IN SEARCH OF THE DARK AGES – AN EXPERIMENTAL CHALLENGE

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ABSTRACT

Most direct source detections beyond \(z \sim 7\) are likely to arise from wide-field narrowband surveys of Ly\(\alpha\) emission in the J band. For this to be true, the Ly\(\alpha\) emission must somehow escape from compact star-forming regions (CSR) presumably associated with massive haloes. Since the Ly\(\alpha\) escape fraction is \(\lesssim 10\%\) from an emitting region of size \(\sim 1\) kpc, these objects will be difficult to find and hard to detect, requiring \(\sim 30 – 100\) hours at each telescope pointing on 8 – 10 m telescopes. For CSR sources, existing large-format IR arrays are close to ideal in terms of their noise characteristics for conducting wide-field narrowband surveys where pixel sizes are 0.1′′ or larger.

However, we stress that Ly\(\alpha\) can also arise from external large-scale shocks (ELS) due to starburst winds, powered by CSRs, ploughing into gas actively accreting onto the dark halo. The winds effectively carry energy from the dense, dusty environment of a starburst into lower density regions, where the escape probability for Ly\(\alpha\) photons is greater. ELS emission is expected to be considerably more clumpy (\(\lesssim 100\) pc) than CSR emission. For ELS sources, IR arrays will need 1 – 2 orders of magnitude improvement in dark current in order to detect dispersed clumpy emission within the environments of massive haloes. These sources require an IR camera with small pixels (\(\sim 0.01′′\)) and adaptive optics correction (e.g., GSAOI on Gemini), and will therefore require a targeted observation of a Dark Age source identified by a wide-field survey. For either targeted or wide-field surveys, the deepest observations will be those where the pixel sampling is well matched to the size of the emitting regions. We show that there are only 3 – 4 J-band windows \(\{z = 7.72, 8.22, 8.79, 9.37\}\) suitable for observing the Dark Ages in Ly\(\alpha\); we summarize their cosmological properties in Table 1.

Subject headings: cosmology; first stars; intergalactic medium; galaxies — high redshift

1. INTRODUCTION

In recent years, we have come to recognize that the ‘ionization epoch’ may lie just beyond our current observational horizon (cf. Fan et al. 2000; 2003; Kneib et al. 2004). Structure formation models in CDM cosmologies appear to show that this epoch took place at \(z = 7 – 12\) (Gnedin & Ostriker 1997; Haiman & Loeb 1998). Recent wide-angle polarization measurements with WMAP (Kogut et al. 2003) suggest the ionization epoch could have been well under way by \(z \sim 17\). However, this may conflict with the inferred high column densities in \(z \sim 6\) quasars (e.g., Wyithe & Loeb 2004). Since cosmic ionization requires only a tiny fraction of the primordial gas to be converted into stars or black holes (Loeb & Barkana 2001), it is possible to construct a wide range of scenarios (Bromm, Coppi & Larson 1999, 2002; Nakamura & Umemura 2001; Abel, Bryan & Norman 2000, 2002; Bromm & Larson 2004; Barkana & Loeb 2000; Wyithe & Loeb 2003; Haiman, Thoul & Loeb 1999; Fryer, Woosley & Heger 2001). Clearly, the first observations of the Dark Ages will have a dramatic impact on our understanding of this new frontier.

In conventional CDM simulations, CSR sources are associated with the cores of massive haloes. Since the distribution of dense peaks collapsing out of an evolving Gaussian density field is well constrained (Miralda-Escudé 2003; Peacock 1999), bright CSR sources are expected to be rare. These will be difficult to find even with well optimized wide-field surveys which exploit large pixels (\(\sim 0.1′′\)). However, the number of detectable sources above a given flux level at a fixed epoch is more uncertain. This requires a detailed understanding of how and when Ly\(\alpha\) emission is produced, and how it manages to escape its immediate environment (Neufeld 1991; Haiman & Spaans 1999). Even the most optimistic calculations (Baron & White 1987) show that Ly\(\alpha\) detections will be a major observational challenge on 8 – 10m telescopes. The possible discovery of a lensed candidate galaxy at \(z = 10\) by Pelló et al. (2004) demonstrates the power of lensing to extend our observational reach. However, the total number of sources accessible this way is limited by the small total volume of the universe that is strongly magnified by foreground lenses.

