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A Next Generation Deep 2-μm Survey: Reconnoitering the Dark Ages

Jeremy Mould[A,B]

[A] Swinburne University, Hawthorn Vic 3122, Australia. Email: jmould@swin.edu.au
[B] ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)

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Abstract: The next generation 2-μm sky survey should target nascent galaxies in the epoch of reionization for spectroscopic followup on large telescopes. A 2.5-m telescope at a site on the Antarctic plateau has advantages for this purpose and for southern hemisphere infrared surveys in general.

Keywords: infrared: general — galaxies: high redshift — telescopes

1 Introduction

Until around 400 million years after the Big Bang, the Universe was a very dark place. There were no stars, and there were no galaxies. Scientists would like to unravel the story of exactly what happened after the Big Bang. The Pathfinder for an International Large Optical Telescope (PILOT) survey telescope and the James Webb Space Telescope (JWST) could pierce this veil of mystery and reveal the story of the formation of the first stars and galaxies in the Universe. Among other things, the next generation infrared sky survey should target spectra and images of the first galaxies. The JWST, Giant Megellan Telescope (GMT), Thirty Meter Telescope (TMT) and European Extremely Large Telescope (E-ELT) need a source list. This can be provided by the PILOT survey telescope (Lawrence et al. 2009).

An important, current infrared sky survey is the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007). That survey has covered 7500 deg^2 of the Northern sky, extending over both high and low Galactic latitudes, in *JHK* to $K = 18.3$. It reached three magnitudes deeper than the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). UKIDSS provides a panoramic atlas of the Galactic plane and is composed of five surveys. There are two deep, extra-Galactic elements, one covering 35 deg^2 to $K = 21$, and the other reaching $K = 23$ over 0.77 deg^2.

The current state-of-the-art survey is the VISTA Kilo-degree Infrared Galaxy (VIKING) survey (Sutherland 2008). The VIKING survey will image the same 1500 deg^2 of the sky in Z, Y, J, H, and K_s to a limiting magnitude 1.4 mag deeper than the UKIDSS Large Area Survey. It will provide very accurate photometric redshifts, especially at $z > 1$, an important step in weak lensing analysis and observation of baryon acoustic oscillations. Other scientific drivers include the hunt for high-redshift quasars, galaxy clusters, and the study of galaxy stellar masses.

The capacity of PILOT to go 2–3 mag beyond VISTA is considered in this paper, which concentrates on high-redshift galaxies. A full case would have a broader scientific focus. Testing an AST3 (Antarctic Schmidt Telescopes, a trio of 50-cm optical telescopes) prototype (Zhao et al. 2010) for a survey class telescope has commenced.

2 A PILOT Survey

A design study of an infrared 2-m class telescope on the Antarctic plateau was carried out by Saunders et al. (2008). Further details are provided by Lawrence et al. (2002a) and on the PILOT website,[1] including the particular challenges of boundary layer turbulence and water condensation. Other concepts have also been discussed, for example, the Kunlun Dark Universe Telecope (KDUST)[2] and see Ichikawa (2010).

Features of the PILOT design (Saunders et al. 2008) are: an Offner relay reflective cold stop design (diffraction limited); on chip guiding; to beat read noise down by non-destructive reads; and 8K × 8K arrays giving a field $16' \times 16'$ at 0.125 arcsec per pixel. The background at K is assumed to be 1 mJy arcsec^{-2}, that is 14.54 mag. The 0.2 arcsec aperture background would be $K = 14.54 - 2.5\log(\pi 0.01) = 20.8$ mag. With a Near Infrared Camera and Multi-Object Spectrometer (NIC — MOS) sensitivity detector for $H = 25$, the signal to noise ratio (SNR) = 0.5 in 900 s with the background adjusted for aperture. To reach SNR = 2 requires 16 times longer, that is 4 h.

