Stars and Galaxies
Input for the Science Case for an ELT

Luc Arnold, Roland Bacon, Roger Davies, Richard de Grijs,
Tim de Zeeuw, Jose Espinosa, Colin Frayn, Gerry Gilmore,
Raffaele Gratton, Konrad Kuijken (Co-Chair), Michael Merrifield (Co-Chair), Knut Olsen,
Eline Tolstoy, Paul van der Werf, Rosie Wyse (editor)

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1 Overall Summary

1.1 The Role of OWL

A very large optical-infrared telescope will allow us to derive the important processes of galaxy formation and evolution in the full range of environments. Several complementary lines of attack are possible, directly connecting the high redshift Universe, where the old stars now near the Sun formed, with the present-day Universe. Both the star formation histories of galaxies and the mass assembly histories of galaxies will be elucidated. We know that interactions and mergers between galaxies occur and play a (probably crucial) role in determining the morphological type of a given galaxy, but we do not know what merged, or when it merged – how do the merging histories of (non-baryonic) dark matter and of baryons compare? Similarly, stars clearly form(ed) at some rate from gas, but at what rate, where, with what stellar Initial Mass Function, and what were the effects of this star formation on the remaining gas? What is the connection between galaxies and the supermassive black holes at their centres? OWL will provide the answers.

Galaxies are assemblies of stars, gas and 'dark matter'; resolution of an external galaxy into its individual stars is a crucial step to deciphering its present state and its past evolution. For this, high spatial resolution is required. Further, stars of all ages should be studied, requiring sensitivity sufficient to include low-luminosity stars (like the Sun). The motions of the stars reveal the spatial distribution of the mass within the galaxy, and the chemical abundances and ages of the stars reveal the past star formation history. Only with the high spatial resolution and sensitivity of a 100m-class telescope can one carry out detailed study of the physical properties of individual representative stars in galaxies out to the nearest large cluster of galaxies, the Virgo cluster; this benchmark is required to encompass representative samples of the entire Hubble sequence of galaxy types, since it is only in galaxy clusters that significant numbers of large elliptical galaxies are found. The most common type of galaxy in the local universe is a gas-poor dwarf. However, the detection of extended, low surface brightness galaxies beyond the Local Group has been effectively prevented by their low contrast on the sky. OWL will break this surface brightness barrier by resolving these dwarfs into their constituent stars. Across the Hubble sequence, the metallicities, ages and radial velocities of even the oldest stars will be measured, providing the star formation histories and chemical enrichment histories of the local Universe. Kinematic signatures in the motions of stars identify recent mergers, while the overall potential well shape – and thus the true three-dimensional distribution of the ubiquitous dark matter – can be determined from the equilibrium kinematics.

These studies of the present-day mature galaxies should be – and with OWL can be – complemented by studies of present-day merging galaxies, with full coverage of the important parameters of mass ratio in the merger event and the time since first closest approach. Again, the star formation histories and chemical enrichment histories will be obtained, and the merger parameters derived. Thus we will map both the Hubble sequence of 'normal' galaxies and the Toomre sequence of merging galaxies, perhaps 'normal' galaxies in formation. Indeed we will be able to determine whether these mergers will produce galaxies with similar properties to those mature galaxies in the local Universe.

Further, OWL will allow direct study of high redshift objects at $z \gtrsim 1$ – when the bulk of star formation is inferred to have occurred – be they individual star-forming regions or independent 'galaxies'. The merger rate is also expected to have been much higher in the distant past, and the data on the stellar populations present at that time will provide an independent and complementary analysis to the 'fossil record' of the past history of present-day galaxies.

The intermediate redshift regime ($z \lesssim 1$) corresponds to look-back times of several Gyr, and thus probes the formation of the intermediate-age populations that are present now in many elliptical galaxies; direct observations will establish the physical state of the galaxies then, and, for example, demonstrate any connection to recent merger events. These timescales are also those of the secular evolution of isolated galaxies, contrasting with the rapid evolution on dynamical timescales of merger events. Secular evolution of a 2-D bar into 3-D bulge has been proposed as the formation mechanism for a significant fraction of present-day bulges, and OWL will again provide the necessary data for the testing of these hypotheses. The central regions of galaxies are now, largely through valiant efforts with HST, known to contain super-massive black holes, and these will unavoidably affect the evolution of the galaxy host, both at early times when the AGN is likely to be most active, and at later times, for example by destroying triaxiality. Again, the unprecedented spatial resolution of OWL, comparable to those achieved by VLBI in the radio, will provide unique insight. Thus OWL will provide the data that are required to underpin an analysis of the physical properties of galaxies over the age of the Universe.

OWL as envisaged is a critical component of a multi-faceted approach to understanding our Universe. GAIA will provide the astrometric capability that is impossible from the ground, supplying the proper motions and distances for objects. OWL complements and thus strengthens the capabilities of ALMA, which focuses on analyses of the dust and gas content of galaxies. Further, OWL will allow spectroscopic observations of targets discovered by NGST through imaging, providing the follow-up data needed for a physical understanding.

