PROCEEDINGS OF SCIENCE

Spectroscopy and the Age of Giant Telescopes

Sarah Tuttle*
McDonald Observatory
2511 Speedway
Austin, TX 78712
E-mail: tuttle@astro.as.utexas.edu

Is your 4 meter telescope just not cutting it anymore? Embarrassed to mention the telescope time you had just the other week when talking about your newest data project? Don't worry, the age of the giant telescope is upon us. I will review the status of the three current ELT projects, as well as spectroscopic technologies focusing on multi-object spectroscopy. HETDEX (the Hobby Eberly Dark Energy Experiment) uses a new approach to large instruments, replicating a spectrograph channel 150 times to produce 33,600 individual spectra across a 22 arcminute field. The technology being built can be easily modified and ported to other telescopes to take quick advantage of the integral field approach. I will touch on the many experiments that await first light as these instruments come to fruition. Let's discuss why we are pouring massive resources into these telescopes and see what they can do for us.

Frank N. Bash Symposium New Horizons In Astronomy,
October 9-11, 2011
Austin Texas

*Speaker.

PoS(Bash11)011

1. Introduction

Telescopes with a primary aperture of 8m or more pepper the mountains of both hemispheres and give us eyes to observe back to the beginnings of the Universe. Bigger is sometimes better but as telescope building becomes an increasingly refined art it is important to also become wiser. Good use of this abundance of photons will allow us to answer a diverse set of questions ranging from the creation and evolution of galaxies, to understanding the primary physics that shapes star and planet formation.

Three giant telescopes loom on the horizon. The US is currently planning for the GMT (Giant Magellan Telescope) and the TMT (Thirty Meter Telescope) while the E-ELT (European Extremely Large Telescope) is an ESO-based project . Understanding what distinguishes each of these telescopes will help us to understand the decisions made in designing, selecting, and building the instrumentation needed to reach our science ambitions.

The technique of multi-object spectroscopy (MOS) (of which integral field spectroscopy is a subset) has been exploited to great effect in the last decade. The ability to achieve a three dimensional "image" of the object (in reality an x, y, λ data cube) allows us to better compare observations to models and to dissect the interactions that govern the physics that shape our universe. The first light instruments identified for all three ELTs implement a variety of MOS techniques, discussed throughout.

In this paper I will first review the science cases for the largest telescopes and some plans for early instrumentation to meet those needs. Section 3 reports on the progress of the three currently slated ELTs (Extremely Large Telescopes). Next, I will discuss the techniques most commonly used in multi object spectroscopy and their advantages. Section 5 will cover the costs of large telescopes and their operations. Finally, I discuss replication as one answer to the question "How do we build cost effective instruments for ELT class telescopes?"

2. Science Cases for 40m class Telescopes

The costs and risks associated with increasingly large ground-based telescopes are high. As you will see below (Section 6), decades of money, collected across large collaborations (and many countries) is necessary to consider building a telescope on this scale. Operating costs will be non-trivial, and a single night of data will come at a high price. What science drivers make this next step imperative? Figure 1 shows some of the advantage over 8m class telescopes, highlighting the sensitivity and resolution regimes for different observational cases.

2.1 Exo-Planets

The first exoplanet was discovered twenty years ago, orbiting a pulsar (PSR 1257+12) [1]. Through diverse detection methods, including microlensing [2, 3, 4], radial velocity [5, 6], timing [7], and direct imaging, that number slowly moved upwards. As of December 2011, 721 planets have been observed, the majority through radial velocity methods (662 planets in 538 systems). The recent work of the Kepler satellite (currently having detected 35 planets over the last 2 years, with over 2000 planet candidates) has accelerated the rate of discovery and has changed the parameters

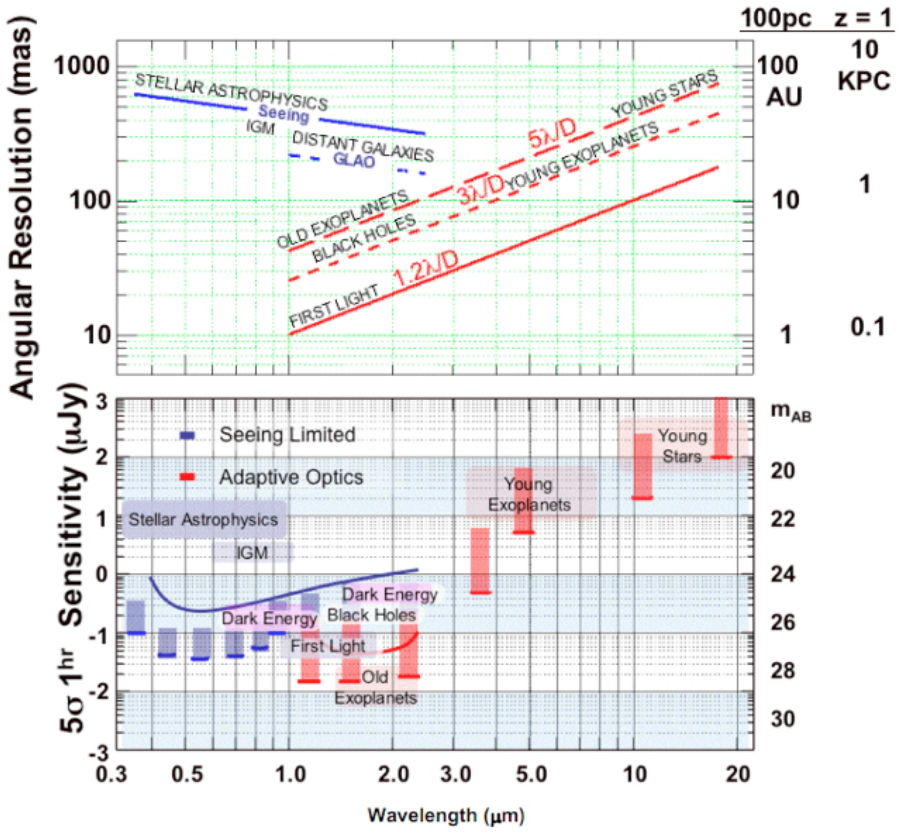
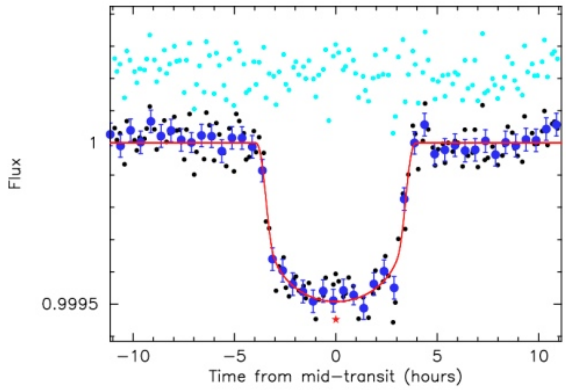


