Stellar Populations as Building Blocks of Galaxies
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Stellar populations – the next ten years

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Abstract. The study of stellar populations is a discipline that is highly dependent on both imaging and spectroscopy. I discuss techniques in different regimes of resolving power: broadband imaging (R∼4), intermediate band imaging (R∼16, 64), narrowband spectral imaging (R∼256, 1024, 4096). In recent years, we have seen major advances in broadband all-sky surveys that are set to continue across optical and IR bands, with the added benefit of the time domain, higher sensitivity, and improved photometric accuracy. Tunable filters and integral field spectrographs are poised to make further inroads into intermediate and narrowband imaging studies of stellar populations. Further advances will come from AO-assisted imaging and imaging spectroscopy, although photometric accuracy will be challenging. Integral field spectroscopy will continue to have a major impact on future stellar population studies, extending into the near infrared once the OH suppression problem is finally resolved. A sky rendered dark will allow a host of new ideas to be explored, and old ideas to be revisited.

1. Introduction

This conference has provided us with a timely reminder of why stellar population studies continue to generate great interest in our quest to understand stellar/galactic formation and evolution. In a recent summary, we reviewed the case for resolved stellar population studies (Bland-Hawthorn & Freeman 2006), and so refrain from repeating these arguments here; another perspective is offered by Wyse & Gilmore (2006). The importance of near field studies has been stressed most recently by Springel, Frenk & White (2006):

> At present, the strongest challenge to ΛCDM arises not from the large-scale structure, but from the small-scale structure within individual galaxies. It is a real possibility that the model could be falsified by measurements of the distribution and kinematics of matter within galaxies...

The detailed study of the stellar content of galaxies is well grounded in cosmology. The field exploits many observational techniques across almost the full electromagnetic spectrum. The observations are so rich in detail that they present both theorists and simulators with a strong challenge, i.e. to establish useful empirical models that provide a context for these data, and identify those observations that are of primary importance. It is no exaggeration to say that contemporary data far outstrip theory and simulation: our understanding of the observations is very rudimentary when we consider even simplified toy models (e.g. closed vs. open box), and especially so within the context of the ΛCDM paradigm.

But here I concentrate on the observational techniques and address in part how these are motivated by the scientific questions. Given that we are already overwhelmed by vast imaging data sets, is there a case for considering new approaches to data collection? In short, the answer must be yes. More sophisticated techniques can yield better data that in turn shed light on the existing data sets, and may even simplify the paradigm rather than complicate it further. It is often the case that more and better data can reveal weak effects that are of paramount importance to our basic understanding, a fact well understood by medical science and an issue that we return to below.

Much like mathematical physicists who utilize the properties of discrete or continuous functions, a stellar populations researcher has the option to study discrete (point source photometry) or continuous (diffuse light/surface photometry) data. Nowadays, this distinction is somewhat artificial in that both frequently arise in the same observations; often one is removed to get to the other, e.g. surface brightness fluctuations (SBF) and the removal of point sources. It is worth noting that studies of resolved stellar populations in excellent seeing are now achieving effective surface brightness levels that are well below those of surface photometry (Brown *et al.* 2003; Bland-Hawthorn *et al.* 2005, see Appendix).

Imaging techniques, in particular imaging spectroscopy, will continue to develop in the years ahead. The review focuses on resolved studies of galaxies, rather than multi-object astrometry and spectroscopy (R $>$ 5000) of Local Group galaxies that I will defer to a separate review. I start with a reminder of the power of imaging science (including imaging spectroscopy) before addressing how it is likely to evolve in the years ahead. I address new technologies and new concepts that may play an important role in future stellar population studies, before suggesting new avenues for future research.

2. Imaging science – what is it good for?

This meeting has provided an opportunity to review what are the essential characteristics of data that advance our understanding of stellar populations. A familiar proverb is that a picture is worth a thousand words. Our images captivate the imagination of the general public, and astronomers have exploited this to great effect in recent years, as witnessed by ongoing public support for the Hubble Space Telescope (HST). But astronomical machines are sold on the scientific return, and from these images we learn about stellar structures and morphologies, subcomponents (e.g. bulges), substructures (e.g. streams), small-scale vs. large-scale power, and asymmetries, gradients and profiles.