The PLT is a European Polar Large Telescope and a 2-μm survey would be an interesting basis for a European-led collaboration. Their design incorporates a 40′ field. Equally, the proposed Japanese Dome F 2-m infrared telescope or the planned Chinese Dome A 2.5-m infrared telescope would be a fine choice for a survey. The Australian peer review of PILOT advised that the

[1] http://www.aao.gov.au/pilot/pilot_status.htm
[2] http://www.kdust.org

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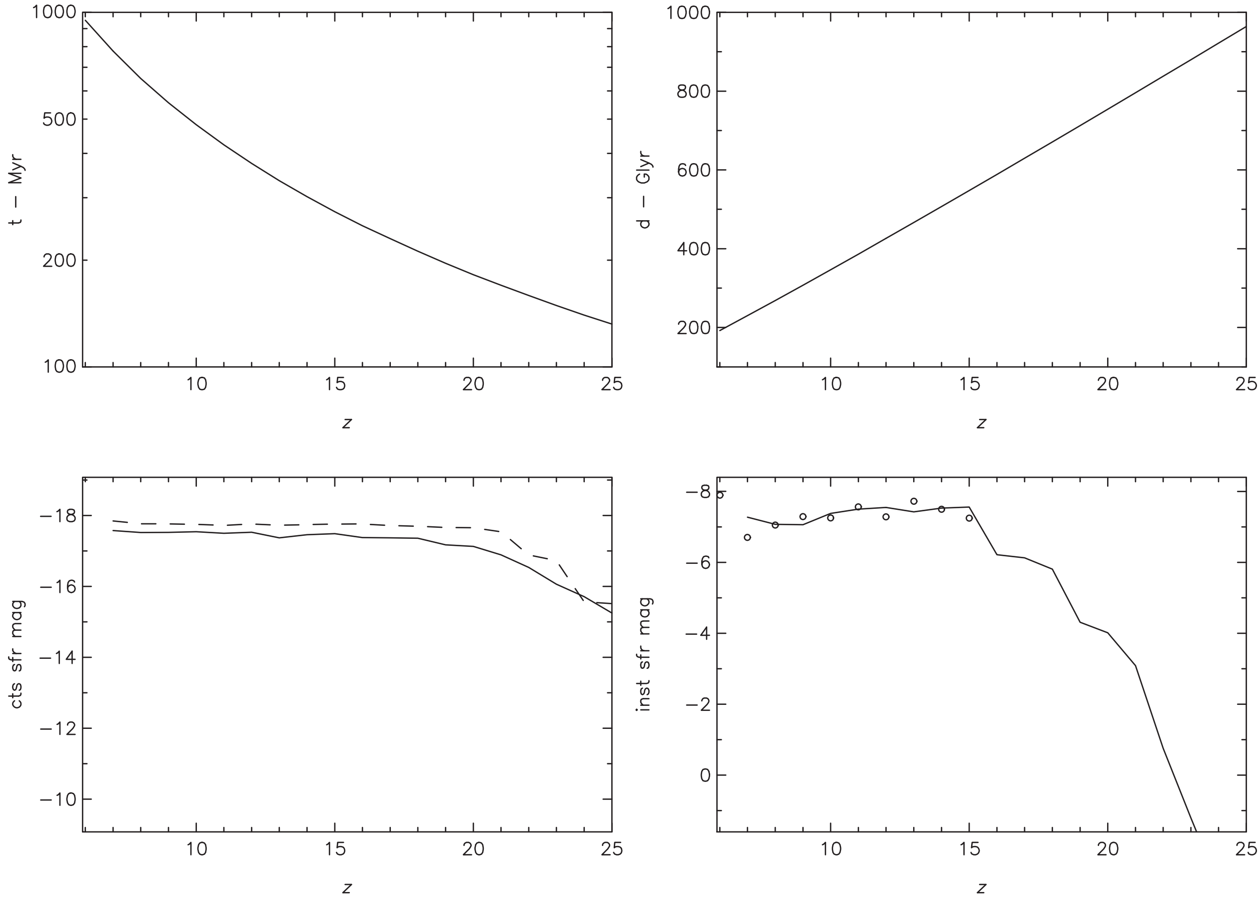

