Deep Near-Infrared Surveys — Understanding Galaxy Evolution at \( z > 1 \)

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Abstract

Deep near-infrared (NIR) surveys are critical to our current, and even more to our future, understanding of galaxy evolution in the early universe. In this review I will be discussing the relevance of deep NIR surveys and looking at the information provided by different types of survey: broad-band imaging, spectroscopic observations and narrow-band imaging. In particular I will be looking at the future possibilities for faint galaxy work provided by forthcoming, innovative, NIR instrumentation being developed for the next generation of 8 m telescopes.

1 Why The Near-Infrared?

The initial interest in the NIR for studies of galaxy evolution came from the realisation that at low redshift \((z < 1)\) the NIR K-corrections for different morphological classes of galaxy are very similar (Figure 1). Thus by selecting in the NIR the morphological mix of the sample, \textit{i.e.} the ratio of galaxies with young and old stellar populations, would be insensitive to redshift if there was no evolution. Thus any evolutionary signature would be more clearly seen.

This led to many early NIR surveys at relatively bright magnitudes (e.g. [13],[15]) which confirmed a general picture of very little evolution in early-type galaxies along with a general increase in the space density of star-forming systems at low redshift. Such surveys are reviewed elsewhere in these Proceedings [14].

Here we will consider deeper surveys, with IR magnitudes typically \( K > 19–20 \) in which a significant number of galaxies lie beyond a redshift of unity. At these redshifts the prominent optical emission and absorption spectra features are shifted into the NIR. For example the [OII] and Ca H and K lines are in the \textit{J}-band for \( z > 1.6 \) and for \( z > 2 \) the \textit{H}\textalpha{} line lies in the \( K \)-band. This has so far provided a natural limit for redshift surveys in the optical, the deepest
Figure 1: K-corrections in ultraviolet through optical to NIR broad-bands for galaxies with elliptical (old stellar populations) to Sc (star-forming populations) spectral energy distributions (SEDs). It can be seen that in the $K$-band the band-shifting effect is very similar for the different SEDs. In contrast in the $U$-band elliptical SEDs are dimmed by many magnitudes relative to later types even at moderate redshifts.

extending to $z = 1.5$ [6]. For $z = 1–4$ the K-corrections will no longer be as uniform as in the brighter surveys (see Figure 1) but there is still less variation than in optical and UV bands. Also the galaxies selected in deep NIR surveys are being observed in rest-frame optical light, thus their NIR properties can be compared with the well-studied optical properties of local galaxies. Thus evolutionary signatures of rest-frame optical parameters (colours, luminosities, line strengths) etc. can be determined in a fairly model-free manner.

The problem of course with studying very faint sources in the NIR is increased brightness of the night sky. This is mainly due to the emission of very many narrow OH lines (Figure 2). The key concept behind the next generation of NIR instruments is to filter out these lines and reduce this background.

2 Imaging Surveys

Most activity in deep NIR cosmological work has concentrated on the deep $K$-band counts [8][23]. Much has been made of their significance — in particular the turnover (or lack thereof) in the faint end and it’s implications for the cosmological geometry. This has been because the $K$-band counts have been found to lie closer to the prediction of a Robertson-Walker metric than in any other band (optical/Far IR/radio) and $K$-band counts are ‘insensitive to evolution.’

We must bear in mind though that beyond $K \sim 19$ the galaxies are at high-redshift and being observed in rest-frame optical and the evolutionary effects of stellar populations are not necessarily negligible. Moreover these effects tend to be of $O(z)$ due to their time dependence and so will always win out over cosmological effects of order $O(z^2)$. Also any evolution in the space density of galaxies (after all galaxies must form at some redshift) will affect the
Figure 2: Night sky spectrum in $J$ and $H$-bands. 95% of the background comes from narrow OH emission lines.

faint end $K$-band counts. Perhaps more useful than the broad-brush of total counts are the morphologically resolved counts that have been done with the Hubble Space Telescope [1],[9],[16]. These show a picture of evolution where ellipticals evolve slowly (though there is an evolving population of blue compact galaxies [26], [17]), spiral galaxies show a more rapid evolution (with significant changes in morphological appearance [30]) and there is dramatic evolution in populations of morphologically irregular and peculiar galaxies, including mergers (Figure 3). It should be noted that differential evolution is found in the deep surveys independently of the known uncertainties in the local luminosity function (for a discussion thereof see [14]).