1.2 The Targets for OWL

The scientific goals were outlined above; the technical requirements are set in large part by these, and by the properties of the targets.

'Cosmic variance' requires that we study a statistically significant sample of each morphological type of galaxy in order to be able to confront theoretical predictions in a robust way. The distribution of galaxies in the nearby Universe is non-uniform. While the nearest dwarf galaxies are only tens of kpc removed, the nearest large spiral, M31, is $\sim$750 kpc distant. Farther away, at distances of $\sim 2-3$ Mpc, many dwarfs and some large spirals are found in the nearby Sculptor and M81/M82 groups of galaxies. M82 is the nearest 'starburst' galaxy with a significant population of 'super star clusters'. Centaurus A is a peculiar elliptical galaxy, providing one example at a specific place along the merger sequence. The well-known morphological-type – density relation describes the fact that only in clusters of galaxies are there examples of elliptical galaxies of the whole range of luminosity; thus to gain an understanding of this morphological-type – density relation, and its importance in the physics of the Hubble Sequence, the Virgo cluster, at a distance of $\sim$ 15 Mpc, must be within each. The Antennae galaxy system is the nearest example of an ongoing 'major merger'. NGC 3115 is an SO galaxy with a bimodal field stellar halo and globular cluster system, perhaps indicative of a merger event, and a well-established central supermassive black hole. Table 1 gives the distance moduli of these galaxies and clusters, and the angle subtended by 1 pc at their distances. For comparison, the diffraction limit of a 100m telescope is 0.8 milliarcsec at 300nm, 2.2mas at 800nm, and 6mas at K-band (2.2μm.) Note that these angular resolutions are comparable to those obtained by radio VLBI techniques, allowing very complementary observations on similar scales.

Table 1: The Scales of OWL

Object	$(m–M)_o$	θ(1 pc)	ra (J2000)	dec
LMC	18.5	$4''$	05 23	–69 45
M31	24.3	$0.3''$	00 43	+41 16
Sculptor Group	26.5	$0.11''$	00 23	–38 00
M81/M82	27.8	$0.06''$	09 55	+69 40
Cen A	28.5	$0.04''$	13 25	–43 00
NGC3115	30.2	$0.02''$	10 05	–07 42
Virgo Cluster	30.9	14 mas	12 26	+12 43
Antennae Galaxy	31.5	10 mas	12 00	–18 53
50Mpc	33.5	4 mas	...	...
Arp 220	34.5	2 mas	15 34	+23 30
Perseus Cluster	34.5	2 mas	3 18	+41 31
Stephan's Quintet	35.0	2 mas	22 36	+33 57
Coma Cluster	35.0	2 mas	13 00	+28 00
Redshift $z \sim 0.1$	38.5	...	...	...
Redshift $z \sim 0.3$	41	...	...	...

Determination of the age distributions of the stellar components of galaxies requires that the study include the oldest stars, those with a main sequence lifetime that is of order the age of the Universe. Stars like the sun, on the main sequence, with $M_V \sim +4.5$, $M_K \sim +3$, can, with OWL, be studied right out to, and including, the Virgo cluster. Evolved low-mass stars, on the upper RGB (hence fainter than around $M_V \sim -2.5$, $M_K \sim -6.5$, TRGB/AGB) can be studied all the way to redshifts of around $z \sim 0.1$, while massive stars and star clusters will be accessible at cosmological distances, $z \gtrsim 0.3$.

1.3 The Approach

The aim of the science described here is to provide a comprehensive understanding of the physics of galaxy formation and evolution. We develop four complementary lines-of-attack, each providing unique insight, and which taken together (and augmented by the matched capabilities of other future projects) allow a complete picture to be drawn. We first outline (section 2 below) the advances that OWL will make in our understanding of the present-day Hubble sequence of galaxies; these are examples of relaxed galaxies, for which morphology and underlying stellar populations are linked. Our current theories of galaxy formation tell us that all large galaxies were initially many smaller ones, and that this Hubble sequence is a product of a varied merging history, with the rate of mergers and mass ratio of the merging entities being important. Thus a study of nearby galaxies still in the throes of merging, as described in section 3, provides the information to assess this apparently critical evolutionary phase.

Direct observations of the integrated stellar populations in galaxies at cosmological distances (section 4) allows a comparison to be made with the inferences from study of old stars in examples along the present Hubble sequence. Lastly, the brightest phase in a galaxy's evolution is probably when it hosts an AGN – and we now understand that perhaps all galaxies go through this phase – and OWL will literally open up the Active Universe, as described in section 5.