During the Dark Ages, gas accretion onto protogalactic cores must have been well under way. Galactic nuclei at the highest redshifts observed to date (\(z \sim 5\)) exhibit solar metal-licities, and therefore appear to have undergone many cycles of star formation (Hamann & Ferland 1999). Most galaxy cores early in their evolution must have experienced starburst-driven winds. Early protogalactic winds will have carried large amounts of energy, with relatively low dust/metal content, away from the complex circumnuclear environment (Desjacques et al. 2004).

In order to understand physical processes associated with the first sources, we will need to resolve the Ly\(\alpha\) structures. But, as we now show, detecting emission powered by outflows is a different experimental challenge from that posed by wide-field searches.

1 On leave from the University of Wollongong
2. THE Lyα CHALLENGE

2.1. Wind-scattered Lyα emission

The difficulty of detecting Lyα during the Dark Ages is emphasized in recent simulations by the GALFORM consortium (Lacey et al. 2004; Cole et al. 2000). The GALFORM simulations assume that all Lyα is produced by star formation, and that 10% escapes through the action of galactic winds. The simulations are adjusted so as to reproduce the Lyman-break and submillimetre galaxy number counts at presently observed wavelengths. Down to a limiting flux magnitude of \( f_{\text{lim}} = 3 \times 10^{-19} \frac{\text{erg}}{\text{cm}^2 \text{s}^{-1}} \), they predict only about ten sources per square arcmin will be observable across the entire redshift range corresponding to the J band. The flux limit is equivalent to a star formation rate of a few solar masses per year which is easily high enough to drive large-scale winds (Heckman 2003; Veilleux 2003).

The most efficient mechanism for Lyα escape is scattering by neutral H entrained in an outflowing wind (Chen & Neufeld 1994). The best observed starburst galaxy M82 reveals UV-scattered bicones along the minor axis (Courvoisier et al. 1990; Blecha et al. 1990) on a scale of 500 pc to 1 kpc. This corresponds to a spatial scale of 0.1 – 0.2″ at \( z \approx 8 \). Thus wide-field searches of rare massive haloes will need to exploit pixels on this scale in order to find CSR sources. The scattering wind may be clumped but, as we discuss below, the individual clumps are likely to fall below the detection limit.

2.2. Wind-driven Lyα emission

We now examine the likelihood that most of the Lyα is distributed in small clumps which are cooling out of dissipating gas, and spread over a larger volume than Lyα arising directly from star forming regions.

During the early stages of galaxy formation, collapse is likely to be comparable to star formation as a source of energy for the gas. Cold gas accumulated in the collapse of a small halo (Rees & Ostriker 1977) produces an initial burst of star formation. If the energy released into the nascent interstellar medium by star formation greatly exceeded that released in the collapse, then the bulk of the gas would be unbound from the young galaxy. On the other hand, the mechanical energy required to limit the initial burst of star formation is comparable to the binding energy of the gas, which is roughly the energy needed to significantly rearrange gas within a galaxy. Thus, if the burst of star formation is self-limiting, its feedback cannot fall well short of the binding energy of the gas, i.e., the energy released by the collapse.

Since radiative cooling times of gas at the virial temperature are much shorter than dynamical times in low mass protogalaxies, feedback can only be stored briefly as thermal energy. Energy rapidly lost to radiation is ineffective as feedback. Only feedback energy that is converted to kinetic (and later potential) energy can be effective in limiting star formation on the dynamical timescale. Effective feedback needs to induce rapid large-scale flows, i.e., winds, so we assume that the primary channel of feedback is through winds. This argument requires a moderately high efficiency for the conversion of energy released by star formation into wind energy, but that is consistent with observations of starburst winds (e.g., Strickland & Stevens 2000).