Figure 1: The projected sensitivity and angular resolution of the GMT as a function of wavelength. The bottom panel uses bars to show the improvements in sensitivity over current 8m telescopes. Blue cases are seeing limited while red are diffraction limited in both panels. ($http://www.gmto.org/Resources/GMT-ID-01404-GMT_{S}cience_{C}ase.pdf$)

of the "average" planet being detected, now discovering the lower mass Earth-like planets, as well as those in orbits most like the Earth as seen in figure 2 [8].

Radial velocity searches are possible from current telescopes, but require large amounts of time which limits meaningful statistical sampling especially when studying planets orbiting M and L dwarfs [9]. Moving to an ELT with adaptive optics makes even the detection of Terrestrial planets possible.

New instrumentation enabling high contrast imaging is crucial to push down to low mass ranges and smaller orbit systems (0.5-50 AU). Initial work can be done with the Infrared Imaging Spectrograph (IRIS), planned as a first light instrument for TMT. IRIS providing both a 16.4 arcminute field of view (diffraction limited, 4 mas sampling) as well as an IFU. This probes both bright planets in small orbits (10-15 AU in star forming regions) and bright "self-luminous" wide separation planets [10]. Plans also exist for the Planet Finding Imager (PFI), which exploits the large primary aperture and high-contrast adaptive optics [11]. E-ELT also has a Phase A instrument (EPICS) targeting exoplanets through direct imaging, spectroscopy and polarimetry [12, 13].



Parameter	Value
Effective temperature, T_{eff} (K)	5518 ± 44
Surface gravity, log g (cgs)	4.44 ± 0.06
Metallicity, [Fe/H]	-0.29 ± 0.06
Projected rotation $v \sin i$ (km s^{-1})	0.6 ± 1.0
Density, g cm^{-3}	1.458 ± 0.030
Mass, $M_\odot$	0.970 ± 0.060
Radius, $R_\odot$	0.979 ± 0.020
Luminosity, $L_\odot$	0.79 ± 0.04
Kepler Magnitude (mag)	11.664
Age (Gyr)	Not determined
Distance (pc)	190
Orbital period, P (days)	289.8623 +0.0016/-0.0020
Epoch, T0 (BJD-2454900)	66.6983 ± 0.0023
Scaled semi-major axis, a/R_*	186.4+1.1/-1.6
Scaled planet radius, R_p/R_*	0.0222 + 0.0012/-0.0011
Impact parameter, b (eccentric orbit)	0.768 + 0.132/-0.078
Orbital inclination, i (degree)	89.764 + 0.025/-0.042
Transit duration, Δ (hours)	7.415 + 0.067/-0.078
Radius, $R_\oplus$	2.38 ± 0.13
Mass, $M_\oplus$,(1σ, 2 σ, & 3σ upper limits)	36, 82, 124
Orbital semi-major axis, a (AU)	0.849 + 0.018/-0.017
Equilibrium temperature, T_{eq} (K)	262

NOTE. - Uncertainties are standard deviation or +1σ/-1σ unless otherwise noted.

Figure 2: Data from Kepler-22b, a transiting exoplanet with a period of 290 days. High resolution spectroscopy, analysis of the Kepler photometric, and HIRES data from Keck (taken over the course of a year) combine to demonstrate this is the first exoplanet found in the habitable zone. The left panel shows the folded light curve with model fit in red, and individual observations with black dots. (Reproduced by permission of the AAS and the author) [8]

2.2 Resolving Stellar Populations

Rich clusters contain the origins of many stars, but are difficult laboratories to study for star and planet formation. Observing these crowded stellar populations, especially the faint cluster members, is difficult. Being able to resolve cluster members means generating an increasingly deep and accurate initial mass function (IMF) [14, 15, 16]. Resolved positions of these stars then provides a distribution based on mass, with implications for formation scenarios - could collisions or mergers be involved in cluster formation?

Much of the work to explore the fundamental physics will be conducted using nearby protostars[17]. Being able to probe the central portions of collapsing protostellar systems will illuminate the processes that dictate how star systems (binary or multiple) and planetary systems form, as well as how outflows occur and influence protostars and their disks[18]. These questions ideally require very high resolution (R = 100,000) to probe low velocity absorption features, allowing measurement of temperature, density, and velocity.

2.3 Galaxy Assembly and Evolution

Astronomy is a field where we are generally unable to set our own experiments, but instead find the experiments running and observe them, the answers motivating the next set of questions. The evolution of galaxies has been an intriguing field since we first learned that galaxies were not individual island universes. Originally imagined within a black box, removed from the influence of the universe as a whole, we now know that the universe is an organism with galaxies retaining the imprint of the beginning [19], and that galaxies are shaped by interactions, both with other galaxies and with the IGM they have grown within.