2 Resolving galaxies into stars I. The Hubble Sequence

The Hubble sequence represents the product of galaxy evolution up to the present, and contains stars formed in the earliest phases of the Universe, together with those born yesterday. Through detailed study including the oldest 'fossils' it will be possible to unravel the mysteries of the formation history of these galaxies. With an ELT, long-lived stars, comparable in mass to the Sun, may be resolved in galaxies out as far as the Virgo cluster. Thus one may obtain deep colour-magnitude diagrams and spectra of stars of all ages in all normal environments (with the exception of only the very dense inner regions). Reaching to the Virgo cluster is critical in that only here is there a significant population of elliptical galaxies of a range of luminosities. This would be the first opportunity to analyse in detail the stellar populations across the entire Hubble Sequence of galaxies, including ellipticals. The spatial resolution of a diffraction-limited large optical telescope is critical to overcome crowding, and a 100m telescope is required to study the brighter galaxies at their half-light radius - without it work is limited to the less representative outer regions where crowding is less of an issue. The more luminous elliptical galaxies and bulges are of lower surface brightness (Kormendy 1977), aiding this endeavour.

The types of issues one can address – and understand – are in a broad sense whether the Milky Way is a typical spiral galaxy, is the Local Group a typical galaxy environment, are most bulges scaled-down ellipticals etc. At the distance of the Virgo cluster, a solar metallicity, solar mass main sequence star has $V \sim 35.5$. Thus, provided one is not limited by crowding (see Table 2), OWL will allow deep CMDs to below the oldest turn-off, moderate resolution spectroscopy of the lower RGB, and high-resolution spectroscopy of the upper RGB/AGB (and of course of more massive stars). Thus the distribution of ages, chemical abundances – including detailed elemental abundances – and accurate kinematics will be available, and this fossil record may be used to derive the two complementary aspects of galaxy formation and evolution – the mass assembly history and the star formation history. These are likely not to be the same, but are probably related through such effects as tidally-induced star formation. The mass assembly history is complicated since one really wishes to dintinguish whether the mass being added is baryonic, non-baryonic, gas, stars etc. However evidence is written in the stellar kinematics, in that signatures of previous orbits can persist, particularly in angular momentum, and in the stellar (atmospheric) chemical abundances, which are essentially unchanged throughout most of a star's life. The star formation history is given in the age distribution, and this together with the chemical abundances allows chemical evolution models to be developed that constrain gas flows etc. and allow a test of the validity of star formation 'laws' (e.g. Wyse & Silk 1989; Kennicutt 1989).

Complementary to excavating the past star formation, a 100m-class telescope also allows present-day star formation regions to be studied over a range of environment, and the interaction of such regions with their surroundings to be observed. Is star formation 'triggered'? Is 'feedback' positive or negative?

2.1 The Star Formation History Across the Hubble Sequence – when and how do stars form?

2.1.1 Old Field Stars

The age distributions for the oldest stars in galaxies across the Hubble Sequence have a particularly important role in constraining theories of galaxy formation. Determining the epoch of the onset of star formation in disks is a crucial constraint on hierarchical-clustering models, since currently the only mechanism to form large extended disks as observed, within CDM-dominated models, is to delay their formation until after a redshift of unity (Weil, Eke & Efstathiou 1998; Thacker & Couchman 2001 – astroph/010606). This could be disproven by the identification of significant populations of old stars in disks at large galactocentric distances. This can easily be achieved with OWL through deep CMDs for the inter-arm regions of disks, with an emphasis on the low surface brightness outer regions, out to the Virgo cluster. At even greater distances, identification of Blue Horizontal Branch stars in outer disks would be a significant constraint. Such data also constrains the law of star formation in disks (e.g. Ferguson et al 1998), since some models posit a 'threshold' gas surface density that should be exceeded.

The age distributions of stars in bulges and ellipticals are obvious discriminants of theories of their formation. Were bulges to be associated with inner disks, as 'bar-buckling' models for bulges would predict (e.g. Combes..), then the ages of inner disks and bulges should be more similar than if bulges and disks are separate and distinct. If bulges date from the last merger event that occurred with a mass ratio of close to unity, with the disk being accreted subsequent to that event (e.g. Kauffmann ref) then one would expect that bulges surrounded by larger disks would be older than bulges surrounded by smaller disks. Further, in this picture ellipticals are just bulges that have not been able – either through lack of time, or through being in a crowded environment – to accrete a disk, and there should be strong similarities between bulges and ellipticals.

A 100m telescope will open up to study the rich and varied populations of bulges and ellipticals from the Local Grup out to and including the Virgo cluster.