If collapse and the initial burst of star formation make comparable energy inputs to the ISM, we can estimate both using the spherical collapse model. To form a disk, gas must dissipate at least the vertical component of its velocity dispersion, i.e., \( \sigma^2/2 \) per unit mass. For a dissipative collapse — one producing cold gas — the energy dissipated is several times this, so we use the estimate of \( \sigma^2/2 \) per unit mass dissipated by gas in the collapse. The time taken for a halo to virialize is roughly equal to its turn around time, i.e., half of its collapse time, \( t_c \).

If the energy dissipated in the collapse is dissipated in half of the virialization time, the dissipation rate \( 4M_G\sigma^2/t_c \), where \( M_G \) is the gas mass involved in the collapse.

Dark energy is insignificant for collapse at \( z \approx 8 \), so that the mean density of a halo collapsing at \( t_c = 3\pi/(4Gt^2) \), giving the virial radius for a halo of mass \( M \) as \( R = (GM/c^2)/(4\pi^2) \), then gives \( \sigma^2 = 0.5(2\pi GM/t_c)^{2/3} \), so that \( \sigma \approx 53M_{10}^{1/3} \text{ km s}^{-1} \), where the halo mass \( M = 10^{10}M_{10} \) and \( t_c = 6.27 \times 10^8 \text{ yr} \) [\( z = 8 \), in \( \Lambda \text{CDM with } (h, \Omega_m, \Omega_\Lambda) = (0.7, 0.3, 0.7) \)]. Little Lyα can be produced in the collapse unless the gas is heated over \( \sim 10^5 \text{ K} \), i.e., unless \( \sigma \gtrsim 10 \text{ km s}^{-1} \), requiring halo masses exceeding \( 10^9 M_{10} \).

Using the baryon fraction determined by WMAP (\( f_b = \Omega_b/\Omega_m \approx 0.17 \); Spergel et al. 2003) and assuming that all baryons are gaseous in the collapse, the dissipation rate in the gas during a collapse is \( P_d \approx 4f_b M_G\sigma^2/t_c \approx 2 \times 10^{40}M_{10}^{4/3} \text{ erg s}^{-1} \). Instantaneous dissipation rates will show a significant spread about this value. The fraction emerging as Lyα photons depends on the shock temperature and the fraction of photons that escape. Higher escape fractions are favoured by low optical depth and low abundances (low dust content). In standard \( \Lambda \text{CDM}, \) very few \( 10^{10} M_{10} \) halos collapse before \( z = 8 \) (Cole et al. 2000).

While the fraction of Lyα photons escaping from starbursts is small, a significant part of the energy carried off by galactic winds is ultimately likely to be dissipated in shocks. These are another potential source of Lyα photons and, from above, the energy in the winds is comparable to that dissipated in the collapse. The winds effectively carry energy from the dense, dusty environment of a starburst into lower density regions, where the escape probability for Lyα photons is greater. Starburst wind speeds are high and not strongly dependent on the properties of the hosting halo. This means that if starbursts...
are triggered in halos smaller than $10^{8} \, M_{\odot}$, then the terminating shocks of galactic winds may produce Ly$\alpha$ although the collapse shocks cannot.

From above, the mean baryon density in a dissipationless halo collapsing at $z = 8$ is $3 \pi f_{\rm b}/(G m_{\rm H} t_{\rm f}^{2}) \approx 0.036 \, \text{cm}^{-3}$, where $m_{\rm H}$ is the mass of hydrogen. Since dissipation significantly increases the density of the gas, the typical density of gas running into shocks during a dissipative collapse can be somewhat larger than this. The collapse is fairly chaotic and collapsing gas is likely to encounter several shocks before finally reaching its destination. Provided that the effects of radiation transfer are not too significant, the depth of the emitting region behind a radiative shock is approximately equal to the product of the postshock cooling time and velocity. In a strong shock, the gas density is increased by a factor of 4, the speed is decreased by the same factor and the postshock temperature is $T_{\rm ps} = 3 \mu m_{\rm H} v_{s}^{2}/(16k)$, where $v_{s}$ is the shock speed and $\mu m_{\rm H}$ is the mean mass per particle. Fig. 1 shows the width of the postshock cooling region for a preshock electron density of 0.036 cm$^{-3}$, for metal abundances of 0, 0.1 and 1 solar.

