata et al. 2009), or rest frame optical (Yang et al. 2011). Recently, however, Dijkstra & Loeb (2008) suggested a further observable to help in discriminating between models: the polarization signal on the Lyα line itself.

2 Polarizing Lyman-alpha

Lyα photons may scatter wherever they encounter neutral hydrogen, causing their propagation in HI to pose a diffusion-like problem (Osterbrock 1962; Auer 1968; Adams 1972; Harrington 1973). Feedback – the return of kinetic energy to the interstellar medium – seems to be at play in every star-forming galaxy, introducing velocity shifts between the neutral ISM and the nebulae in which Lyα is produced. Resonance scattering (in the core of the frequency redistribution profile and coherent in the rest frame) upon bulk accelerated gas will therefore shift Lyα photons to frequencies at which they encounter subsequent neutral gas at substantially lower optical depths, greatly enhancing the likelihood of transmission. This is though to be the origin of the red-shifting of Lyα compared with other spectral tracers (Kunth et al. 1998; Shapley et al. 2003; Tapken et al. 2007; Steidel et al. 2010; McLinden et al. 2011). However a frequency shift may be introduced even if the scattering medium is static, due to the natural redistribution profile of the transition. Wing scattering is much less frequent than resonance scattering, but the net effect is again to shift the photon to optically thin frequencies, which is thought to be the origin of double-peaked Lyα profiles (e.g. Tapken et al. 2004).

However besides frequency redistribution, there are further important differences between the core and wing scatterings, that result from quantum mechanical differences in the hyperfine splitting of the $^2P_{1/2}$ and $^2P_{3/2}$ levels. Scatterings in the core obey an isotropic phase function and on re-emission have no preferred direction for the electric field vector, whereas scatterings in the wing are analogous to Rayleigh scattering (Stenflo 1980). Wing scatterings through the $^1S_{1/2} \leftrightarrow ^2 P_{3/2}$ channel (a) have a preferential scattering angle of $\pm\pi/2$ and (b) can carry a high degree of linear polarization, P, up to $\approx 40\%$ (Chandrasekhar 1960). The pertinent question to observers then becomes whether astrophysical bodies are able to systematically polarize Lyα. What is needed is a geometry in which photons that have scattered through an angle of 90° are preferentially observed. In the case of a point source of photons that is surrounded by a spherically symmetric scattering medium, any photon that is emitted in the plane of the sky and is subsequently observed must have scattered through a net angle of 90° (see Bower 2011 for an illustration).

Rybicki & Loeb (1999) first visited the problem of Lyα photons scattering in a neutral (i.e. pre-reionization), predicting that P should be substantial; small centrally but $P \approx 30-40\%$ at observable radii. Furthermore, at these radii they predicted the angle of the polarization vector, χ, should orientate tangentially to the circle centered upon the central source. This scenario was re-visited by Dijkstra & Loeb (2008), who suggested IGM-scattered Lyα should be polarized to much lower levels, but made further predictions for scattering in outflowing neutral shells, and for Lyα photons produced in situ at large radii by cooling gas that inflows along spherically symmetric trajectories. The results suggested that the new scenarios should both result in little Lyα polarization at small impact factors, but P that increases to measurable values near the limb. These two scenarios can then be further disentangled by the variation of P across the line profile, which should reverse based upon the direction in which the gas is flowing. However, it has been further mentioned (Dijkstra & Loeb 2009) that should the accretion be filamentary, emergent P could be reduced to unmeasurable levels by the low volume filling factor of the neutral gas. Finally Lee & Ahn (1998) have suggested that moderate polarization signals ($P \sim 5\%$) may be measurable even for spatially unresolved systems, provided the underlying geometry is sufficiently anisotropic. Clearly these theoretical treatments of polarization have evolved to the point where they need to be tested.

3 The status of Lyman-alpha polarimetric observations

This is a fledgling field with only two journal articles, and the reader is referred directly to Prescott et al. (2011) and Hayes et al. (2011); here we briefly summarize. Both observations targeted individual LABs known to have counterparts. Prescott et al. (2011) observed LABd05 from Dey et al. (2005) – a system known to host a strong active nucleus – with the SPOL instrument at the 2.3 meter Bok telescope. They reported a total aperture integrated polarization signal consistent with zero $\lesssim 5\%$ within a radius of 4 arcsec. By performing partial azimuthal averaging over several radial bins they found $P < 12\%$ (1σ) at 4 arcsec.