It is clear that the next step is to combine high-resolution with multi-colour photometry to allow the study of the evolution of stellar populations within galaxies. This will allow us to answer questions such as the epochs of bulge and disk formation, where the star-formation takes place in different parts of galaxies as a function of epoch, etc. An early example is the pioneering work of Abraham et al (Figure 4) using optical colours from the Hubble Deep Field (HDF).

It is highly desirable to be able to extend such work in the NIR both because of the extended colour baseline to enable accurate determination of stellar populations and to track the rest-frame galaxy properties to high-redshifts. The ideal instrument for such investigations would be a multi-band camera on a 8 m telescope equipped with Adaptive Optical (AO) correction to deliver high-resolution. A wide field is not needed due to the high surface-density of $z > 1$ galaxies, in fact with many detectors it would be better to splice in colour (i.e. using dichroics to cover many bands simultaneously) than to cover a large area as AO correction is limited by the size of the isoplanatic patch.

Using such a camera in the UV–NIR many ‘super-HDFs’ could be observed and this ‘morphophotometric’ work extended to $z \sim 4$. A related technology being developed at the AAO [25] is the concept of Rugate filters (Figure 5) to allow broad-band observations in the NIR while still filtering out night sky OH light. The Rugate transmission functions are multiply peaked and can be tuned to allow light through only in OH-free regions. This is achieved by stacking many hundreds of layers of different refractive indices and thickness, the mathematical problem of ideal design, subject to constraints of cost, has been solved at AAO and enable $S/N$ gain factors of $\sim 2$ to be realised. This noise-reduction technique will allow us to go deeper at a fraction of the cost of building a new telescope with a larger aperture.
3 Spectroscopic Surveys

While the signatures of evolution are clear enough in the deep imaging surveys the determination of the type of evolution, i.e. whether it is in luminosity of space density or something more complicated, requires redshift information in order to construct luminosity functions. Redshifts are most reliably obtained by spectroscopy — determination by non-spectroscopic methods is subject to great uncertainty. For example see Figure 6 which shows two independent estimates of photometric redshifts for faint galaxies in the HDF in comparison with subsequent spectroscopy.

Spectroscopic surveys in the optical have determined luminosity function evolution out to $z = 1$ (Figure 6) — to go beyond and probe the $z = 1–4$ regime we need to do multi-object NIR spectroscopy as the key spectroscopic features are redshifted in to the $J$-band.

Background suppression is even more critical for dispersed light and two principal techniques have been proposed to go deep in the NIR:

1. **OH Suppression.** Light can be dispersed in a spectrograph at high resolution ($R = \lambda/\Delta\lambda \simeq 4000$), filtered through a mask which is ruled to block light at the position
Figure 4: Morphologically resolved spectrophotometry from Abraham et al (work in progress). This is just one galaxy (at $z = 0.79$) from a sample of dozens in the Hubble Deep Field and morphologically appears ‘proto-spiral.’ Selected morphological regions of the galaxy ($A$, $B$ and $C$) are segmented from the image and their pixels plotted in $U - B$, $B - V$ and $V - I$. The thin and thick lines show the tracks of single-epoch burst and continuous star-forming stellar populations from [4] of 40% solar metallicity and with ages at various points indicated. The arrows, at the bottom right, indicate SMC and Milky Way reddening laws for $A_B = 0.4$ mag. It can be seen that to first order the colours lie along a sequence of progressively older stellar populations, a very encouraging agreement with the model colours. By isolating the populations morphologically the colours show less dispersion than do global colours of unresolved objects. It can also be seen that the ‘proto-bulge’ ($B$) is the reddest component and the $B - V$ colours clearly indicate that the star-formation has truncated. The ‘proto-arm’ components ($A$ and $C$) have bluer and younger colours, the offset in $U - B$ and less so in $B - V$ indicating these regions are dustier. Even with just optical $UBVI$ imaging it is possible to constrain the ages of morphologically resolved stellar populations while allowing for dust and metallicity uncertainties. Resolved deep NIR imaging has enormous potential for improving upon this type of analysis and will allow this ‘morphophotometric’ work to be highly constrained at $z > 1$. 
of OH lines in the spectrum, and undispersed (generally by reflecting back through the same optical path) to form an image of the slit. This image can be then be detected (giving a very narrow background suppressed image) or sent on through a conventional low-resolution \((R \sim 500)\) IR spectrograph to give an OH-suppressed spectrum. Such instruments are being built by several groups (e.g. Scaramella, these proceedings). One disadvantage is that the extra optics can reduce the throughput by a factor of two reducing the \(S/N\) gain to only 2-3. Some sort of multi-object arrangement can be had by use of fibres.