2.1.2 Rich Star Clusters

Based on their internal velocity dispersions (of around 10km/s), globular clusters in the Milky Way appear to have no dark matter haloes, and hence are really different from dwarf galaxies, despite having similar total luminosities ($M_V \sim -8$) and velocity dispersions. Indeed, the Fornax and Sagittarius dwarf spheroidals have systems of globular clusters that contain about as many stars as do the host galaxies. What determines how and when rich clusters form? In the Milky Way galaxy the globular clusters are classic tracers of the first stars to form, being old, metal-poor and in an extended spatial distribution, with little orbital angular momentum. However in other galaxies, in particular those with elevated rates of star formation, 'young' globular clusters are apparently forming (e.g. Whitmore & Schweizer 1995; Kennicutt & Chu 1988; Larsen 2001). This is clearly an important mode of star formation, that may have dominated the early phases of galaxy evolution. What determines the mass spectrum of bound clusters? What determines the fraction of stars that form in unbound systems?

Starbursts on large scales are likely to be common features of early galaxy evolution, as evidenced, for instance, by the intriguing sample of star-forming galaxies at high redshifts, $z \gtrsim 3$, recently identified as 'U-band dropouts' (the Lyman continuum break at 912Åbeing redshifted to the U-band, cf. Steidel et al. 1996, Giavalisco 1997, Lowenthal et al. 1997). The inferred star formation rates are $\sim 100\mathrm{M}_\odot/\mathrm{yr}$, with similar amplitude of gas outflows inferred from the ISM lines (e.g. Pettini et al. 2000). Nearby examples of such active starburst galaxies include M82, NGC 1140, NGC 1569, and NGC 5253. Without exception, these nearby starbursts are riddled with recently formed luminous star clusters, confined to the active starburst regions.

We want to understand the star formation physics in this extreme environment, to compare with the opposite extremes of the low star-formation rate, low density outer disks, and to pin down the underlying determining parameters of star formation on galactic scales. What drives the formation of such clusters, what are the masses and mass ranges of the clusters, what is the stellar initial mass function, what is the age range within a given cluster, and cluster to cluster? These clusters may well be progenitors of globular clusters (many galaxies show evidence for several globular cluster populations, suggesting a number of episodes of cluster formation), but a direct link is yet to be established.

To answer these questions requires measurement of fundamental physical parameters: sizes, masses, ages, abundances. OWL will provide them for the local starbursts, and these can then be used to understand the physics in the high-redshift starforming galaxies, in which the details of the starforming process cannot be observed.

To estimate cluster masses requires measurement of the virial parameters i.e. surface brightness profiles and velocity dispersion profiles. As these clusters are often affected by extinction, near-IR high-dispersion ($R \sim 30000$ or higher) spectroscopy and imaging, at a scale of 1–10pc with S/N of 20 per resolution element, are required. With ELT this type of measurement is possible out to the Coma cluster, well beyond the nearest few examples of (post-)starburst galaxies. Current 10m-class telescopes allow such measurements only in a global sense in the nearest galaxies with young super-star clusters. It is important to build dynamical models based on resolved kinematic measurements to test for M/L variations inside each cluster, as may be caused by mass segregation or star-formation differences within each cluster.

Each cluster forms, to first order, a single, coeval population, and is therefore relatively simple to model. The dynamical masses can be used to constrain the IMF in these clusters and compared with photometric measurements. Importantly this information also allows much more secure ages to be determined, so that the progress of the star formation through the starburst, as well as the survival rate of the clusters, can be traced. Abundances obtained from optical and nIR spectroscopy of the clusters and their surroundings will provide direct information on the chemical yields produced in this star formation mode, and on the speed with which the enriched ISM is mixed.

Complementary spectroscopy of the starburst regions in between the clusters will allow relative importance of the cluster/diffuse star formation modes to be measured.

[FIG - antennae or M82 pictures or similar]

In many starburst galaxies, large-scale galactic winds are observed, which are supposedly generated by the active starburst events taking place in their cores. Emission line spectra will probe, on scales of 5-10 pc, what we anticipate will be a complex transition region between the clusters and the base of the wind and can test predictions of models for galactic superwinds, such as the expected gas transfer rate, gas pressure, and energy input needed for the supernova-induced driving force. These are general physical processes, and the results can be applied at all epochs. As discussed further below, 'feedback' for massive stars plays a particularly important role in hierarchical-clustering pictures of galaxy formation, to supress star formation at high redshift. Understanding the mechanism is crucial.

Did all galaxies with globular clusters undergo a star-burst phase at early times? How does one understand the high specific frequency of globular clusters in dwarf spheroidals? Indeed no one scenario for the formation of globular cluster systems works for all galaxies across the Hubble sequence. There are currently thought to be at least three processes through which GC systems may form. Giant elliptical galaxies may build up their systems in galaxy mergers through the combination of the progenitor systems (e.g. Forbes et al. 2000) and through the formation of new clusters in the merger (e.g. Schweizer et al. 1996). Galaxies such as the Milky Way and M31 likely formed many of their clusters *in situ*, perhaps in the hierarchical collapse of the halo (Côté et al. 2000), or more simply as Jeans mass condensates (e.g. Fall & Rees 1985; Harris & Pudritz 1994). Parts of GC systems may also have been built through the accretion of the clusters of companion galaxies (Lin & Richer 1992). Indeed, the Sagittarius dwarf is merging with the Milky Way (Ibata et al. 1994), in the process contributing some of its $\sim$4 GCs to the halo (Da Costa & Armandroff 1995). There is also speculation that the nuclei of dwarf galaxies could be proto-globular clusters (e.g. Freeman 1993).