The emergence of imaging spectroscopy (IFU, tunable filter) is a result of the community wanting the photometric integrity of direct imaging, with the benefits of spectroscopic information across the field. Imaging spectroscopy provides significant advantages over conventional slit techniques, and are less prone to losses and artefacts due to seeing (Cecil 2006). We explore this topic in more detail below, and conclude that imaging spectroscopy will become more firmly entrenched in the next decade.

Since the 1960s, we have mastered the use of broadband images to obtain limited information on stellar temperatures, luminosity, surface gravity, mass, ages, dust content and star formation history (for a recent review, see Bessell 2005). What is generally true is that more spectral bands over a broader spectral baseline provide more information of the sources under study†. Thus, we make use of intermediate (e.g. Stromgren filters) and narrow spectral bands to provide more specific information, in particular, better spectral classification (e.g. Geneva-Copenhagen survey: Nordstrom *et al.* 2004) or galaxy typing (e.g. COMBO-17 survey: Wolf *et al.* 2003).

What is clear is the continued importance of the broadest possible spectral baseline in stellar population studies. The Balmer jump (u band) region provides temperatures of OB stars and surface gravities of cool stars, and metallicity information for stellar type F and later. In combination with the u band, a b or g filter provides metallicity information for stellar type A and later. Filter bands spaced further apart provide

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† This assertion can be difficult to argue if the sensitivities in the narrower bands lead to marginal detections, e.g. continuum sources vs. emission-line sources.

temperature information that is moderately independent of metallicity and gravity. Accurate K band stellar photometry, in combination with optical bands, can be used to unravel the age-metallicity degeneracy, and provide more precise corrections for stellar extinction.

3. Photometric precision

A central tenet of the applied sciences that simply measuring the same old quantities to increasing levels of precision will often yield fundamentally new physical insight†. A good discussion of what is required to achieve this in astronomical photometry is given by Stubbs & Tonry (2006). The power of photometric precision is well demonstrated by the Sloan Digital Sky Survey (Gunn *et al.* 2006) that achieved 5σ depths of $(u, g, r, i, z) =$ (22.0, 22.2, 22.2, 21.3, 20.5). The SDSS is comparable in depth and sampling to the all-sky surveys of the UK Schmidt (UKST) and Oschin Schmidt telescopes during the 1980s. However, the SDSS magnitude and colour precision is unrivalled at $(r, u-g, g-r, r-i, i-z) =$ (2%, 3%, 2%, 2%, 3%), a fact that has led to an extraordinary bounty of new results. A similar comparison can be made between the space-borne Galex UV (Martin *et al.* 2003) and the Ultraviolet Imaging Telescope surveys.

Arguably, precision photometry has provided the greatest impetus to the study of stellar populations in recent years. In resolved stellar imaging, examples include the use of non-parametric methods to derive believable star formation histories in nearby dwarf galaxies (Aparicio, this meeting) and in Local Group galaxies (Brown *et al.* 2006). In photometric imaging, some of the most impressive uses of precision photometry involve distance determinations for galaxies: e.g. cepheid distances (Freedman *et al.* 2001); surface brightness distances to galaxies (Tonry *et al.* 2001) and its close cousin, "tip of the red giant branch" distance estimates (Tully et al 2006). At much higher redshift, other uses include redshift determination through the photometric drop-out technique (Steidel *et al.* 1996). All of these techniques exploit known properties of the stellar populations.

If our goal is to learn more about a source by dividing up the spectral domain into more bands, this requires a higher level of photometric precision within and between the bands. This is because the errors combine in quadrature and quickly propagate through the analysis when one wants to compare complex intercombinations of photometric colours.

Pushing to even higher levels of precision, there is a strong case to be made for sub-millimag photometry of hundreds of thousands of stars in order to establish accurate relative ages through asteroseismology. This was the primary motivation for the ESA Eddington satellite which is unfunded at the present time. Science in the time domain is broached in the following section.

4. Imaging science – how will it evolve?

Time domain. The time domain is clearly an area of parameter space that has been barely explored to date. The MACHO project (Alcock *et al.* 1997) taught us that there is much to be learnt from stellar populations through variability studies.

Two important survey projects, Pan-STARRS‡ (north) and the Large Synoptic Survey Telescope (south), are set to dominate the optical landscape in the next decade by

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† Dyson (1999) has argued that modern science began in 1729 with Bradley's astrometric measurements that were recorded with an accuracy of 6 significant figures. Bradley first established that the Copernican view was correct, detected stellar aberration due to the Earth's motion, and measured the speed of light to an accuracy of 1%. In the next century, Michelson spent several decades measuring the higher order aberration coefficients with ever-increasing precision, with profound consequences for physics.