Hayes et al. (2011, Fig 1) observed the system LAB1 from Steidel et al. (2000) – an LAB known to host several Lyman break galaxies – with the FORS2 instrument at the 8.2 metre VLT. We reported integrated $P = 11.9 \pm 2\%$ inside a radius of 7 arcsec, but note that due to the different method of photometric analysis this is not directly comparable with Prescott's upper limit. The morphology of significantly polarized radiation is rather revealing, and shows that significantly polarized regions tend to avoid the highest Lyα surface brightness, emanating instead from more diffuse regions. We did find evidence of P systematically increasing with radius, with a peak azimuthally averaged P of almost 20%. Furthermore we found evidence that, whenever Lyα does show a significant polarization, the angle χ is consistently aligned tangentially with both the overall (circular) azimuthal direction, and also with isophotal contours in the local surface brightness. All of these measurements are in qualitative agreement with a scenario in which there is a preferential direction of the incoming radiation field as it impinges upon the H I scattering medium. We have made the reduced data-products publicly available*.

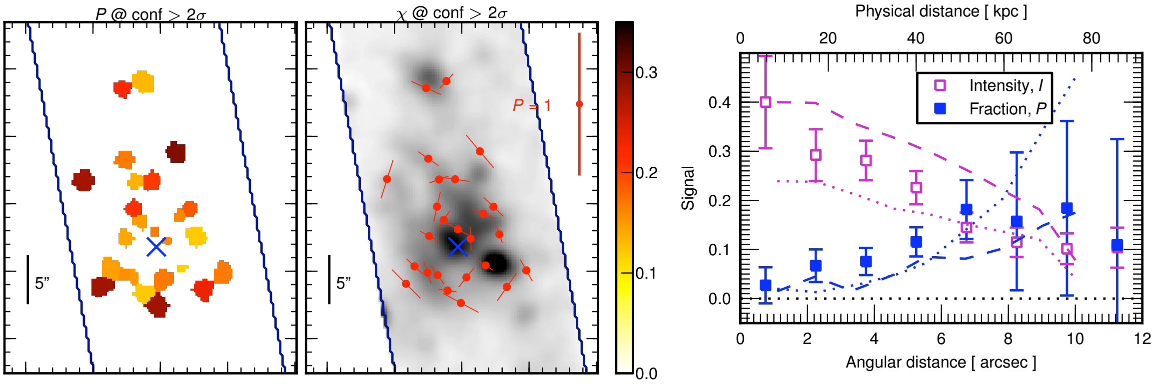

Fig. 1. The observed Lyα polarization of LAB1 (Hayes et al. 2011). The *left* panel shows P for resolution elements in which it was measured to be significant ($P/\Delta P > 2$). The polarized bins clearly avoid the regions of higher surface brightness (c.f. the Lyα image in the *centre* panel), and form an broken ring. Polarized Lyα can be seen from both LAB1 (central main structure) and also LAB8 (smaller structure towards the top). The *centre* panel shows the angle of the polarization vector, χ, for the same bins as the *left* image; χ orientates tangentially to both the overall geometry of the systems and also against the steepest gradients in local surface brightness. *Right* shows the radial distribution profile of the Lyα surface brightness (magenta) and P (blue), measured in concentric annuli centered on the blue cross shown in the *centre* panel. P increases with radius to an angle of about 7 arcsec (≈ 45 kpc) beyond which surface brightness decreases to a level where a meaningful estimate of P is no longer attainable.

4 Prospects and future application

To date, Lyα polarization studies have only employed imaging mode, which is not surprising given the daunting prospect of differential analysis of low surface brightness spectra from $z > 2$ sources. Nevertheless, spectropolarimetry of Lyα may hold substantial promise for more general application. Firstly spectral mode derestricts the observer in terms of the available redshifts and narrowband filters, but more importantly the scattering processes from which the polarization arises also broaden the line and introduce characteristic features (blue bumps and both a knee and ankle on the red side; Verhamme et al. 2006). Thus it is plausible that while the

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*`http://obswww.unige.ch/people/matthew.hayes/LymanAlpha/LabPol/`

line-integrated signal may be low, the polarization signal may reach over 60% in certain features (Dijkstra & Loeb 2008), which will manifest as substantial observational differences at various angles of the wave plate.