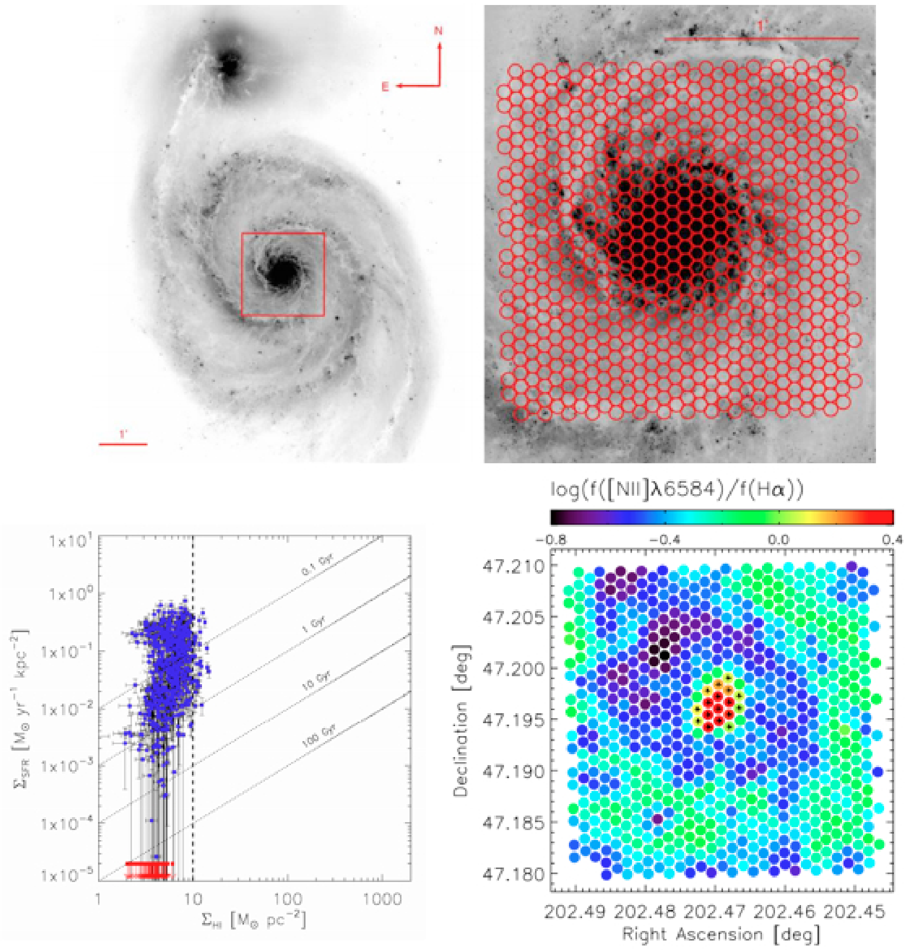


Figure 3: Four views of NGC 5194 from Blanc et al [21]. Clockwise from the upper left panel - The HST+ACS V-band image with the VIRUS-P field of view (1.7' x 1.7') boxed in red. The dithered fiber pattern is shown to the right, with each fiber 4.3" on the sky, or 170 pc at the distance of NGC 5194. The lower right panel shows [NII]λ6584/Hα emission line ratio with the black crosses indicating areas of AGN activity. The lower left panel shows atomic gas surface density versus SFR surface density. The data shown here consist only of the regions unaffected by AGN activity.

ELTs bring several advantages to bear on the question of how galaxies evolve. In particular, we do not yet know what physical processes are dominant generically across the growth of galaxies. Fundamental work in the field began with local and unresolved galaxies, leading to studies of star formation and dust as global properties [20]. Extensive work has now been done to resolve local star formation spatially (see figure 3) in the optical [21][22], directly measuring gas at radio and UV wavelengths [23], and evolution of galaxies out to z=2 [24]. Working with spatially resolved data identifies the root cause of the physical conditions in the galaxy as well as the possible external influences such as winds and filamentary streams.

At high redshift we are still limited to unresolved data. Integral field units on the upcoming ELTs will allow this exciting spatially resolved work to continue. IFUs matched to the appropriate physical scale can take tens of spectra over the area of high redshift galaxies, offering comparisons with current lower redshift work.

2.4 Cosmology

Understanding of the very high redshift universe (z > 7) will benefit greatly by an increase in primary size as well as the improved adaptive optics that will accompany the new largest telescopes. Extending many current works, including identification of quasars and other high redshift galaxies, star formation rates, and density and composition of the IGM will elucidate the early state of the Universe as well as its evolution.

The formation of single stars or clusters is not the only science case that benefits from resolving stellar populations. The nature of dark matter and its distribution throughout the universe is still poorly understood. Currently we can study the radial mass profiles of dwarf galaxies, a population whose mass is dominated by dark matter, and differentiate dark matter models [25]. Using an ELT will increase the sample size by a factor of ten and improve the velocity measurements down to 5 km/s accuracy.

Increased telescope size also opens a window into the faint baryonic matter that dominates the matter budget hidden away in the intergalactic medium (IGM)[26, 28]. The IGM is described as the "Cosmic Web" and traces the distribution of matter left behind as gravitational instabilities have collapsed [27]. This predominately hydrogen gas has been studied mostly in absorption using quasars as illuminators along the line of sight [29]. With a small number of sources, metallicities, distributions and even sizes of clumpy gas have been revealed[30]. The recent installation of the Cosmic Origins Spectrograph (COS) on HST has improved the resolution of absorption lines in the IGM as well as improved source statistics[31]. The increase in primary aperture on the ELTs also means galaxies can be used as well as quasars for background objects. Probing the distribution and make up of the gas along this increased number of lines of sight (with decreased bias) will reveal the larger filamentary structure. Outstanding questions in galaxy evolution rely on understanding the accretion and outflow of gas, and it will be crucial to understand the reserve of hydrogen that galaxies are born within.

2.5 The James Webb Space Telescope

It is important to briefly note that even the most advanced ground-based telescopes benefit from complementary space-based observations [32]. Ground-based telescopes have an advantage in primary aperture, mass restrictions, and accessibility. This translates to observing increasingly small and faint sources within reasonable exposure times. In space, telescopes such as JWST provide a much reduced background and access to much redder wavelengths, pushing observations beyond redshifts of 20. This combination probes the oft neglected extremes as opposed to the commonly studied brightest and most accessible objects.