Initially, the collapsing gas flow may be coherent on larger scales than the postshock cooling length in Fig. 1. In that case, cooling shocked regions are sheetlike and emission is brightest at caustics where we see folds in these sheets projected onto the sky. The cooling gas is subject to thermal and other instabilities that will generally cause it to fragment on about the scale of the cooling length. (The flow into any further shocks is likely to be considerably more chaotic.) For haloes in the mass range of interest, the shock speeds in the collapse are, at most, $100 \rightarrow 200 \, \text{km} \, \text{s}^{-1}$. In a pristine gas, the inferred size of cooling clumps is roughly 100 pc, or 0.02$''$ at a redshift of $z \approx 8$. The small size of the cooling region demands an infrared imager which utilizes small pixels ($\approx 0.01''$) and adaptive optics correction. However, we point out that rapid winds from starbursts can produce significantly larger cooling regions.

Since gas is compressed significantly in a dissipative collapse, the time scale for star formation in a clump of collapsing gas can be much shorter than the dynamical time of the collapsing system ($\approx 10^{8} \, \text{yr}$). Massive stars take only $\sim 10^{8} \, \text{yr}$ to produce supernovae, giving plenty of time for starbursts and their winds to get underway while other gas continues to collapse into the system. Interaction between infalling gas and starburst winds can lead to further shocking of both. This process is observed in M82 where the outflowing starburst-driven wind impinges directly on infalling gas at a radius of 11 kpc (Yun, Ho & Lo (1994) producing observable H$\alpha$ and x-ray emission (Devine & Bally (1999), Lehnert, Heckman & Weaver (1999)).

3. EXPECTED LY$\alpha$ SURFACE BRIGHTNESS

We now examine whether wind-powered Ly$\alpha$ emission in small clumps can be detected with an 8m telescope using an adaptive optics imager with small pixels (0.02$''$). We assume that the total energy released in Ly$\alpha$ at a fixed star formation rate is comparable to what is generated in large-scale shocks driven by the starburst, and that this emission escapes without attenuation. As discussed in §2.2, this assumes a high conversion rate of the supernova energy into wind energy (e.g., Strickland & Stevens (2000)). From surveys of nearby dwarf galaxies (Martin (2003), Veilleux (2003), we adopt a wind radius of 5 kpc. At $z \approx 8$, the shock occurs at 1$''$ radius and is barely resolved. Naively, if the wind energy escapes along bipo-

![Fig. 2.— Filter profiles used in our GSAOI calculations. The Lorentzian profile ($m = 1$) shown in black is the expected response of a high finesse (N=40) tunable filter. The green profile ($m = 2$) is the low-cost filter option, the blue profile ($m = 3$) is the high-cost filter option.](image)
TABLE 1  
BASIC COSMOLOGICAL PARAMETERS FOR THE FOUR DARK J-BAND WINDOWS.