Deciding which processes dominate the formation of GC systems requires measurements of metallicities, ages, and kinematics of cluster systems in galaxies spanning the entire Hubble sequence. The study of individual resolved stars in globular clusters in the Local Group will be possible with GAIA and 10m class telescopes. OWL will extend this to more distant systems, with the surface brightness at which confusion sets in decreasing with distance. Thus while the regions fairly close to the centres can be studied for globulars in the Sculptor group, only the extreme outer parts are feasible in the Virgo cluster.

Integrated light studies of globular clusters are possible with a 100m telescope out to cosmological distances; these provide an overall metallicity, radial velocity, and age constraints from line index strengths, cf Cohen et al; Cote et al Keck observations of the globular cluster systems of M87 in Virgo.

2.1.3 Feedback from Stars

Feedback from massive stars into their surroundings plays a crucial role in several aspects of galaxy formation and evolution. For example, the chemical enrichment of the IGM in clusters clearly indicates that the gas was processed through stars, presumably in galaxies. Indeed galactic superwinds, driven by rapid star formation, are among the most remarkable structures associated with starburst galaxies (e.g. Lynds & Sandage 1963, McCarthy et al. 1987, Heckman 1998 (ASP Conf vol 148, p127, Shopbell & Bland-Hawthorn 1998). The well-established mass–metallicity relationship for galaxies also can be most easily understood if metal-enriched outflows occur preferentially in lower mass galaxies, but that most if not all galaxies lose metals to the IGM (cf. Kaufmann & Charlot 1999). Further, the 'over-cooling problem' of hierarchical-clustering cosmologies (e.g. White & Frenk 1991 and all the recent papers) by which essentialy all the baryons would form stars at early times unless somehow prevented, and the requirement to produce large extended disks point (within the CDM scenarios) to strong feedback that reduces the star formation efficiency at early epochs (e.g. Navarro and Steinmetz 1997; Weil et al; Thacker & Couchman 2001). But how does feedback actually work? The effects are clearly non-linear and the theory is completely incapable at present of describing the physics. Innovations need observations.

StarBursts

Following the discussions of super-star-clusters above, OWL will allow detailed study of the transition region between a galactic starburst, its associated star clusters, and the superwind. This requires observing at mid-infrared wavelengths (5-25 micron) where the radiation is dominated by thermal emission from hot dust grains, with contributions from ionized gas and molecular features. Spectroscopic observations in the mid-IR bands (complementing the imaging capability of NGST) will allow us to distinguish between supernova-induced shocks and radiative heating generating the superwind and will possibly lead to the first direct evidence for super star clusters in the mid-infrared. OWL's spatial resolution is well matched to the physical scales of $\sim$ 5-10 pc associated with the star clusters, supernova remnants, and their expected interaction zones. We will thus be able to study the small-scale physical processes which combine to drive a large-scale flow.

Optical absorption-line studies of the cool ISM that is entrained with the hot wind have been successfully carried out for local starbursts (Heckman, Lehnert, Strickland & Armus, 2000), using moderate resolution spectroscopy and analysing the Na D line at 5890 Å. This leads to estimates of outflow velocities and mass flow rates. This can be extended to higher redshifts provided there is a background source, or the optical continuum of the target galaxy itself is strong enough. The kinematics of the ISM from absorption-line studies have been analysed for Lyman break galaxies at $z \sim 3$ (Pettini et al. 1998), again finding outflows to be common.

The sensitivity of OWL will allow a large sample to be studied, over representative luminosity ranges, for a range of redshifts, so that the evolution of feedback can be determined.

Quiescent Star Formation

Is star formation sequential, in that supernovae etc can trigger gravitational collapse in nearby regions (e.g. Elmegreen and Lada 1977)? Or is feedback negative? We have actually very little information on the detailed interaction of stars (especially high-mass stars) and their environoment in HII regions, and especially not the effect of metallicity. In our Galaxy we have a problem of perspective, and we also have a rather limited number of star-formation environments we can probe, and almost no variation in metallicity. Most of the star-formation takes place in the disk of our Galaxy, which means it is subject to variable extinction and uncertain geometry. By looking to external environments such as interacting systems like the Magellanic Clouds we can explore the effects of environoment and metallicity on the star-forming properties. Including star-forming dwarf irregular galaxies, BCDs or outer regions of spiral galaxies further increases the variety of metallicity and star-forming rates that can be studied.