3. On the Horizon - The Next Generation of Ground Based Telescopes

Here we review briefly the status of the three next generation ground-based telescopes being planned. Over the last decade, several more have been discussed but groups have naturally formed based on approach, geography, and primary science drivers. Some of the fundamental characteristics of the individual telescopes can be found in Table 1.

PoS(Bash11)011

Table 1: ELT Parameter Comparison

Telescope	Collecting Area (m^2)	Throughput	FOV ($arcmin^2$)	Resolution Range	Scaled AΩ
GMT	387	0.8	145	1500-5000	1.00
TMT	705	0.7	40.5	500-5000	0.44
E-ELT	1190	0.6	25	300-2500	0.4

Table 2: GMT Phase A Instruments

Name	Type (R)	Bandpass (μm)
GMACS	MOS Spectrograph (2000)	0.38 - 1.0
GMTNIRS	Spectrograph (50000-10000)	1.15-5.3
NIRMOS	MOS Spectrograph (3000)	0.9-2.5
MIISE	Imaging Spectrograph (1500)	3.0-25
HRCAM	AO Imager	0.9-5.0
QSpec	Slit Spectrograph (30000)	0.3-1.0

3.1 Giant Magellan Telescope Status

The Giant Magellan Telescope (GMT) is being built by an international consortium including groups from Australia, Korea, and the United States. The telescope site has been chosen at Las Campanas, Chile in the southern hemisphere. Las Campanas is an excellent observing site, having several telescopes currently on location. This means the infrastructure to support the telescope is substantially developed. The telescope optical design includes a primary constructed of seven 8.4m mirrors. The first primary mirror is built and the second casting was begun in mid-January 2012. Phase A instrument studies took place and down selection has begun (see Table 2). GMT is expected to see first light in 2019.

3.2 TMT Status

The Thirty Meter Telescope (TMT) started off as a collaboration between the Association of Canadian Universities for Research in Astronomy(ACURA), California Institute of Technology, and the University of California. Now it has expanded to include groups from China, India, and Japan. TMT will be based in the Northern hemisphere on Mauna Kea, and is in many ways a descendent of the Keck observatories. The primary mirror is composed of 492 segments, with 82 unique shapes and optical prescriptions to be achieved. Each segment will be controlled by three actuators to give the final primary mirror shape.

TMT selected three early light instruments in 2006 which are moving ahead. IRIS [10], the Wide Field Optical Imager and Spectrometer (WFOS)[33], and the Infrared Multislit Spectrometer (IRMS) were chosen to be flexible in scope and allow early work on characterizing the telescope as other instruments were built. Two of the three (IRIS and IRMOS) contain IFUs, and design of the three show a balance between targeting breadth and depth of the objects observed. IRIS will come online first and be the only early light instrument to operate at the diffraction limit.

Table 3: TMT Early Instrumentation

Name	Type (R)	Bandpass (μm)
IRIS (Early)	Imager/Spectrograph	0.8-2.5
IRMS (Early)	Spectrograph (4600)	0.95-2.45
WFOS (Early)	Imager/Spectrograph (1000-5000)	0.31 - 1.0
IRMOS	Spectrograph (2000-100000)	0.8-2.5
MIRES	Echelle Spectrograph (5000-100000)	8.0-18.0
PFI	Imaging Spectrograph(<100)	1-2.5
NIRES	Echelle Spectrograph (20000-100000)	1.0-5.0
HROS	Spectrograph (50000)	0.31-1.1
WIRC	Imager	0.8-5.0

Table 4: E-ELT Phase A Instruments

Name	Type (R)	Bandpass (μm)
CODEX	Spectrograph (135000)	0.37 - 0.72
EAGLE	Spectrograph (4000)	0.80 - 2.45
EPICS	Imager/Spectrograph/Polarimeter	0.6 - 1.65
HARMONI	IF Spectrograph (4000- 20000)	0.47 - 2.45
METIS	Imager/Spectrograph (Low and High)	2.9 - 14
MICADO	Imager/Slit Spectrograph (<3000)	0.8 - 2.5
OPTIMOS-DIORAMAS	Wide-Field Imager/Slit Spectrograph (Low)	0.37 - 1.6
OPTIMOS-EVE	Fiber MOS (5000-30000)	0.37 - 1.7
SIMPLE	Echelle Spectrograph (130000)	0.8 - 2.5

3.3 E-ELT Status

The European Extremely Large Telescope (E-ELT) is ESO's contribution to the current effort to the next generation of telescopes. The E-ELT will have a primary mirror 39.3m in diameter with a field of view of .1 of a square degree. The primary is built of just less than 798 1.4m segments. The mirror design is somewhat unusual, using a five-mirror design. Adaptive optics are integrated into the telescope design. A site has been selected at Cerro Armazones, Chile in the southern hemisphere. After passing a design review in December 2010, E-ELT construction is expected to begin in January 2012 [34]. It is expected to begin operation roughly a decade later. Phase A studies were completed and recommendations were made for two first light instruments: a single-field near-infrared wide-band integral field spectrograph and a diffraction-limited near-infrared imager. The next suite of instruments expected are a high resolution spectrograph, a multi-object spectrograph, and a mid-infrared imager/spectrometer. See Table 4 for details of the current instruments in development.

The end of 2011 brought approval of the next year's budget, moving the E-ELT towards final approval by member states in mid-2012. Component development is also set to begin this year in preparation for final approval. The final construction cost of the E-ELT is currently estimated to be 1 billion euro.

3.4 Adaptive Optics

Adaptive optics are crucial for many of the science goals discussed above [35] (see figure 1). Each telescope has a different approach to implementation, and some instruments will integrate their own AO systems [11]. Design work is under way and will likely evolve even as the telescopes come online[36].