| Wavelength (µm) | 1.06 | 1.12 | 1.19 | 1.26 |
|-----------------|------|------|------|------|
| Redshift        | 7.72 | 8.22 | 8.79 | 9.37 |
| Time since Big Bang (Gyr) | 0.66 | 0.60 | 0.55 | 0.51 |
| Time before present (Gyr) | 12.80 | 12.85 | 12.91 | 12.95 |
| Physical scale (kpc/arcsec) | 4.92 | 4.73 | 4.53 | 4.35 |
| Luminosity distance, d_L (Mpc) | 77283 | 82979 | 89667 | 96398 |
| Flux, F = L_4/4πd_L^2 (10^{−20} erg s^{−1} cm^{−2}) | 1.40 | 1.21 | 1.04 | 0.90 |
| Physical depth, D (Mpc/1000 km s^{−1}) | 1.099 | 0.929 | 0.849 | 0.779 |
| Comoving depth, D_c (Mpc/1000 km s^{−1}) | 8.798 | 8.565 | 8.312 | 8.078 |
| Physical volume, 1'×1'×D (Mpc^{3}) | 0.088 | 0.075 | 0.063 | 0.053 |
| Comoving volume, 1'×1'×D_c (Mpc^{3}) | 58.5 | 58.7 | 59.0 | 59.1 |

Note. — The cosmology is \((h, \Omega_0, \Omega_L) = (0.7, 0.3, 0.7)\). The comoving volume is essentially constant over the windows and the total timespan is only 150 Myr.

The expected flux from a source with luminosity \(L_s = 10^{41} \text{ erg s}^{-1}\), in units of \(10^{−19} \text{ erg cm}^{-2} \text{s}^{-1}\), only varies by 50%.

4. SURVEY METHOD
4.1. Wide-field Lyα survey

We envisage an initial survey with a wide-field, large-pixel imager which scans over several fields in order to identify an initial list of CSR sources. This is the primary motivation of the DAZLE instrument under construction at the Institute of Astronomy, University of Cambridge for the Very Large Telescope (Bland-Hawthorn et al. 2003) and see also http://www.ast.cam.ac.uk/~optics/dazle which exploits high performance \(R = 1000\) interference filters closely spaced in wavelength within the J-band. The wide-field (6.9′ square) observations are built up in interleaved sub-exposures by switching between the two filters: the images are then deconvolved in order to detect signals in one band that are not evident in the other. This technique has been widely used with the Taurus Tunable Filter (TTF) on the AAT and has led to the identification of a line-emitting populations out to z ~ 5 (e.g., Bart et al. 2004).

Each target field with DAZLE will require long exposures, and may require several fields in order to find a single source. Table 1 summarises the cosmological properties of the four ‘dark’ windows in the J-band originally identified in the DAZLE design study (Cianci 2003) and see also http://www.aao.gov.au/dazle which are clearly evident in Fig. 3.

We now present SNR calculations for a wide-field and an adaptive optics near-IR imager on an 8m telescope. The calculations utilize both airglow and absorption spectra at a spectral resolution of \(R = 10000\) (cf. Offer & Bland-Hawthorn 1998). We adopt instrumental parameters for DAZLE and for the Gemini South Adaptive Optics Imager (GSAOI) to be commissioned in 2005: the key numbers are listed in Table 2 (McGregor et al. 2003). Note that several of the parameters are expressed over a range: the lower value is used in our ELS calculation (GSAOI), and the upper value is used in our CSR calculation (DAZLE). The GSAOI will utilise a HAWAII-2RG array, under development for the James Webb Space Telescope, which is expected to have exceptionally low dark current. DAZLE exploits a HAWAII-2 array which has a much higher dark current, but which is adequate for wide-field surveys, as we show below.

The equivalent luminosity for the quoted Lyα flux and the physical size of the Lyα blobs is given in Table 1 as a function of redshift. Since the blob sizes in our calculations are larger than the AO-corrected psf of GSAOI, we do not consider the J-band Strehl ratio in our calculations. The J-band airglow spectrum was normalized to the expected J-band counts given in McGregor et al. (2003). We consider two limiting cases in the other. This technique has been widely used with the TTF on the AAT and has led to the identification of a line-emitting populations out to z ~ 5 (e.g., Bart et al. 2004).