The study of the most active starforming regions in the LMC is prime territory for 8m telescopes eqiupped with adaptive optics fed spectrographs. However extending the work to the local group requires a larger telescope, and out to the Virgo cluster - the distance at which our sample of the universe begins to be representative in terms of environments sampled - will require the resolving power and collecting area of a 100m telescope.

Star formation rates are often estimated from the H-alpha flux, assuming a simple relationship (e.g. Kennicutt 19xx). A direct test of this is possible by resolving at least the brightest of the already-formed stars in HII regions in a wide range of environments. This is difficult: a large HII region can contain some 10^5 stars in a volume 10pc across, thus a resolution of 0.01 pc is required for an uncrowded view of the stars. At the LMC 0.01pc subtends an angle of 40mas, out in the local group 2mas. While such work will still not bring the full IMF into view, IMF variations at the high-mass end would be an important clue to its universality. This work is just beginning, e.g. (Henning et al. 2001 A&A, 370, 100).

[FIG- from Henning et al]

Further, the physics of the effects of stellar winds on the HII region is an important ingredient for galactic chemical evolution modelling. How efficiently do stars transfer their metals to the environment? How well-mixed is this enriched gas? A comparison between HII regions which have, and which have not, suffered a supernova explosion will shed light on how SN enrichment proceeds. These questions requires a detailed spectroscopic look at the emission-line gas in the HII region and its dynamics ($R \sim 10000$). An IFU will provide a complete picture in these very complex environments. Angular resolution is the prime requirement.

It is important to understand the star formation conditions in as wide a range of environments as possible. Only this way can *reliable* extrapolations to what is seen at lower resolution at cosmological distances be made, and the starformation history of the universe as a whole be constructed.

2.2 Mass Assembly History

2.2.1 Disk heating

Stellar disks are thin because they are cold, in the sense that the random stellar motions are much smaller than the organised streaming motions, reflecting the dissipation and conservation of angular momentum that is inherent in disk formation (e.g. Fall & Efstathiou 1980). But thin stellar disks are fragile, and there are many possible heating mechanisms that could puff them up. Some of these processes are internal, such as the Spitzer-Schwarzschild (1951; 1953) mechanism by which stars gain random motions through encounters with large clouds in the ISM (at that time undetected!). Some of these processes are external, such as the effects of the accretion of a satellite galaxy, and accompanying incorporation of some of that satellite's orbital energy into the internal degrees of freedom of the disk (e.g. Velaquez & White 1999). Disentangling these processes is challenging. Further, star formation could occur during the slow dissipational settling of gas to the mid-plane, again providing for older stars in a thicker component. The amplitude of any vertical metallicity tradients is an important discriminant. OWL will allow detailed study of external disk galaxies.

To date, it has only been in the solar neighbourhood of the Milky Way that there is direct evidence – from distributions of kinematics and ages – for a correlation between age and vertical velocity dispersion, most easily understood as a manifestation of the evolution of the kinematics of stars with age, with the stellar population becoming progressively heated and thickened (e.g. Wielen 1977). The detailed form of the correlation between kinematics and age is as yet rather poorly defined (e.g. Fuchs et al. 2001) even at the solar neighbourhood, but it is clear that the combination of a variety of scatterers is required (e.g. transient spiral arms, Giant Molecular clouds; Jenkins 1992). The observations of surface brightness profiles of external galaxies (e.g. Searle and van der Kruit) imply that scale heights are constant with radius and this cannot be understood by these scattering mechanisms. Clearly for an understanding of the general physical mechanisms that form stellar disk, we need the detailed age, kinematics and metallicities for disk stars far from the solar circle, and indeed for external disk galaxies. The astrometric satellites FAME, SIM and GAIA will map the Milky Way and much of the Local Group. OWL will provide the requisite data (albeit line-of-sight velocities) for more distant systems.

2.2.2 Thick disks

The efficiency with which scatterers confined to the disk plane can heat a stellar population decreases once those stars are heated and on orbits that take them out of the plane for a substantial fraction of the time. Thus while the kinematics of the bulk of local disk stars can be understood by such scatterers, there is a substantial population – the thick disk – that is too hot. The thick disk of the Milky Way does not show a vertical abundance gradient, arguing against a slow dissipational setting (Gilmore & Wyse 1985). Sufficient heating could, however, be induced by the accretion of a reasonably massive satellite galaxy (e.g. Gilmore & Wyse 1985; Ostriker 1990; Velazquez & White 1999). In a merger, the orbital energy is absorbed into the internal degrees of freedom of the merging systems, resulting, in a minor merger, in the disruption of the small system and the heating of the large system. Given the rather continuous star formation in thin disks, the age distribution of stars in the thick disk then would directly reflect the merging history of the disk. The fact that the thick disk appears to be uniformly old then means that the Milky Way disk did not suffer a significant merger for a very long time (e.g. Gilmore & Wyse 2001). How do other disk galaxies compare? The information required is again age distributions, metallicity distributions and kinematics, as a function of location above the thin disk plane.