Figure 1 The 2-μm window is sensitive to epoch of reionization objects from as far as redshift 25. Time since the Big Bang and luminosity distance in billions of light years are shown in the upper two panels. The remarkably small bar at $z = 23$, d = 200 Gyrs in the upper right panel is a Hubble radius. The lower panels show the *K* band evolution of continuous star formation stellar populations (left) and single burst stellar populations (right). The instant of star formation in the latter case was assumed to be the epoch of recombination. The dashed line in the left panel is the result for metallicity one twentieth solar. The open circles in the right panel are the result of direct look up of the Leitherer et al. (1999) Starburst99 table. The solid line results from interpolation in the table in age and integration over the *K* bandpass.

project should be further studied but await international collaboration.[3] This now appears possible.

3 Science Goals

Although there are many scientific goals for a survey that is deeper than any previous survey — for example, the lowest mass stars and star formation regions in our galaxy (see also the ARENA (Burton et al. 2010) and Dome F proposals) — one of the most exciting is finding galaxies at redshifts greater than 10 from the *H* dropout method. This technique measures redshift by means of the Lyman break in the spectral energy distribution of stellar populations. These have no flux at 1.6 μm, but are detected at 2.2 μm. The redshift of these is $1.6/0.09 - 1 = 17$. Spectra of these objects would be obtained with JWST or a ground-based extremely large telescope.

In this context, the Antarctic advantages are almost diffraction-limited images over a wide field, and low 2-μm background. Lascaux et al. (2011) show median free atmosphere seeing of 0.23, 0.30 and 0.36 arcsec for Dome A, Dome C, and the South Pole, respectively. This combination is only available from the Antarctic plateau, high altitude balloons, and space. The best sites at temperate latitudes typically offer 0.8 arcsec seeing.[4]

The competition with PILOT is a space-based survey, in particular, the Wide-Field Infrared Survey Telescope (WFIRST; Levi et al. 2011). WFIRST is focussed on exoplanets and dark energy. The advantages of WFIRST are that it was top ranked in ASTRO 2010;[5] it could deploy a broad *K* filter; and there are no clouds. The disadvantages of WFIRST are that it has a smaller aperture (1.5 m) and therefore a somewhat lower resolution; there is only a 3-yr mission lifetime; and a proposed 2020 launch. Furthermore, the cost would be an order of