3.5 OH Suppression

A brief mention, when discussing the next generation of ground-based telescopes, must go to the new technology of OH suppression. A glance at Tables 2, 3, and 4 show that exploiting available infrared wavelengths is ideal. However, the abundance of sky lines makes much work difficult. Even when individual lines are suppressed, scattered Lorentz wings pollute the continuum to a level that is difficult to remove. Several new techniques are underway to completely remove the photons from the skylines and prevent their entrance into an instrument to scatter and degrade efficiency[37, 38]. The ELTs will benefit greatly from technology which eliminates skylines and makes the infrared an even more fruitful band [39].

4. Multi-Object Spectroscopy : Techniques and Current Instruments

Multi-object spectroscopy (MOS) refers to any technique that captures multiple spectra simultaneously in an exposure. The ability to observe many objects simultaneously provides improved statistics without untenably long observing programs, and this is one reason why multi-object spectrographs have become common on large telescopes. Spatial and spectral information is measured with a MOS, and this three dimensional sampling puts the onus on the instrument designer to balance resolution and field of view across the available detector area[40]. One way to think about these trades can be seen in figure 4.

Multi-object spectrographs come in several flavors. At one end of the range we find plug plates and masks, such as the Sloan Digital Sky Survey (SDSS) [41] and DEIMOS (on Keck) [42]. Masks or plates must be generated for each field, and for plug plates human interference is required to route fibers every time a field changes. Increasingly, technology is used for flexibility and reliability. Robots or magnets move fibers (or small packed bundles) from target to target. HYDRA has been used at NOAO facilities for many years and through several upgrades. It uses robotic positions over a field of view of 60 arcminutes diameter and places 288 fibers that can be reconfigured in 20 to 25 minutes [43, 44]. The positioning accuracy is 0.3 arcseconds, and the minimum spacing between fibers is 37 arcseconds. Fields do not need to be specified weeks or months in advance to machine the plates, and it decreases the likelihood of incorrectly locating fibers. All of these methods are limited from any sort of integral field packing due to the external coverage of the fibers or bundles - objects are lost when they are too close to be covered by interfering fibers but spaced to far apart to fill a single element. This is usually resolved by ignoring one object, or if they are both of extreme interest (or the field is very crowded) by taking a second configuration on the same field.

Integral field units (IFUs) provide contiguous coverage of a field. Taking an image gives spectra of the entire field of view and there is no configuration or orientation to change. The fill factor or distribution of fibers across the field can vary, as shown in figure 5. Bundles might be close

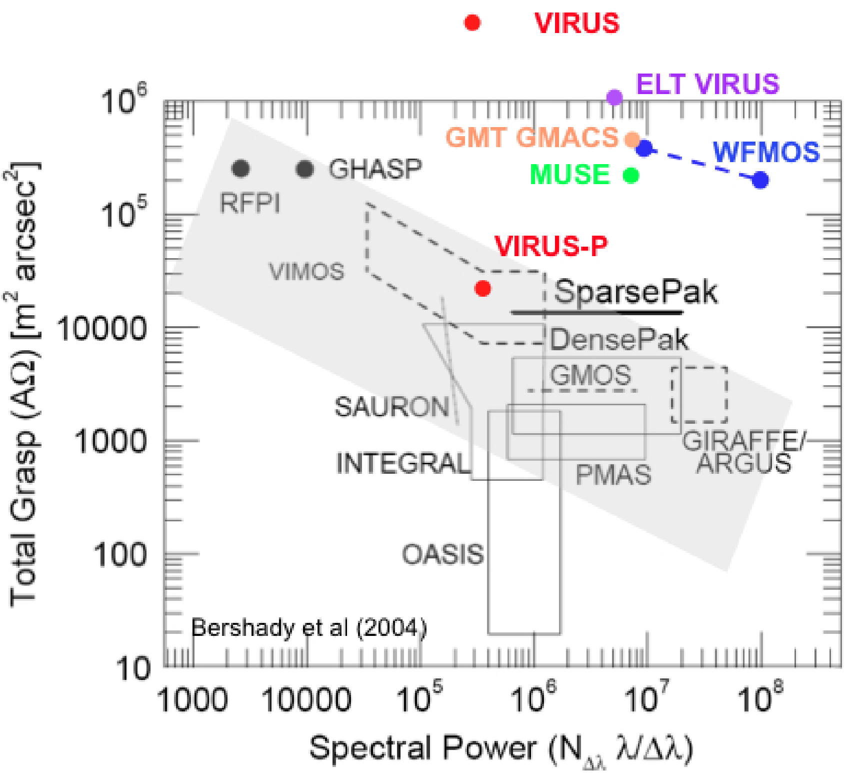


Figure 4: A modified figure from Bershady [40]. Spectral power versus total grasp of many of the current and planned MOS instruments shown.

packed to provide relatively complete coverage, such as with FIREBALL [45] or Densepak[46]. Fibers can also be distributed to target a more specific science result, such as with Sparsepak [47]. The fibers in Sparsepak were distributed to study local galaxies, splitting the fibers (and therefore detector coverage) between the dense center of the galaxy, the more diffuse halo, and providing an optimized number of fibers (7) along the edge of the field of view for sky coverage (see figure 5). Image slicers and fiber optics are often deployed to these ends, as well as lenslet arrays[48]. Micro-shutters are an interesting technological development as they introduce the idea of a configurable integral field - bright objects could be occulted, for example, and faint structures could be searched for with deep exposures[49].

The flexibility of these instruments has meant that a steady stream of exciting results have continued. The Sloan Digital Sky Survey is, even a decade after its first data release, being used to do compelling new research, contributing to large scale structure work in the local universe[50].