Table 2

| System parameter | Value |
|------------------|-------|
| Reduced telescope area | \((\pi/4) \times 7902 - 1302\) cm^{−2} |
| System throughput | 0.27 |
| Filter throughput | 0.80 |
| Detector pixel size | 0.02′ - 0.1′ |
| Detector read noise | 5 e^{-1} |
| Detector dark current | 0.003 - 0.05 e^{-1} |
| Night-glow continuum | 2 - 5 Rayleigh \(\text{A}^{-1}\) |
| Source flux | 3 - 30 \(\times 10^{−20}\) erg cm^{−2} s^{−1} |
| Source diameter | 0.04′ - 0.20′ |
| Total SNR for source | 3 - 5 |
| Exposure time | 3600 s |

Note. — For parameters shown over a range, the lower bound is specific to the ELS (GSAOI) case, the upper bound refers to the CSR (DAZLE) case. The one exception is the night sky continuum where we incorporate both bounds in both calculations. The reduced telescope area incorporates the loss due to the Cassegrain hole (M2 stop). The filter throughput assumes an IR detector that cuts off at 2.5µm; this reduces to 60% for a detector cut-off at 5µm due to the need for additional optical density layers for long wavelength suppression. The exposure time determines the number of read noise contributions to the summed image.
the night-glow continuum between the OH lines (e.g., Jones, Bland-Hawthorn & Burton 1996): the actual night-glow continuum level is unknown but is bracketed by the quoted values in Table 2. The night-glow surface brightness is quoted in Rayleighs (R) per Angstrom where R = 10^9/4π photon cm^−2 s^−1 sr^−1.

At a fixed spectral bandpass defined by R, the wings of the filter profile must be considered. Jones, Bland-Hawthorn & Burton (1996) demonstrate that the out-of-band blocking of an interference filter with m cavities is closely matched to a Butterworth function of degree m. We have incorporated the Butterworth profile (see Fig. 2) in our calculations. The single cavity (m = 1) is the Lorentzian profile of a tunable filter in the high finesse limit (Bland-Hawthorn & Jones 1998). The relatively low-cost DAZLE filters utilise m = 2 (two cavity), although there is also a high-cost option with m = 3. We assume that placement within the instrument does not degrade the effective bandpass, an issue discussed at length by Bland-Hawthorn et al. (2001).

Both m = 2 and m = 3 filters are risky and highly expensive items to manufacture since the multi-cavity dielectric coatings can exceed 10µm in total thickness, requiring hundreds or even thousands of layers. As was found in the DAZLE study, this can be greatly exacerbated by the need for high optical density to achieve long-pass blocking2 by the interference filter.

In Fig. 3, the horizontal lines indicate we need 40 ks per field in order to achieve a 5σ detection in one or other band, but note that the DAZLE technique surveys twice the volume of a single R = 1000 filter image. (If the detection relies on the differencing of on-line and off-line bands, its statistical significance is reduced to 3.5σ.) An (almost) equivalent strategy is to halve the exposures per field, and to observe two fields in two closely spaced bands. Once tentative sources have been identified, in order for the emission to be Lyα, the source should not be evident in deep ugriz images (i.e., AB mag ≥ 28) corresponding to rest-frame Lyman continuum.

4.2. Targetted Lyα survey

The initial wide-field survey will do little more than identify tentative sources for closer study. At this point, we target specific sources for further study with a high resolution imager and adaptive optics. The initial survey will need to target fields in the vicinity of IR-bright stars which can be utilised for AO correction. A particular advantage of narrowband filters is that the AO correction is not hampered by atmospheric refraction which can spread point sources over tens of pixels within a broadband filter.

For a targetted study, we require only a single narrowband filter, and need only achieve 3σ per blob within the Lyα nebula to map the distribution of ionized gas. But Fig. 3 shows that the total exposure times per source are 100 ksec. At R = 1000, there appear to be a dozen useful windows within the J-band. However, in our design study for DAZLE (Cianci 2003), we find that only 3–4 windows are practical. For a filter placed at the pupil, there is a slight phase effect over the field such that the passband at the filter edge is bluer than at the centre of the field. For a filter placed in the converging beam, the passband is broadened slightly.