A natural place to start is to observe CM diagrams for the stars in edge-on disks, to see how the stellar populations vary with distance from the plane. The classic galaxy for such a study would be NGC 891, which lies at a distance modulus of $m - M = 30$ (cf. van der Kruit & Searle 1984). Obtaining a CM diagram down to V=36 ($\sim$ 3 hour integration with OWL) would allow us to study the spatial distribution of stars down to the oldest turnoff, G/K dwarfs. Happily the low surface brightness, low crowding, regions far from the mid-plane are the science focus. Modest-dispersion (R$\sim$3000) optical spectra of giant stars in the disk of NGC891 could be obtained in $\sim$ 1 hour with OWL, allowing a study of metallicity gradients perpendicular to the galaxy's plane, and search for evidence of a discrete thick disk at low metallicities. Similar spectra of such stars in face-on galaxies would provide the complementary measurement of random velocities perpendicular to the plane as a function of metallicity (giving velocities to the requisite ~10 km/s accuracy).

Plausible mergers (mass ratio, stellar fraction etc) unavoidably leave a signature in the vertical structure of the disk, and hence determination of the stellar populations perpendicular to thin disks is of great importance in constraining hierarchical clustering cosmologies, and determining the sequence of galaxy formation.

2.2.3 Gradients and mixing in ellipticals

Two main paths have been proposed for the formation of elliptical galaxies – as a result of the merger of two (disk) stellar systems of approximately equal mass (e.g. Toomre 1977; White 198x; Barnes 199x), or as the result of a highly dissipative, short-lived starburst (e.g. Carlberg 199x). These two extremes may be distinguished by their rather distinct stellar age distributions – much narrower in the case of the short-lived starburst – plus the inferred large metallicity gradients in the highly dissipative case. Kinematic signatures of merging and accretion may also be observable, in particularly in the outer parts where dynamical times are longer.

A 100m telescope would allow intermediate-resolution ($\mathcal{R} \sim 5000$) spectroscopy, suitable for chemical abundance studies and for radial velocities, of individual bright stars in galaxies in the Virgo cluster. This includes the evolved TRGB/AGB stars of old–intermediate-age populations, providing distributions over abundance, age, and kinematics based on samples of 1000s of stars. Determining the kind of stellar orbits populated by stars of different abundances gives powerful insights into the merger history of an elliptical galaxy, such as the number of subunits that made up the galaxy, the amount of star formation that took place after a (minor) merger, and what role gaseous disks played in the history of the elliptical. There is expected to be variation in these properties with environment (cluster vs. group vs. field), so a comprehensive sample of elliptical galaxies is needed for such work.

The outer regions are those where mixing will take longer, reflecting the longer dynamical timescales. These are just those regions of large ellipticals that are accessible to an ELT at the distance of the Virgo cluster. Indeed, those larger ellipticals for which perhaps merging and accretion is more important, are of lower surface brightness (Kormendy 1990) and thus we have the happy situation that the science targets match the capabilities.

Analyses of the strengths of various metal-line indices in the integrated spectra of ellipticals have suggested that there is a 'G dwarf problem' i.e. a lack of metal-poor stars compared to the simplest models of chemical evolution (Chiosi). This has been interpreted as indicating gas (in)flows during the epoch of star formation, within attendant implications for the model of elliptical galaxy formation. However, this result is not well-established (e.g. Maraston and Thomas 2000). Determining the true chemical abundance distribution on a star-by-star basis will provide a definitive result. At a minimum, an abundance spread implies a duration of star formation at least long enough for self-enrichment.

2.2.4 Dwarf Galaxies – Testbeds for Dark Matter?

Dwarf Galaxies are the most numerous galaxies in the local universe, found almost exclusively in association with a larger 'parent' galaxy, with which they are known to interact and merge. Indeed, small systems of mass comparable to dwarfs are believed to be the first systems to become self-gravitating and form stars, at redshifts $z \gtrsim 10$. Did they merge into the large galaxies we observe today? Are they related to the faint blue galaxies at redshifts $z \sim 1$?