5. Large Telescopes and Their Costs

The community has looked ahead to 40m class telescopes for the last 15-20 years [51]. One of the most difficult things for astronomers to wrap their minds around is the cost of running large telescopes. Early work done to understand and project the cost of new telescopes made even the cost of a 5m class telescope appear prohibitive [52]. But successful large telescopes beat this

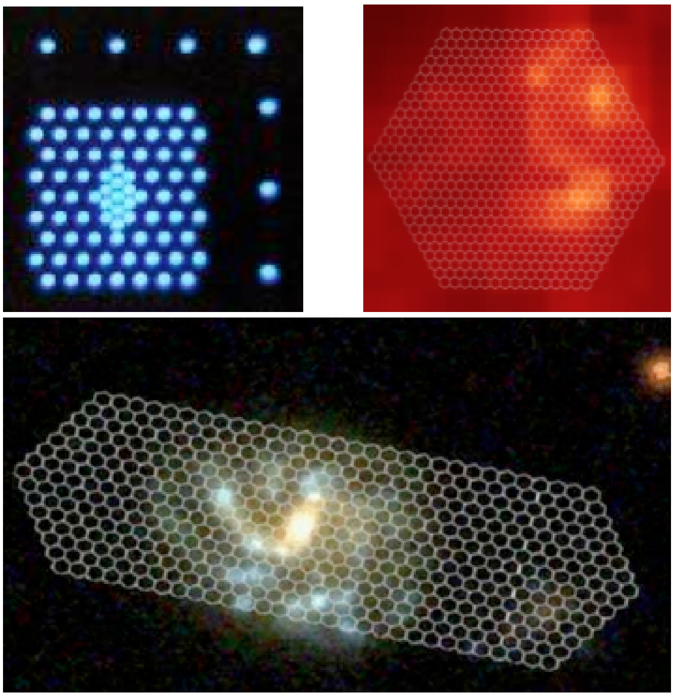


Figure 5: Three IFU configurations. The top right shows Sparsepak illuminated from the slit end [47]. The top left shows an overlay of the FIREBall bundle on a simulation of an IGM clump at z=1 [45]. The bottom image is a proposed IFU for TMT (J. Larkin)

prediction. Stepp et al [53] discuss that if one were to extrapolate from the Kitt Peak Mayall 4m to Keck I, the projected cost was 4 times more than the actual cost.

A conversation that has been taking place for the last several years centers on the need to shut down many smaller telescopes to move forward in support of next generation telescopes. Creating extended cost benefit analysis of these choices is difficult, as each subfield and scientist have different scientific interests and agendas, and most feel they can use almost any instrument to good effect. Given these conditions, how do you decide to cut 10 1m telescopes to support one 5m? How do you value infrastructure and experience? Many of these questions have been asked and answered, and I try to summarize here some of the relevant work.

van Belle et al [54] review the changes in cost as a direct effect of the primary aperture of the telescope, as well as development in the engineering approach. Evolution of telescope design over time has led to several eras of telescope cost. Most costs fold in not only the telescope itself but the support systems and buildings (but exclude instrumentation and operations). Earlier telescopes had monolithic mirrors that had no light weighting, large domes which were (eventually understood to be) ineffectual in suppressing seeing, and slow speeds, and were designed on traditional equatorial mounts. After 1980, technical changes improved the cost of increasing aperture size - in particular, the move to alt-az mounts, thin or segmented mirrors, and much faster optical systems (F/# < 1.8). The implication here is that if we build a giant telescope using similar techniques without a significant cost break in technological approach, we might expect to be hindered to the same costing, which places a thirty meter telescope at over $2 billion (as seen in figure 6). The rough

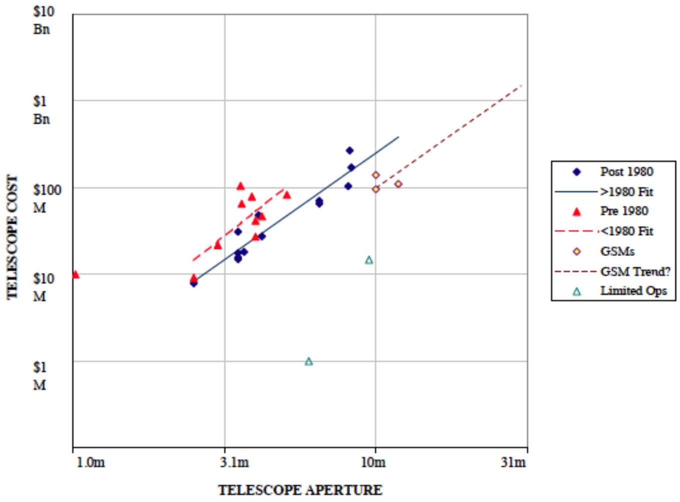


Figure 6: Telescope diameter versus telescope cost. Data found in [54]. The three lines show the trend with pre-1980 technology, post-1980, and a possible projected trend for the ELTs.

cost estimate for GMT is currently $700 million.

Construction costs are not, in the end, the dominant cost of telescopes. Over the course of a 30 year lifetime, an intermediate sized telescope (4-10m) will cost two to three times its construction costs [53]. This is estimating the operating costs at 3 to 6 percent of the construction cost of the facility, and doesn't include instrument development. For such large projects, cost savings must be found where available.

6. Replication as a Solution

One possible way to ameliorate the cost of large telescopes is to provide cost efficient instrumentation. Here I briefly describe the current status of the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) [55] and its replicated spectrograph VIRUS [56]. VIRUS takes advantage of small scale optics and replication of optical and mechanical components to provide spectroscopy of 33,600 fibers (1.5 arcseconds on the sky) spread across a 20 arcminute field. The baseline survey observes 60 square arcminutes, probing a volume of 9 Gpc to measure the baryonic acoustic oscillation by mapping Lyman α emitters from $2 < z < 4$. The spectrograph has a bandpass of 350-550nm with a R = 900. We predict roughly 750,000 Lyα emitters will be detected.

VIRUS is designed to minimize the size of individual optics while optimizing sky coverage The fibers are packed into 82 IFUs which then split again at the slit to feed 164 spectrograph channels. The cameras are a f/1.33 vacuum Schmidt design, with two channels enclosed in a single cryostat. Figure 7 shows some of the replicated spectrograph parts in progress as well as the lay out of the camera and the VIRUS "pair" (two channel assembly).