‡ A related project in the southern hemisphere is SkyMapper, essentially a single Pan-STARRS telescope at Siding Spring Observatory.

extending beyond SDSS both in the time domain and in source sensitivity (combined exposures). The first of these will make use of four 1.8m telescopes, each with a 3° field. Pan-STARRS will repeatedly survey the sky with 30-60 sec exposures and achieve a single-exposure depth of 24.0 AB mag (5σ). The LSST is a single 8.4m telescope with a 3.3° field that will survey the sky in 15 sec exposures, with a single-exposure depth of 24.0 AB mag (6.5σ). Both surveys will make use of g, r, i, z filters with an additional red y filter for the LSST. The survey étendue (area × solid angle, $A\Omega$) of Pan-STARRS and LSST is 60 and 190 respectively.

Both LSST and Pan-STARRS will reveal an extraordinary richness of new data across the sky, inter alia, identifying homogeneous stellar populations (miras, cepheids, etc.) by their distinct temporal behaviour, proper motions, colours, etc. These populations in turn will provide age and metallicity information as a function of position throughout Local Group galaxies (Luck *et al.* 2006). One of the enduring legacies of these surveys will be the prospect of selecting clean stellar populations untainted by unresolved binaries; the binary fraction can easily exceed 25% in a typical population.

New deep wide-field surveys. The upcoming UKIRT Infrared Deep Sky Survey (UKIDSS; north) and Visible and Infrared Survey Telescope for Astronomy (VISTA; south) both utilize IR-optimized 4m telescopes in order to provide deep $ZYJHK_S$ band photometry over large swaths of the sky. The UKIDSS Large Area Survey will reach 18.4 mag (5σ) for stellar sources over a 4000 deg^2 field, and 0.5 mag deeper for 3200 deg^2 in galactic fields. This is to be compared with the 2MASS and DENIS all-sky surveys that reached 14.2 and 14.0 mag respectively. But first off the ranks will be the VLT Survey Telescope (VST 2.6m) which becomes operational in 2007. The OmegaCAM imager has a 1° field and will supply good-seeing SDSS-style data over a 4500 deg^2 field.

Other noteworthy systems are the IMACS imager on the Magellan 6.5m telescope, and the SuprimeCam imager on the Subaru 8.2m telescope. SuprimeCam sits at the f/2 focus and has an $A\Omega$ product of about 9 (Miyazaki *et al.* 2002). Remarkably, engineers at Canon Inc. believe that the étendue can be increased by an order of magnitude − the so-called HyperSuprimeCam concept − which would have comparable survey power to Pan-STARRS. But the primary science driver for the Subaru cameras is deep multiband optical exposures for observational cosmology, and these share the telescope with a host of other instruments, unlike the dedicated imagers on Pan-STARRS.

Intermediate band all-sky surveys. In an era of precision photometry, it would seem an appropriate time to revisit the power of intermediate band photometry for identifying specific populations. This was to be a mainstay of the ESA GAIA satellite mission in the next decade. But in its latest incarnation, the intermediate photometric filters will not be employed. This is unfortunate as we will still need precise photometry for the billion or more sources to be targetted by this important astrometric mission (Perryman et al 2001; Wilkinson *et al.* 2005). It is clear however that the 5−6D phase space information will have a huge impact on our understanding. The mission will allow for millions of stars to be characterised by their distance, spectral type, luminosity and so forth. It is interesting to observe the scientific impact of even relatively crude photometric distances to stars (e.g. SDSS tomography of the Galaxy; Juric *et al.* 2005).

Short-term gains: fourfold increase in $A\Omega$. Conventionally, we build large imaging mosaics to work in fast beams in order to enhance the étendue of an imaging survey. The unvignetted field however is typically larger but not fully exploited to minimize the cost of detector real estate. For future wide-field instruments, it may be interesting to ask whether full Nyquist sampling is required over the field, particularly with a view to the dithering requirement in most applications today. If the pointing and guiding models are robust, can we simply match the median seeing to the pixel scale, and attempt to double the available field of view? If we dither with sub-pixel offsets, can we recover the psf (e.g. Fruchter & Hook 2002)? This is an experiment that is worth exploring.