[3] http://astronomyaustralia.org.au/publications/ANSOC_Report.pdf

[4] http://www.gemini.edu/sciops/statistics#weatherloss

[5] http://sites.nationalacademies.org/bpa/BPA_049810

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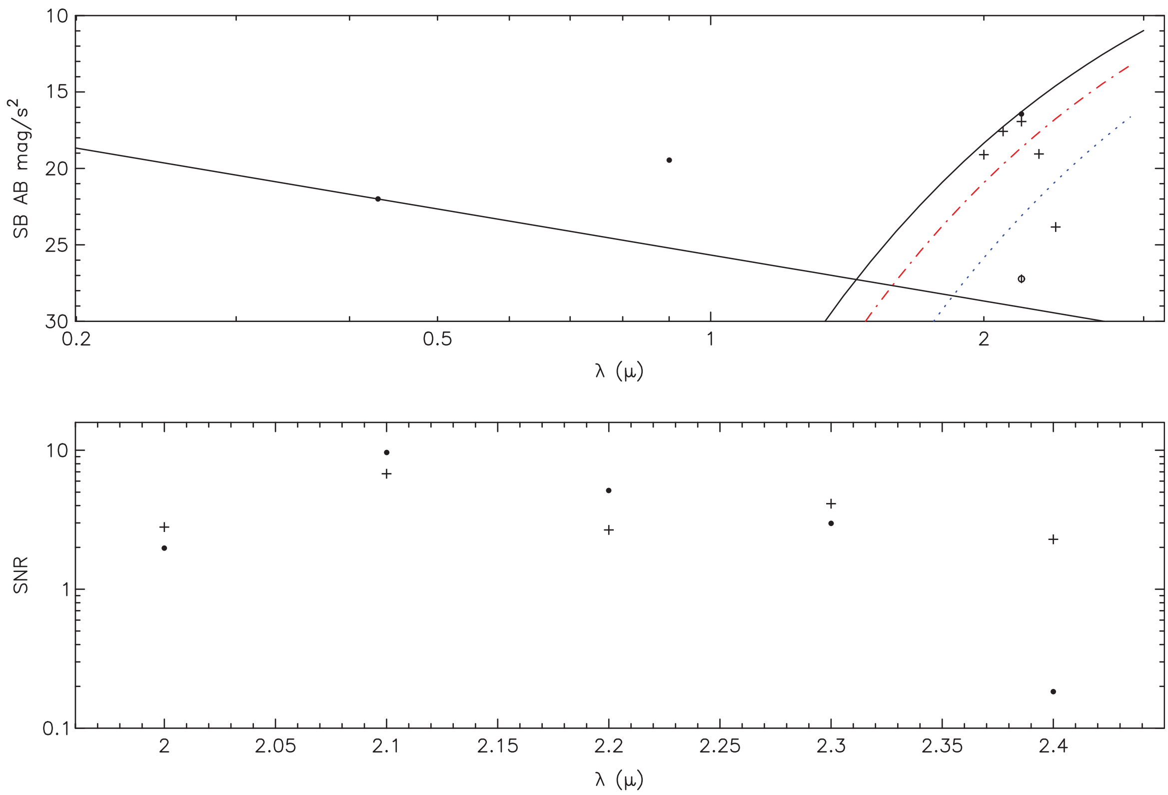

Figure 2 The surface brightness of optical and near infrared photometric backgrounds is displayed in the upper plot. In the optical the Rayleigh scattering wavelength dependence is normalized to B = 22 mag arcsec^{-2}. In the infrared the solid curve is a 300 K blackbody with emissivity 3.8%. The solid symbol at 2.2 μm is 1 mJy arcsec^{-2}. The red (dot-dashed) curve is for 0°C and the blue (dotted) curve for −40°C. The measured *K* band cosmic background is shown as an open symbol with error bars (Wright 2001). In the lower plot the signal to noise ratio for a flat spectrum source observed at −60°C is plotted versus wavelength. Emissivity and transmission assumptions are described in the text. An *I* band background of 19 mag arcsec^{-2} is also shown; at this wavelength OH emission is dominant. Plus signs (+) show a recalculation using the OH intensity from Figure 3 normalized to a wavelength of 2 μm.

magnitude higher than PILOT. The goal is a 200 nJy limit *vs* 70 nJy with PILOT.

The Subaru Deep Field project (Ota et al. 2010) has found of order two Lyα emitters per square degree at $z = 7$. With a similar $\lambda/\delta\lambda = 50$ narrowband filter at *K* dark (Lawrence et al. 2002), PILOT could conduct a similar search at $z = 18$. The constraint on the star formation rate at that epoch is direct, but beyond the scope of the present paper on broadband surveys.

At $z = 8$, the Local Group would occupy some 3′ (Wright 2006). If M31 is −20.3 mag in the blue and it had a 20 times brighter stellar population at age 0.65 Gyr, it would show up at $AB_K \approx 26$, and $K \approx 24$ mag, a solid detection in the proposed survey.

4 The Dark Ages at 2 μm

At 2 μm, the dark ages extend from $z = 6$, when reionization is fairly complete, to $z = 2.4/0.09 - 1 = 25$, when the Lyman limit transits the long wavelength end of the window. The Wilkinson Microwave Anisotropy Probe (WMAP) has characterized this interval as a time of strong, but anisotropic, star formation. Figure 1 shows the duration of this period in time since the Big Bang and the luminosity distance of sources at those redshifts. These immense distances are a great challenge, but at least they protect observers from source confusion. The lower panels show the *K* band evolution of stellar populations with instantaneous and continuous star formation. The single burst simple stellar population is timed to go off at recombination. It ages and the Lyman jump passes through the bandpass at high redshift, showing strong magnitude evolution for this reason. These models were constructed from Starburst99 data (Leitherer et al. 1999) with the Salpeter initial mass function (IMF) and solar composition, and with stellar emission only. The continuous star formation model shows weak evolution, as we are seeing the emission from young stars which are continuously being replenished.