The two instrumental components necessary to the HETDEX project (the Wide Field Upgrade - WFU and VIRUS) are currently under construction and will be installed at the HET starting in the Summer of 2012. VIRUS will come online over the course of the fall with first light of the full complement of spectrographs scheduled for early 2013.

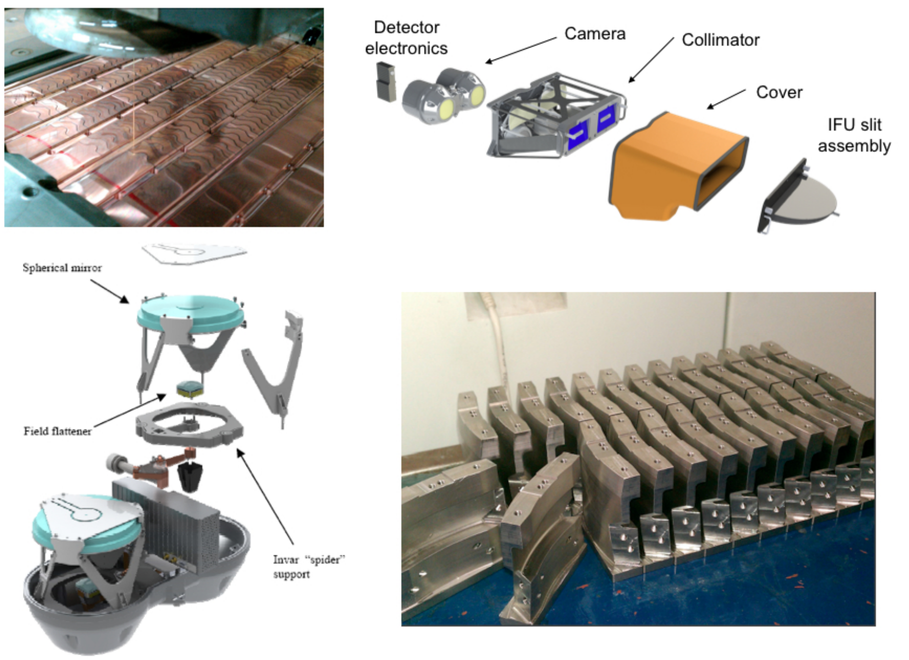


Figure 7: The VIRUS spectrographs. The top left and bottom right show partial batches of two production parts. The copper is part of the cold link and in the process of being cut out using wire electrical discharge machining (wire EDM). The Invar parts in the lower right are mirror mounts and adjusters - three are used in each channel, as can be seen in the exploded view on the lower left. Here you can see the two channels with the upper cryostat removed for easy viewing. The detector controller electronics box is shown in between the two channels. The upper right panel shows the full pair assembly as it will be mounted on HET.

Replication is an attractive possibility for an ELT instrument design. With large telescope instruments it is easy to fall back on designs that include large optics and complex mechanisms to manage the mass and beam size. When internal optics exceed the size of small (1m) telescopes, coatings and handling become prohibitively expensive and technically difficult. A replicated instrument reduces the size of the parts and introduces economies of scale to reduce the overall price of the instrument. A fiber optic IFU or MOS decouples the instrument from the telescope as well, eliminating possible mounting constraints. Instruments can be maintained and upgraded in a similar fashion to segmented mirrors, with a small number coming offline without a severe impact on the usefulness of the instrument.

VIRUS was built based on a prototype instrument (VIRUS-P, now known as the George Mitchell Spectrograph [57]). Although not identical, the prototype allowed proof of concept, lifetime testing of several components in-situ, as well as offered the opportunity to conduct a pilot survey to study the technique of Lyman α detection and mapping with optimization for the fiber IFU [58]. VIRUS-P is now one of the most highly subscribed instruments at McDonald Observatory.

7. Conclusion

The next decade will see first light of one, if not several, ELTs. The investment, in both time and money, is at a level never seen before especially when discussing ground-based instrumentation and competitive with our most expensive space-based missions. It behoves all of us to understand the benefits of these telescopes as they come to fruition.

In the past, the most effective way to control the cost of new telescope facilities is to use technological advances to break the relationship between primary mirror aperture and cost. The last 30 years have made much progress in this area, including light weighted and segmented mirrors. The next break very well might come from changes in approach to instrumentation, such as using replication to decrease the size of individual components and take advantage of economies of scale. Multi-object spectrographs, either through IFUs which achieve coverage over the entire field, or a more dispersed approach (such as single fibers, several small bundles, or slit masks), often offer the best compromise between field of view and detector coverage.

References

[1] Wolszczan, A., & Frail, D. A. 1992, Nature, 355, 145

[2] Udalski, A., Jaroszyński, M., Paczyński, B., et al. 2005, Astrophysical Journal, Letters, 628, L109

[3] Gould, A. 2009, The Variable Universe: A Celebration of Bohdan Paczynski, 403, 86

[4] Gould, A., Dong, S., Gaudi, B. S., et al. 2010, Astrophysical Journal, 720, 1073

[5] Struve, O. 1952, The Observatory, 72, 199

[6] Butler, R. P., Wright, J. T., Marcy, G. W., et al. 2006, Astrophysical Journal, 646, 505

[7] Beuermann, K., Hessman, F. V., Dreizler, S., et al. 2010, Astronomy and Astrophysics, 521, L60

[8] Borucki, W. J., Koch, D. G., Batalha, N., et al. 2012, Astrophysical Journal, 745, 120

[9] Riaud, P., & Schneider, J. 2007, Astronomy and Astrophysics, 469, 355

[10] Wright, S. A., Barton, E. J., Larkin, J. E., et al. 2010, Proceedings of the SPIE, 7735,

[11] Macintosh, B., Troy, M., Doyon, R., et al. 2006, Proceedings of the SPIE, 6272