Short-term gains: fourfold increase in resolution and sampling. Driver and colleagues have amply demonstrated the advantage of even moderate improvements over the SDSS in the median seeing. They used the Wide Field Camera on the INT 2.5m to image 10,000 galaxies over a 37 deg^2 field complete to $B \sim 24$ mag. Their median seeing is roughly a factor of 2 better than the SDSS (Lemon *et al.* 2002) resulting in markedly better bulge-disk decompositions (Allen *et al.* 2006). This emphasizes the importance of imaging cameras on good sites for resolved studies. My colleagues and I have recently completed more than 40h of optical imaging on nearby galaxies using the GMOS imaging spectrograph on Gemini South with seeing in the range $0.55 - 0.65''$ over the full $5.5'$ field. Two hour exposures result in 3σ point source detections of 27.0 AB mag (Bland-Hawthorn *et al.* 2005). Few galaxies have been mapped to this level of sensitivity. Important exceptions are the few nearby galaxies that have been studied with the HST, as we have seen at this meeting.

Sub-arcsecond imaging over the widest possible field. We have barely begun to exploit wide-field imagers on the best observing sites to study nearby galaxies. The LSST, Pan-STARRS and VISTA surveys are expected to achieve $\approx 0.7''$ FWHM median image quality, although a smaller subset of observations at lower sensitivity may achieve $0.5''$ FWHM.

Consistently higher quality data will require dedicated photometric imagers. Both Magellan IMACS and Subaru SuprimeCam have recorded $<0.5''$ psf FWHM in optical bands over their half-degree fields. A superior system is the HyperSuprimeCam facility now under discussion at Subaru: there is the prospect of achieving a 2° corrected field at the prime focus of this 8m telescope! Facilities like these are needed to observe of order 10,000−100,000 galaxies to examine the environmental influences on galaxies, and more specifically stellar populations within individual components.

Beyond the well established morphology/luminosity dependencies on environment, Blanton *et al.* (2006) and Park *et al.* (2006) assert that the environmental influences on SDSS galaxies are very weak. But it is likely that higher resolution imaging of these large galaxy samples will reveal stronger influences once the different galactic components are properly separated.

Stellar population studies will always benefit from improved image quality. When studying the resolved stellar populations, the problem remains even at $0.5''$ FWHM of distinguishing stars from background galaxies, particularly in the diffuse outer parts of nearby galaxies (see Ellis & Bland-Hawthorn (2007) for a detailed analysis of this point − the `GalaxyCount` java calculator is freely available at www.aao.gov.au/astro/GalaxyCount). This ambiguity all but disappears in HST studies. Clearly, there is a strong case for a long-term HST program to target a large sample (~ 100) of nearby galaxies in a magnitude-limited survey.

Near diffraction-limited imaging over the widest possible field. There are numerous advantages to be gained from sampling at higher angular resolution, as evidenced by the extraordinary gains of HST with its small telescope aperture. The most important gains include: lower sky background per pixel, sources observed at higher intrinsic resolution, better star/galaxy and star/star separation. These are some of the reasons behind the major investment in adaptive optics and the projected enormous investment in ELTs.

Beyond Hubble, what prospects are there to achieve $\leqslant 0.25''$ seeing at optical/IR wavelengths with a wide-field ground-based facility? At optical wavelengths, the only prospect under discussion is the 2m PILOT survey proposed for Dome C in Antarctica (Burton *et al.* 2005). There has been talk of "quasi" HST-quality imaging from simple ground-layer correction, although it remains to be seen whether a 2m telescope located at 30m above the snowpack can achieve this performance for a useful fraction of the time. The Australian community is currently engaged in a study to look at the practicality of this project with two commercial telescope builders. Such a facility could be devoted to the long-term study of stellar populations in nearby galaxies, and indeed is one of the key science drivers for the project.

An interesting case has been made for "Lucky imaging" whereby I band images are read out at high frame rates using a low-noise E2V Technologies L3CCD (Law, Mackay & Baldwin 2006). In the best conditions, they achieve diffraction limited images over roughly an arcminute using the NOT 2.6m, but the overall operational efficiency is low.