Suggestion that Extremely Large Telescopes (ELT) could be used to extend such studies raises the question of whether such an instrument will ever become a reality. Of proposed E-ELT instruments[†], the *Exo-Planet Imaging Camera and Spectrograph (EPICS*, Kasper et al. 2008) includes the *EPOL* polarimeter (Keller et al. 2010) and looks like a possibility. Other ELT instruments for which polarimetric capabilities have been discussed include the *Planet Formation Imager* and *Second-Earth Imager for TMT (SEIT)* for the *Thirty Meter Telescope*, and the *Giant Magellan Telescope* lists polarimetry among the necessities to meet their high level science requirements. This field is currently motivated almost exclusively by exo-planetary science (scattering of stellar light in planetary atmospheres) but it is the development of the instrumentation that is paramount. We cannot say whether we will be able to turn *EPICS* directly to a Lyα galaxy; it should be optically possible, but may require tweaks in the design and/or additional settings. In this eventuality the level of detailed work we undertook on LAB1 (Hayes et al. 2011) could be performed in around four hours. Consequently a moderately sized ELT programme dedicated to Lyα polarimetry could quite easily target a full distribution of selected targets, and even reach full statistical significance.

ELT speculation aside, there is still much left to do with 8 m telescopes. Two Lyα-emitting sources (LAB1 and LAB8) have been studied in depth (Hayes et al. 2011), and one (LABd05) has shallow constraints (Prescott et al. 2011). Yet over 2000 compact LAEs and ~ 100 LABs are known. We cannot state that the current results generalize to all LABs, and many complicating factors could result in both higher and lower polarization levels. LAB1 is known to host LBGs, while others harbor AGN (Dey et al. 2005; Wilman et al. 2005; Geach et al. 2009), composite populations (Colbert et al. 2011), or nothing measurable. Moreover, LABs were first targeted with the polarimeter due to their apparent enigmatic and controversial status regarding homogeneity and energy balance. HzRG haloes are less controversial – there is no energetic problem – but have not been tested. Lyα emission in these cases is likely the result of in situ ionization, coupled with shock excitation/ionization from feedback and where tested, Lyα seems to be if anything less polarized than the continuum (Cimatti et al. 1998; Vernet et al. 2001). These spectroscopic results could indeed suggest that HzRGs are fundamentally different to LAB1, although the observations and analysis methods are not directly comparable. Compact Lyα sources also remain unexplored with the polarimeter. Targeting resolved objects ensures that even if the system is completely spherically symmetric, analysis can be performed in individual regions where the Stokes vectors do not all cancel, and polarization can be detected. However that LAEs and Lyα transport are spherically symmetric does not sound likely to be the case in general, and symmetry is most likely broken on unresolved scales. Thus we may also expect a measurable polarization signal from LAEs (Lee & Ahn 1998).

Interpretation in the field of optical polarimetry of high-z sources has never been straightforward and whatever results from future Lyα polarimetry, the interpretation will again be challenging. Current state-of-the-art simulations assume density and kinematic structures that vary smoothly and continuously, which is unlikely to be the case in real galaxies. The smooth spherically symmetric accretion of gas is currently disfavored, with multi-phase filamentary streams preferred. Any superwind ejected by the galaxy is also unlikely to remain stable when encountering the circumgalactic medium, and clumpy outflows such as those favored by Steidel et al. (2011) may be prevalent. What is urgently needed is for the implementation of Lyα polarization in all Lyα radiative transport codes (without accelerators!), and predictions to be made with various application. This includes systematic explorations in clumpy media that brute force the parameter space of clump distribution and covering fraction, and detailed post-processing of cosmological simulations. With limited instrumentation and demanding observations, and a complex problem with few constraints, we need dedicated theoretical and observational developments that proceed in parallel.

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