5 Survey Bandpass

As shown in Figure 2, the background varies rapidly across the 2-μm window. The calculation assumes 3.8% mirror emissivity, ε_M, which has been obtained on Gemini South, and zero atmospheric emissivity, ε_λ. Ashley et al. (1999) measured the background at an Antarctic site. Understanding their results requires a detailed model of ε_λ and the atmospheric transmission, T(λ), which equals $1 - \varepsilon_\lambda$ according to Kirchoff's Law. Water vapour

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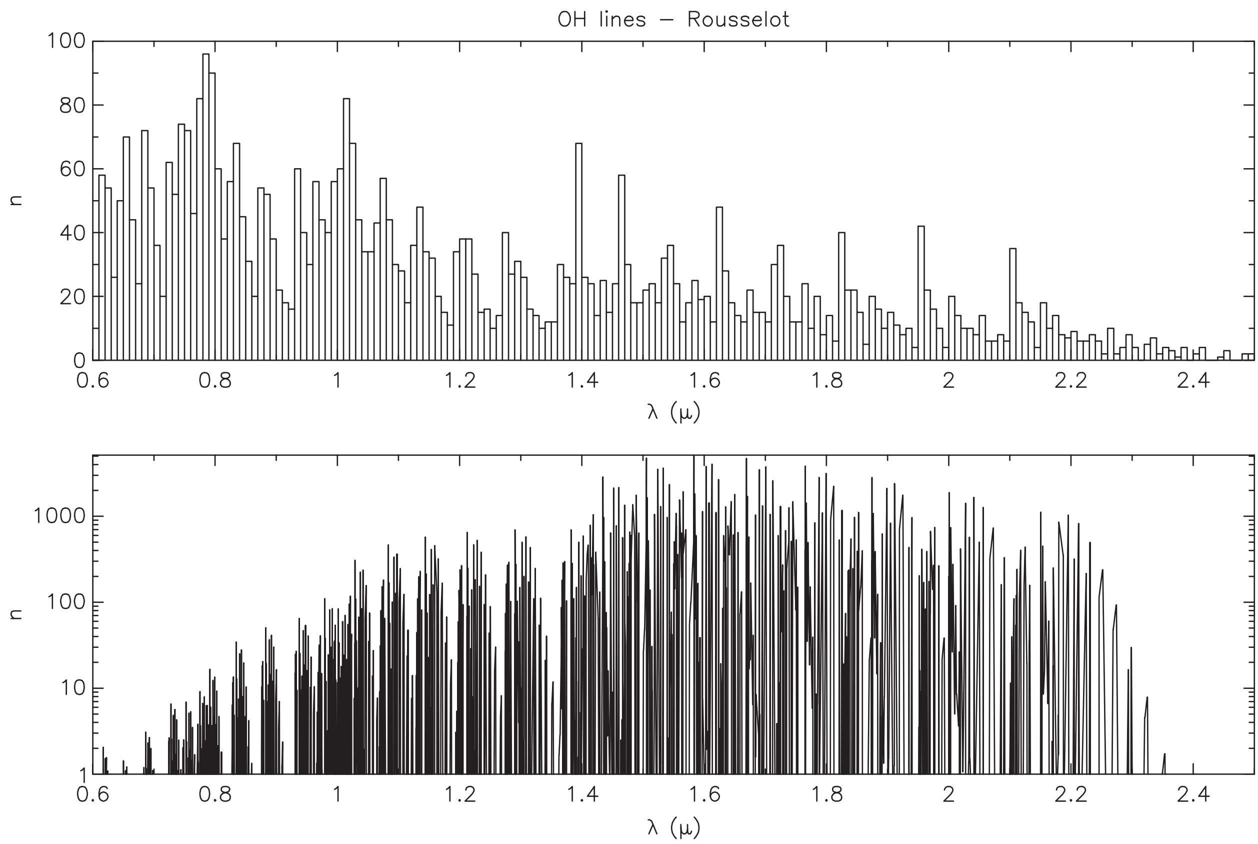