At IR wavelengths, things look more promising. Existing AO systems have begun to deliver on science (see cfao.ucolick.org/links for links to these projects). The Keck AO system has produced more than 100 research papers over the past decade (Liu 2006). Typical Strehl ratios at K are 0.2 with a best operational value of 0.4. Both Gemini and the VLT are close to commissioning multi-conjugate AO (MCAO) systems that promise $0.2''$ image quality on 1-$2'$ scales. The Gemini-N Altair system combined with the near IR imager NIRI has been used to study stellar populations in M31 (Olsen et al 2006). The system can achieve Strehl ratios of about 20-25% at H and K, with psf variations $\sim$3% and photometric accuracies of $\sim$5% (Olsen 2006, private communication), both with natural and laser guide stars. Soon, the MCAO f/30 focus will be available at Gemini South and will produce a corrected field of $1'$, and a usable field of up to $2'$. This focus will feed instruments such as the GSAOI infrared imager and the Flamingos-2 infrared spectrograph. Comparable performance is offered by the VLT/NACO system as demonstrated by Cresci *et al.* (2006) in a study of intermediate-redshift galaxies in 20 fields close to natural guide stars.

Liu (2006) provides a good discussion of the advantages of ground-based AO over HST in the near IR. These include the use of novel instruments, higher observing efficiency (although terrestrial weather is more of a hindrance than space weather), and 3-4× better spatial resolution in the near IR ($0.05''$ fully corrected). In contrast, the disadvantages are the need for tip-tilt stars, a fully corrected field on sub-arcminute scales, and complex and variable psf leading to heterogenous data.

But do we need to achieve the diffraction limit for population studies? This is not altogether clear. In my opening remarks, I alluded to the importance of studying stellar populations out to Virgo. It would seem that stellar crowding demands the smallest possible psf. The diffraction limit is really only achieved in practice at high Strehl ratios, i.e. where the 80% EE diameter is close to the angular diffraction limit. Existing ground-based studies suggest that this is going to be very difficult to achieve in J and H, and challenging at K. However, in an important study, Olsen, Blum & Rigault (2003) find that high Strehl ratios may not be required in crowded fields because of the SBF contribution of unresolved stars.

So are there compelling science drivers for rigorously diffraction limited imaging (extreme AO), beyond that of identifying material and planets around nearby stars? A strong case can be made for studies of the diffuse stellar populations in the vicinity of compact sources (e.g. AGNs, SNe, GRBs), and in these rare instances, high Strehl ratios are probably called for.

Accurate measurement with future space-based and ground-based imagers is going to demand powerful software codes that take into account the variable psf properties over the field. The JWST psf will have the 6-pointer structure arising from the Fourier transform of the segmented mirrors. ELTs will have a similar psf structure, but compounded by atmospheric distortion. One of the most serious of these is anisoplanatism, i.e. field varying psf due to the slowly varying field angle as the source tracks across the sky. It will take complex computer codes to restore the photometric accuracy (see the web site cfao.ucolick.org/meetings/psf_reconstruction for detailed discussions). The real gains in these codes are likely to come from incorporating the extra information from the wavefront sensor telemetry.

Configurable fields. We mentioned above that the available field at the focal plane of many telescopes is often much wider than the exploited field of existing instruments. Detector real estate, particularly IR arrays, is often a limiting cost in instrument design, particularly so at IR and mid IR wavelengths.

But the imaged fields do not need to be defined by a contiguous region (Bland-Hawthorn *et al.* 2004). Indeed, for high redshift fields (e.g. Hubble Ultra Deep Field [HUDF]), the information content can be as low as 5%, i.e. the fraction of pixels that contain useful information. Several observatories, in particular the AAO, are working on robotic positioners that would allow random patches of sky to be reformatted efficiently with relay optics to be packed onto a wide-format detector. Such systems are likely to be a feature of future instrument suites on ELTs, e.g. deployable IFU wide-field spectrographs (McGrath & Haynes 2006), and multi-object AO systems (MOAO; Hammer *et al.* 2004).

Ultradeep imaging. Astronomers keenly await the awesome reach of the James Webb Space Telescope (JWST) expected to launch in the middle of the next decade. In a recent review, Gardner *et al.* (2006) describe the scientific potential of this facility. The NIRCam imager will allow for diffraction limited, broadband and intermediate band imaging (R$\sim$ 4, 10, 100) in the window $0.6 - 5\mu$m for a field of view and pixel sampling comparable to the HST ($2.2' \times 4.4'$) but at much higher sensitivity, particularly in the mid IR. The MIRI camera will allow broadband imaging in the window $5 - 27\mu$m over a $1.4' \times 1.9'$ field.