Another concern is the difficulty of manufacturing a 0.1λ narrowband filter centred at the prescribed wavelength. Given the restricted tuning capability of an interference filter, and its degraded performance on tilting, it is tempting to consider a tunable filter for Lyα imaging. However, the upper envelope of the filled region in Fig. 3 shows the expected poor performance of a filter profile with Lorentzian wings.

The above considerations require that we accept a window which is actually twice as broad as the design bandwidth. In Fig. 3, we note that there is only a handful of good windows available at R = 500. In terms of photometric stability, the windows near 1.06µm, 1.19µm and 1.26µm are the most ideal. The window at 1.12µm suffers from variable and complex atmospheric absorption. The relevant cosmological parameters for these four windows are given in Table 1.

The 1.12µm window could be recovered if two IR arrays were placed side by side in the image plane, and these devices were moved back and forth every few mins, in synchrony with nodding by the telescope, such that we build up two separate fields of view. This mechanical form of ‘nod & shuffle’ (cf. Glazebrook & Bland-Hawthorn 2001) would average out atmospheric effects, and at the same time minimize the read noise penalty, although it incurs a √2 penalty from dark current noise.

If systems can be controlled, the total long exposure times of 30 hr per field are not unreasonable. If there are weak OH features in the dark windows, these are likely to be variable and may define the systematic noise limit. Note that if pixel stability dominates the noise limit, a Dark Age experiment cannot be carried out since this leads to short exposures (Fowler-8 sampling) and results in a huge read noise penalty. However, D. B. Hall (2003, personal communication) has found that the HAWII-2RG arrays have comparable stability to some of the best optical detectors.

5. THE IMPORTANCE OF DARK CURRENT

We now show that the IR arrays specified in Table 2 are ideally suited to the proposed experiments. If the J-band windows are truly dark, the read + dark noise contribution defines the limiting sensitivity we can reach. This is illustrated in Fig. 4 which shows the total exposure time required in the 1.06µm window to achieve SNR = 3 on a Lyα blob with a total flux of 3 × 10^20 erg cm^−2 s^−1. Here we assume a filter with R = 1000 and m = 3. This calculation is specific to GSAOI: the pixels are 0.02” and the read noise is 5 e−. At the top of the figure, the blobs are spread over many pixels which greatly increases the effective background from dark current.

The results are only weakly sensitive to the number of separate exposures since the dark current noise dominates for exposures longer than about 500 sec. Note in particular how the uncertainty in the dark sky continuum leads to some uncertainty in the detectability of Lyα blobs. For CSR source sizes of 0.2”, the existing HAWII-2 arrays are well suited to wide-field Lyα surveys of this kind.

The implication here is that the pixel size must be well matched to the expected size of the Lyα emitting regions. If the pixels are much larger than the emitting blobs, night-glow...
CONCLUDING REMARKS

It is clear that something quite extraordinary took place over a time span of a few hundred million years which led to the complete ionization of the intergalactic medium. The epoch of (re)ionization is likely to attract a great deal of attention over the coming decade.

We have shown that detecting sources beyond \( z = 7 \) is going to be very challenging on 8 – 10m telescopes. But since 30 – 100m telescopes will not be in operation until the next decade, narrowband imaging is likely to dominate studies of the Dark Ages for years to come. We have outlined a strategy based on wide-field surveys to identify star formation in massive haloes, followed by detailed studies with an adaptive optics imager. The optimal technologies for both kinds of study will be available in the next few years.

It is often observed that major discoveries are made within five years of a new technology (e.g., Harwit 1981). What is less well known is that this statement normally applies to experiments which achieve the systematic noise limit of the apparatus. Glazebrook & Bland-Hawthorn (2001) argue that the systematic limit possible with nod & shuffle spectroscopic observations argues for total integration times measured in months or even years. Since large telescopes are general user facilities, it is relatively rare that hundreds of hours are devoted to a single target field. But in order to reach back to the Dark Ages, observing programmes of one or two weeks at a time will be essential.

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