2. **OH Avoidance.** The idea here is simply to build a high-resolution \(R = 4000\) spectrograph and ignore the \(\sim 10\%\) of the pixels contaminated by OH lines. The problem is the necessity of a large detector area to get good wavelength coverage for redshift determination. For example three 1024\(^2\) NIR detectors would be required to cover the \(J + H\) bands at this resolution. Some designs introduce cross-dispersing echelle type elements to reformat for one detector, although again this introduces extra optics. It is extremely important to control scattered light — if it is not reduced below the 1\% level the supposed gain is lost. This is by no means trivial to design for. Proposed designs include CIRPASS (Parry *et al* in Cambridge) which will have 30 Integral-Field fibre units positionable over a 10 arcmin field of view and the 400 fibre multiobject AUSTRALIS design by Taylor (AAO) and Colless (MSSSO) to operate on the ESO VLT.

With such instruments coming online in the next 3–4 years we can foresee measurement of the galaxy luminosity function out to redshifts \(z = 1–4\). It is also possible to use current NIR spectrographs — for example [18] has been using CGS4 on the UKIRT to measure \(H\alpha\) in galaxies at \(z \sim 1\). By observing sources with *known* redshift, it is possible to choose them so \(H\alpha\) avoids the OH lines, and the limited wavelength range at high-resolution is not as important.

Many of the proposed instruments feature Integral-Field Units, which opens the possibility of resolved spectroscopy of \(z = 1–4\) galaxies and the prospect of more detailed mapping of stellar populations, than is possible with just broad-band colours, as well as measuring quantities such as Tully-Fisher and \(D_n - \sigma\).

4 **Narrow-Band Imaging**

Rotation of the problem space by 90° leads us from 3D spectroscopy to narrow-band imaging. There have been many surveys looking for emission line galaxies at high-redshift, using fixed
Figure 6: Left: Comparison of photometric and spectroscopic redshifts in the HDF [7], [19], [24]. Photometric redshifts exhibit a broad scatter, especially for blue galaxies where the flat SED can fit a wide range of redshifts.

Right: The luminosity function evolution to $z = 1$ determined from the AFRS [10] and CFRS [20] redshift surveys. The primary evolutionary effect is in the space density of galaxies at $M_B \sim -20$.

narrow-band filters, in both the optical (e.g. [5]) and recently in the NIR (e.g. [29]) which have found extreme objects but are not sensitive enough to reveal normal star-forming populations at $z > 1$.

At AAO we have a developed a new approach to narrow-band imaging using the Taurus Tunable Filter [2]. The goal is to provide a narrower filter which is better matched to the typical emission-line widths of galaxies ($R \sim 1000$) than are fixed glass interference filters ($R \sim 100$). This gives the maximum $S/N$ contrast against sky in the line. Moreover the wavelength and resolution of the TTF is adjustable and can be scanned over the range. This has been accomplished using a Fabry-Perot type technology — the key developments are:

1. Being able to reduce the plate gap down to 2–15 $\mu$m compared to 100–200 $\mu$m in a conventional Fabry-Perot. The latter gives resolutions of $R \sim 10,000$ which is too high to match galaxy lines.