On a similar timescale, we may expect to see results from one of the proposed ground-based extremely large telescopes (ELT), in particular, the 24.5m Giant Magellan Telescope (GMT), the 30m telescope (TMT) or the recently announced European 42m ELT (E-ELT). These telescopes will be optimized for near-infrared performance although will extend into the optical and mid-IR. At the diffraction limit, these telescopes will rival or even exceed the performance of the JWST, particularly if the OH suppression problem is finally resolved and the AO systems prove to be stable over arcmin-scale fields. In practice, there will be major gains from combining ground-based AO imaging with space-based imaging of the same source (e.g. Vacca et al 2007).

5. Imaging spectrographs

Tunable imaging filters. I summarize the main technologies elsewhere (Bland-Hawthorn 2000). The first general user tunable filter was the Taurus Tunable Filter (TTF) that was operated at the AAT 3.9m and WHT 4.2m during the years 1995−2003. The scientific legacy is described in Bland-Hawthorn & Kedziora-Chudczer (2003).

There are several optical systems that are commissioned or close to commissioning that are a direct consequence of the TTF. These include the Maryland-Magellan Tunable Filter (MMTF), the Osiris tunable filter on the GTC 10.2m (Cepa *et al.* 2003), and the SALT Tunable Filter. The Osiris spectrograph is particularly powerful as it will provide tunable imaging (R=50−5000) and spectroscopic capability over the range 370 to 1000

instrument	mirror	D	type	window	AO	field of view (″)	pixel scale (″)	R	N&S
GMOS	Gemini-N	8	Fibre	Optical	N	5×7, 5×3.5	0.2	1080−7100	N
GMOS	Gemini-S	8	Fibre	Optical	N	5×7, 5×3.5	0.2	1080−7100	Y
NIFS	Gemini-N	8	Slicer	IR	AO	3×3	0.1	5000	N
GNIRS	Gemini-S	8	Slicer	IR	N	3.2×4.8	0.15	1700−5900	N
ARGUS	VLT	8	Fibre	Optical	N	11.5×7.3 or 6.6×4.2	0.52, 0.3	19000−39000	N
VIMOS	VLT	8	Fibre	Optical	N	54×54 or 13×13	0.67, 0.3	200−2500	N
SINFONI	VLT	8	Slicer	IR	AO,N	8×8, 3×3, 0.8×0.8	0.25−0.025	1500−4000	N
IMACS-IFU	Magellan	6.5	Slicer	Optical	N	6.9×5.0, 4.2×5.0	0.2	1800−10,000	N
INTEGRAL	WHT	4.2	Fibre	Optical	N	7.8×6.4, 33.6×29.4	0.45, 2.70	200−10,000	N
OASIS	WHT	4.2	Lenslet	Optical	AO,N	7.4×10.3, 2.7×3.7	0.26, 0.09	200−4000	N
SAURON	WHT	4.2	Lenslet	Optical	N	41×33, 11×9	0.94, 0.27	3000	N
SPIRAL	AAT	3.9	Fibre	Optical	N	22×11	0.7	1500−13,000	Y
SparsePak	WIYN	3.5	Fibre	Optical	N	72×71(sparse)	4.7	5000−21,000	N
DensePak	WIYN	3.5	Fibre	Optical	N	30×45	3	5000−21,000	N
UIST	UKIRT	3.8	Slicer	IR	N	3.3×6.8	0.24, 0.12	1000−4000	N
PMAS	Calar Alto	3.5	Fibre	Optical	N	8×8	0.5	1500−8000	N
WIFES	ANU	2.3	Slicer	Optical	N	25×31	0.5	3000−7000	N
CIRPASS	Cambridge	–	Fibre	IR	AO,N	13×4.7, 9.3×3.5	0.36, 0.25	3000	N

Table 1. A summary of operational integral field spectrographs. (1) instrument (2) telescope (3) telescope diameter in metres (4) technology (5) wavelength of operation (6) AO, natural seeing, or both (7) field of view in arcseconds (8) pixel scale in arcseconds (9) resolving power (10) nod & shuffle operation?

nm at high efficiency. The JWST will also incorporate a restricted tunable filter for use at infrared and mid-infrared wavelengths in the next decade.

Tunable filters are immensely powerful for conducting star formation studies in both distant and nearby galaxies. The instruments are tuned to narrow bands in order to provide a very high contrast between emission lines and the neighbouring stellar continuum. However, Ryder, Fenner & Gibson (2005) demonstrate the power of tunable filter imaging in tracing variations in stellar abundance from absorption line variations over the face of galaxies. They tuned the TTF bandpass to an equivalent Lick index, and control bandpasses were observed to check the integrity of the measurement over the field. Both methods are likely to be exploited extensively with the new facilities.