Figure 3 The upper plot shows the number density of OH lines from Rousselot et al. (2000). The lower plot shows the intensity.

opacity, dominating the short wavelength side of the window is the key component. It is interesting to examine how SNR varies with wavelength across the window for a flat spectrum (per unit wavelength) source: $\mathrm{SNR}(\lambda) \propto w(\lambda)/\sqrt{W(\lambda)}$, where w is a window function and W is the Wien function for blackbody radiation. It is easy to show that $\mathrm{d}\log W/\mathrm{d}\log\lambda = \mathrm{h}\nu/\mathrm{kT} - 5$, where the quantities h, v, k, T are Plannck's constant, frequency, Boltzmann's constant and temperature respectively. The window function is given by $w = (1 - \varepsilon(\lambda))/\sqrt{(\varepsilon(\lambda) + \varepsilon_M)}$. The value of w is 5 when $\varepsilon = 0$, and the 10% power points of w (assumed here to be at 2.0 and 2.4 μm) occur when $\varepsilon(\lambda) = 0.5$. At other wavelengths Tr = 1. This is the basis of the SNR calculation in presented in Figure 2.

Figure 2 suggests no clear basis for adopting a non-standard K filter. All wavelengths contribute to the overall SNR more or less equally. The observations of Ashley et al. (1999) show a 2-μm background that falls from 2.3 to 2.4 μm. A more precise calculation would require atmospheric opacity modelling and inclusion of the OH emission background. A partial mapping of that background is provided in Figure 3. Matsumoto, Matsuura, & Noda (1994) find balloon based K sky brightness of 130 μJy arcsec^{-2}.

6 Survey logistics

If one implemented a 20′ field, the survey rate with PILOT is 26 yr sr^{-1}, assuming an unrealistic 180×24 clear hours per year. However, Lawrence et al. (2002b) find a K background of 210 ± 80 μJy arcsec^{-2}. If this were adopted, the survey time would drop by a factor of 0.21^2 to a little over 1 yr sr^{-1}. Sky background is a major uncertainty. This necessitates further study both observationally and by simulation. The PLT design offers 40′ and therefore 6 yr sr^{-1}. A full survey would produce ~100 Pb of data to do 2π sr. This is not a serious problem according to Moore's Law. Raw data would be back-loading for the observatory fuel supply. Supernova monitoring would require computation and communication of a catalog in real time.

The focal plane for the PILOT telescope is ambitious and would be a good basis for international collaboration. Optical alignment of 2-m wide field telescopes has proved challenging (e.g. Kaiser et al. 2010) and these lessons can be taken on board through collaboration.

PILOT would not be obsolete until a proposed KDUST 8-m telescope became operational. That would reach $AB_K = 29$ mag.

7 Conclusions

Important targets at high redshift await the next generation 2-μm survey. These include galaxies with 10^8 year-old stellar populations at redshift 6, pair production supernovae from massive stars at $\mathrm{M}_K = -23$, activity from the progenitors of supermassive black holes, and young globular clusters with million year free fall times and mass to light ratios approaching 10^{-4}. These are some

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of the inhabitants of the epoch of reionization that will surprise us when we know where to point our spectrographs. There is time to test the AST3 prototype (Zhao et al. 2010) and build this telescope, before narrow field adaptive optics corrected instruments such as GMTIFS[6] (GMT Integral Field Spectrograph. GMT is the Giant Magellan Telescope) start to clamour for high-redshift targets.

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[6] http://www.mso.anu.edu.au/gmtifs/infoday/docs/gmtifs_overview.pdf
[7] http://mcba11.phys.unsw.edu.au/~plato
[8] www.caastro.org