2. Large scan range — TTF works from $R=100–1000$ so all uses of conventional narrow band filters are superseded.

3. Improved Anti-Reflection coatings which enable the TTF to be used over a wide bandpass.

The current TTF is optimised for use from 6000-10,000 $\AA$. A blue TTF which will be optimised for work from 3500–6000 $\AA$ is on order and will be available at the AAT in 1998.

The TTF is being used for numerous projects, one that is interest here is the TTF survey for $z > 1$ emission line galaxies in the Hubble Deep Field by myself, working with Abraham and Bland-Hawthorn. Estimates of star-formation rates (SFR) at low redshift and high redshift indicate [22] that the SFR of the universe may peak at $z = 1.5$ (Figure 7) and this agrees with semi-empirical models [11]. Our survey is designed to test these this idea. The key parameters of the survey are:
Figure 7: Star-formation density limits from the compilation of [22]. The points are: triangles — local Hα survey [12], filled dots — the CFRS survey [21], diagonal cross — lower limits from Lyman limit galaxies observed by [28], filled squares — from HDF [22]. The dashed line shows the average rate required to produce the current abundance of metals for $\Omega = 1$ and $H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$.

Note: This diagram should be treated with caution, there are many uncertainties to do with differing methods of measuring SFR, large luminosity function corrections, etc. In this author’s opinion it should be regarded as a ‘first draft’ of the history of SFR in the universe. Independent measurements from diverse techniques based upon larger surveys will add considerably to this picture in the next few years.

1. We scan for [OII] emission over $0.9 < z < 1.5$ in 3 OH-line free regions of the $I$-band: I1: $z = 0.894–0.908$ (0.2 hr/slice), I5: $z = 1.173–1.191$ (1 hr/slice) and I8: $z = 1.426–1.448$, (1.5 hr/slice) for a total of 26 hours exposure. The exposure times were chosen so as to go down to approximately similar line luminosities in the different bands. We covered an area of sky of 24 arcmin$^2$, which is a superset of the entire HDF.

2. The survey was done using the TAURUS system on the William Herschel 4 m Telescope in La Palma, the HDF being a bit too far north for the AAT! We had 4 clear nights in March 1997, with an average of 0.7 arcsec seeing.

3. We aim to establish number counts, of limits thereof, of emission line sources over $0.9 < z < 1.5$. Redshifts we derive from our emission line sources will be fed back into our morphological studies [1].

Some sample data is shown in Figure 8. We are still working on a careful analysis of our March dataset but we believe that tunable filter narrow-band searches will be a productive new technique for finding emission line sources at high-redshift. By careful choice of wavelength the method of OH avoidance is easy to practise, we are working on the design of a NIR TTF device which will be the first to tackle the problem of tunable imaging over a large field (e.g. 0.5 degree on a 8 m at $f/2$ prime focus). Curvature of the plate surfaces can be used to combat phase and non-telecentricity effects and achieve close to the ideal monochromator design. Such a device will allow us to extend such searches out into the $K$-band, and pick up important lines such as $H\alpha$ at $z = 2$ [3].
Figure 8: Deep narrow band images of the Hubble Deep Field (this section is 1.2 arcmin on the side) taken with the Taurus Tunable Filter on the WHT in March, 1997, as part of a search for [OII] emission over the z-range 0.9-1.4. The longer exposure of the 9040A slice allows for the lower CCD QE and cosmological dimming of [OII]. These images show about 1/200 of our data volume. We are currently engaged in searching for emission line sources in these sequences of images which should detect/constrain the SFR over $z = 0.9 - 1.4$.

5 Summary

It is clear that much progress has been made in the last few years in understanding galaxy evolution at $z < 1$, primarily driven by optical studies. We now desire to track this evolution into the $z = 1-4$ regime, where preliminary evidence is mounting that galaxies are living in ‘interesting times’ and to do this we must move our observational methods in to the near infrared. JHK imaging and spectroscopy accesses the rest-frame optical and allows a direct comparison between the local and the distant universe. The night sky brightness is a particular problem at these wavelengths, but a variety of innovative instrument concepts are being proposed to reduce this background, and should allow $z = 1-4$ galaxies to be accessed with the next generation of 8m telescopes.

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