Integral field and image slicer spectrographs. The main technologies are reviewed in van Breugel & Bland-Hawthorn (2000); a variety of science drivers is discussed by Cecil (2006), Morris *et al.* (2006) and Sharp *et al.* (2004). In Table 1, I list the main IFU spectrograph facilities in operation or soon to be realized.

As we have witnessed at this meeting, the SAURON project (TIGER concept) has amply demonstrated the power of IFU spectroscopy for stellar population studies (McDermid *et al.* 2006; Kuntschner *et al.* 2006). Powerful general-user survey instruments like VIMOS on the VLT and the GMOS IFU on Gemini have begun to deliver excellent data on nearby galaxies. Other facilities include INTEGRAL on the WHT 4.2m, SPIRAL at the AAT 3.9m and the WIFES image slicer at the ANU 2.3m (2008). All of these are used in natural seeing, offer resolving powers of up to ∼few thousand, and have longest dimensions of about $<30''$. The VLT GIRAFFE instrument offers smaller IFU fields for multiple targets.

Table 1 shows the trend towards IFU spectrographs on 8m class telescopes, but the power of the 4m class facilities should not be underestimated. The 8m facilities give a fourfold increase in collecting area but the pixel solid angle is an order of magnitude smaller typically. This is not an obvious gain given that the surface brightness of a galaxian stellar population is at or below the sky level, although the gains can be substantial for cuspy core sources or bright emission line sources.

Interesting recent developments are AO-assisted integral field spectrographs (Rutten, Benn & Mendez 2006), e.g. SINFONI at the VLT and NIFS at Gemini South. While the fields of view are small (64×32 format), the latest SINFONI observations of stellar populations and kinematics in distant galaxies show the enormous potential of these devices (Forster-Schreiber *et al.* 2006). An exciting future facility is the MUSE IFU spectrograph slated for the VLT in 2012 (Henault *et al.* 2003). This will have an incredible 300×300 format ($0.2''$ pixels) offering comparable spectral resolutions at optical wavelengths over an arcmin field.

Objective prism imaging. With a dark IR sky background, old ideas will need to be revisited (Bland-Hawthorn 2006). An interesting future prospect is the NIRspec (1-5μm) and MIRI (5-10μm) objective prism spectroscopy on JWST. Both systems will offer R∼100 spectroscopy over a $3.1'\times3.4'$ and $1.4'\times1.9'$ field respectively with a pixel sampling of about $0.1''$. In the next section, I broach another concept to demonstrate how a dark sky can be exploited in new ways.

6. MAXIMUS – a radical instrument concept

On the back of recent developments in photonics, I now propose a powerful new approach to imaging spectroscopy. The concept attempts to `maxim`ize the amount of `us`eful spectral information over a field while minimizing the number of spectral resolution elements. It combines the power of imaging with the power of spectroscopy. I give only a sketch at this time to illustrate how a darkened night sky will allow us to explore new technological avenues.

The instrument retains the constant spatial sampling (i.e. matched to the corrected seeing) across the field, but adapts the spectral resolution to the average flux in a given pixel. This 'prior information' is supplied either by a snapshot image or a deep image from another facility (e.g. HUDF)†.

MAXIMUS makes use of three ongoing developments in photonics: (i) OH suppression through fibre Bragg gratings, (ii) integrated photonic circuits where a fibre feeds light directly into a small (∼few cm) integrated photonic spectrograph (Bland-Hawthorn & Horton 2006), (iii) photonic networks or switchyards.

With the night sky removed, one can now disperse individual pixels at a resolving power that ensures the signal is fairly constant over the observed data cube. Light from the telescope is reimaged by a microlens array onto a bundle of optical fibres. We suppress the night sky in each fibre photonically (Bland-Hawthorn 2006) before directing individual fibres into an optical circuit with the appropriate spectral resolving power. Light from individual fibres is switched to the appropriate circuits via photonic networks much like those already in use by the telecomm industry.

Consider a broadband image of a distant galaxy cluster with total counts ranging from 10 to 10^5 counts with a background count level of 10 counts, say. If all pixels are dispersed at R=4, the skewed SNR distribution spans from 3 to about 320. If all pixels are dispersed at R=4096, the spread is from 0.1 to 10. With the MAXIMUS approach, the SNR variation is only a factor of 3, i.e. from 3 to 10. This is a factor of 30 improvement in the use of spectral resolution elements and allows for much longer exposures, even in the presence of bright sources (e.g. guide stars).