[12] Kasper, M., Beuzit, J.-L., Verinaud, C., et al. 2010, Proceedings of the SPIE, 7735,

[13] Gratton, R., Kasper, M., Vérinaud, C., Bonavita, M., & Schmid, H. M. 2011, IAU Symposium, 276, 343

[14] Kim, H., Whitmore, B. C., Chandar, R., et al. 2011, Bulletin of the American Astronomical Society, 43, #246.17

[15] Greggio, L., Tosi, M., Clampin, M., et al. 1998, Astrophysical Journal, 504, 725

[16] Calamida, A., Comeron, F., & Zinnecker, H. 2011, arXiv:1109.6235

[17] Wolf-Chase, G., Smutko, M., Sherman, R., Harper, D. A., & Medford, M. 2012, Astrophysical Journal, 745, 116

[18] Wang, K., Zhang, Q., Wu, Y., Li, H.-b., & Zhang, H. 2012, Astrophysical Journal, Letters, 745, L30

[19] de Lapparent, V., Geller, M. J., & Huchra, J. P. 1986, Astrophysical Journal, Letters, 302, L1

[20] Kennicutt, R. C., Jr. 1998, Astrophysical Journal, 498, 541

PoS(Bash11)011

[21] Blanc, G. A., Heiderman, A., Gebhardt, K., Evans, N. J., II, & Adams, J. 2009, Astrophysical Journal, 704, 842

[22] Blanc, G. A., Gebhardt, K., Heiderman, A., et al. 2010, New Horizons in Astronomy: Frank N. Bash Symposium 2009, 432, 180

[23] Bigiel, F., Leroy, A., Walter, F., et al. 2008, Astronomical Journal, 136, 2846

[24] Genzel, R., Burkert, A., Bouché, N., et al. 2008, Astrophysical Journal, 687, 59

[25] Strigari, L. E., Bullock, J. S., & Kaplinghat, M. 2007, Astrophysical Journal, Letters, 657, L1

[26] Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, Astrophysical Journal, 503, 518

[27] Cen, R., & Ostriker, J. P. 1999, Astrophysical Journal, 514, 1

[28] Shull, J. M., Smith, B. D., & Danforth, C. W. 2011, arXiv:1112.2706

[29] Danforth, C. W. 2009, American Institute of Physics Conference Series, 1135, 8

[30] Danforth, C. W., & Shull, J. M. 2008, Astrophysical Journal, 679, 194

[31] Green, J. C., Froning, C. S., Osterman, S., et al. 2012, Astrophysical Journal, 744, 60

[32] Kissler-Patig, M., & McCaughrean, M. 2010, The Messenger, 140, 57

[33] Pazder, J. S., Roberts, S., Abraham, R., et al. 2006, Proceedings of the SPIE, 6269,

[34] Gilmozzi, R., & Kissler-Patig, M. 2011, The Messenger, 143, 25

[35] Hubin, N., Ellerbroek, B. L., Arsenault, R., et al. 2006, The Scientific Requirements for Extremely Large Telescopes, 232, 60

[36] Hinz, P. M., Bouchez, A., Johns, M., et al. 2010, Proceedings of the SPIE, 7736,

[37] Bland-Hawthorn, J., Ellis, S., Haynes, R., & Horton, A. 2009, Anglo-Australian Observatory Epping Newsletter, 115, 15

[38] Bland-Hawthorn, J., Ellis, S. C., Leon-Saval, S. G., et al. 2011, arXiv:1112.1694

[39] Günster, S., Ristau, D., & Davies, R. 2011, Proceedings of the SPIE, 8168,

[40] Bershady, M. A. 2009, arXiv:0910.0167

[41] Owen, R. E., Siegmund, W. A., Limmongkol, S., & Hull, C. L. 1994, Proceedings of the SPIE, 2198, 11

[42] Faber, S. M., Phillips, A. C., Kibrick, R. I., et al. 2003, Proceedings of the SPIE, 4841, 1657

[43] Barden, S. C., Armandroff, T., Massey, P., et al. 1993, Fiber Optics in Astronomy II, 37,185

[44] Barden, S. C., & Armandroff, T. 1995, Proceedings of the SPIE, 2476, 56

[45] Tuttle, S. E., Schiminovich, D., Grange, R., et al. 2010, Proceedings of the SPIE, 7732,

[46] Barden, S. C., & Wade, R. A. 1988, Fiber Optics in Astronomy, 3, 113

[47] Bershady, M. A., Andersen, D. R., Harker, J., Ramsey, L. W., & Verheijen, M. A. W. 2004, Publication of the ASP, 116, 565

[48] Matuszewski, M., Chang, D., Crabill, R. M., et al. 2010, Proceedings of the SPIE, 7735,

[49] Fleming, B. T., McCandliss, S. R., Kaiser, M. E., et al. 2011, Proceedings of the SPIE, 8145,

[50] Reyes, R., Mandelbaum, R., Seljak, U., et al. 2010, Nature, 464, 256

[51] Carlberg, R. G. 2006, The Scientific Requirements for Extremely Large Telescopes, 232, 25

[52] Whitford, A. E. 1964, Astronomical Journal, 69, 675

[53] Stepp, L. M., Daggert, L. G., & Gillett, P. E. 2003, Proceedings of the SPIE, 4840, 309

[54] van Belle, G. T., Meinel, A. B., & Meinel, M. P. 2004, Proceedings of the SPIE, 5489, 563

[55] Hill, G. J., Gebhardt, K., Komatsu, E., et al. 2008, Panoramic Views of Galaxy Formation and Evolution, 399, 115

[56] Hill, G. J., Lee, H., Vattiat, B. L., et al. 2010, Proceedings of the SPIE, 7735,

[57] Hill, G. J., MacQueen, P. J., Smith, M. P., et al. 2008, Proceedings of the SPIE, 7014,

[58] Adams, J. J., Blanc, G. A., Hill, G. J., et al. 2011, Astrophysical Journal, Supplement, 192, 5