For the data content of a typical astronomical image (e.g. resolved stellar fields, galaxies), about 50% of pixels are observed in imaging mode (R∼4), 45% of pixels are dispersed at low spectroscopic resolution (R∼16, 64, 256), and about 5% are dispersed at intermediate and high resolution (R∼1024, 4096). There is a conservation principle at work here in that the required photonic circuits at higher resolving power are larger and therefore more expensive, but fewer are needed. In our example, the cores of bright cluster galaxies and emission line sources will be resolved at high resolution, the outer parts at medium resolution, and distant faint blobs will have sufficiently low resolution to perform photometric redshifts, for example. The dark sky will be detected in single detector pixels in order to confirm that useful data have not been overlooked.

The cost of an instrument can be measured in terms of the number of resolution elements (spatial and spectral) that in turn relate to the total number of detector pixels. Assuming that the photonic technologies are realized, this concept may provide the necessary step to realizing the Million Element Integral Field spectrograph (MEIFU) first proposed by the University of Durham (Content, Morris & Dubbeldam 2003). Preliminary calculations suggest that, for the same overall information content, MAXIMUS may require roughly 30 times fewer resolution elements than a traditional MEIFU design at a fixed resolving power.

7. Concluding remarks

Over the next ten years, we can look forward to a time of deep, wide-field imaging surveys from UV to infrared wavelengths, extending to the mid infrared in the next decade. The time domain will identify different populations through stellar variability.

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† One can envisage variants where the spatial binning is varied over the field to conserve flux, much like adaptive binning techniques at x-ray wavelengths.

There is a real need for large surveys of galaxies observed in sub-arcsecond conditions, at optical and infrared wavelengths. This will become possible for the first time with the Pan-STARRS and LSST surveys at optical wavelengths, and with the VISTA and UKIDSS surveys at IR wavelengths. But beyond these surveys, there is a pressing need for large surveys of galaxies observed at 0.2″ FWHM or better, particularly for resolved stellar work. The HST has already demonstrated the richness of information on these scales for Local Group galaxies. In the best seeing conditions, star counts in the outer parts of galaxies are achieving effective surface brightness levels far below what is possible with diffuse light imaging. With the successful commissioning of near-IR MCAO systems, it is likely that the community will look to push AO systems into the red optical region. Since the number of actuators goes as a high power of the photon energy, this will be challenging.

Beyond broadband imaging, the integral field spectrograph (and variant) will continue to play a crucial role, particularly when assisted by adaptive optics. These offer great advantages that we have barely begun to explore. In the next decade, we will see these used over wider fields of view, and with increased functionality (e.g. field configurations). IFUs will be fundamental to ELT operation for a host of reasons, e.g. correcting for deficiencies to high-order atmospheric refraction that cannot be compensated by the field corrector. There is also the exciting prospect of completely suppressing the dominant OH signal such that an IFU can achieve sensitivity on a par with the JWST at near-IR wavelengths (Bland-Hawthorn 2006).

Are there obvious technological arenas that we are not fully exploiting? There is not the space to discuss this question in depth but there are a few that come to mind. Optical interferometry has immense potential, both in terms of existing planned facilities at the Keck and VLT, and proposed arrays that could challenge ELTs. Another area is multiband simultaneity, i.e. observing the same patch of sky with wide-field detectors in multiple bands simultaneously, a concept that is exploited by digital cameras. The increased miniaturization of integrated circuitry means that we can cram more logic into each detector pixel (e.g. active pixel sensing). Tonry & Luppino (2000) raise the prospect of an arrty of microprisms that disperse light over complex pixel structures. One can envisage equivalent technologies, i.e. a cascade of beam splitters that divide up the spectrum and redirect the light to different wide-field detectors. An alternative strategy is to use layered materials that have increasing opacity to the incoming photons with material depth.

But for now, the largest gains are unlikely to come from advances in detector technology. The community awaits wide-field AO systems on the 8-10m ground-based telescope, the refurbishment of HST with WFC3, and four large survey telescopes on sub-arcsecond sites. Beyond here, there is the prospect of JWST and one or more ELTs, all of which offer extraordinary gains over existing systems. There are enormous technological challenges to be overcome, not least the problem of realizing stable and accurate AO-assisted photometry with extremely large telescopes.

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The speaker (right) with Roelof de Jong (left) and Mike Disney (middle).

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