Further, dwarf galaxies may hold the key to several important aspects of dark matter. The low surface brightness, gas-poor, dwarfs in the Local Group have internal stellar velocity dispersions that are sufficiently high that very substantial amounts of dark matter are inferred. However, low surface brightness, gas-rich, dwarf galaxies, for which HI maps are available, have derived mass profiles that are apparently in conflict with the central density cusps predicted by the popular cold-dark-matter cosmologies (Navarro, Frenk & White 1997; Moore et al. 199x). These theoretical central density cusps also make dwarfs very robust against tidal disruption, leading to the prediction that many of them are not assimilated into larger structures, but persist in large numbers – at least an order of magnitude more than are observed, in the Local Group (Klypin et al 1999; Moore et al 1999). Can there be numerous hidden dwarfs, essentially just dark matter? It has been proposed that star formation can be effectively suppressed in these small systems after the epoch of reionisation, when the Jeans mass was supposedly raised above the mass of a typical dwarf (e.g. Bullock et al 2001). However, the dwarfs in the Local Group have had extended periods of star formation (Hernandez, Valls-Gabaud and Gilmore 1999). How general are such intermediate-age populations? The analogues of the Local Group dSph are of such low surface brightness that they must be detected by resolving their individual stars, and thus the population in the Virgo cluster is essentially unknown; indeed our information on dSph beyond the Local Group is very limited (cf. Gallagher & Wyse 1993; Irwin et al 2000). The ELT will allow the discovery of low surface brightness galaxies out to Virgo, by resolving them, and hence determine the faint end of the galaxy luminosity function in a cluster reliably.

What role did/do dwarfs play in the chemical enrichment of the IGM? Are dwarf galaxies forming today, as fragments in tidal arms of interacting galaxies? Numerous low luminosity systems exist in the Virgo cluster – are they actually dominated by dark matter and tidally robust, or are they transient tidal debris? Are dEs in the Virgo cluster the surviving central regions of spirals that underwent 'harassment' (Moore et al. 1996)? Radial velocity studies of the integrated light of dwarfs suggest that indeed the dEs are associated with infalling galaxies (Conselice, Gallagher & Wyse 2001).

These questions and conundrums need a study of the detailed stellar populations in dwarf galaxies in all the environments where they are found, ranging from low density groups to rich clusters of galaxies. Moderate-high resolution spectroscopy (the velocity dispersions of interest are around 10km/s only) of tracers such as RGB or turn-off stars, across the face of the galaxy, provide the necessary data for kinematics/dynamics studies, while also providing elemental abundances. Whether or not dark matter is indeed dominant in turn provides a strong constraint on e.g. models whereby dEs in clusters are formed from spiral disks/bulges through harrassment, since the central regions of spirals have a significantly lower dark matter content than do the local dSph. The age distributions require deep CMDs, to below the oldest turnoff. The combination of age and metallicity data will provide the chemical enrichment history.

Much of the Local Group is within the realm of the existing telescopes. A 100m telescope is required to open up the realm of rich clusters, where dwarf galaxies are particularly abundant. The detailed data discussed above are possible for lowish surface brightness dwarfs in the Virgo cluster. The 100m will break the surface brightness barrier, by resolving the very low surface dwarfs into their constituent stars, allowing them to be identified for the first time, as over-densities in star counts. Thus we will know the faint luminosity function, and will be able to analyse the internal propeties of the faintest dwarfs in Virgo. Even out to the distance of the Coma cluster, the intermediate-age population, traced by AGB stars, can be studied on a star-by-star basis, by imaging and medium-resolution spectroscopy.

Integrated light spectroscopy of dwarfs in the Coma cluster and beyond will provide metallicities, velocity dispersions and rotation velocities. Indeed, dwarfs at cosmological distances can be probed through their integrated light ($M_I \sim -14$, and $z \sim 0.3$ corresponds to $m - M = 41$).

2.3 Odds and Sods

2.3.1 Lithium abundances

The abundance of primordial lithium is a major constraint on BBN and the value of Omega baryon. Recent complementary observations of fluctuations in the CMB (BOOMERANG etc) have hinted at a high value of Ω_b, as do observations of deuterium in hig redshift quasar absorption-line systems (Tytler et al). The current assumption is that the level of the 'Spite Plateau' of lithium in metal-poor halo F/G stars is an estimate of the primordial lithium, but there are suggestions that the amount of lithium could be affected by internal processing/diffusion even in these stars (e.g. Salaris and Weiss 2001). The Spite Plateau at face value favours a lower Ω_b than do the newer results above (but the actual value of the spite plateau depends on temperature scale and this needs checked!). In any case, it is important to measure Lithium in younger metal-poor F/G stars – this can be done by targeting stars in the SMC, which is metal-poor and contains stars of range of ages. Indeed, mapping Lithium as a function of age (keeping mass and metallicity fixed!) will simultaneously constrain primordial abundances and subsequent production rates. This requires deep CMDs from which stars are then selected for echelle spectroscopy. Particularly the spectroscopy requires a 30–100m class telescope.

This work could be extended to the nearest dwarf spheroidals, which represent a considerably lower-density environment than the SMC, which may have repercussions for the internal diffusion in stars (stellar rotation/binarity differences).

[FIG - Li line in hi-res spectrum]

2.3.2 Microlensing

Microlensing has in the past decade opened up the possibility of studying the mass function of unseen populations. Microlensing experiments to the Magellanic Clouds have effectively ruled out a population of stellar-mass objects as the dominant constituent of the dark halo of the Galaxy. Experiments along sightlines towards the bulge have yielded an unexpectedly high number of events, allowing many beautiful experiments involving microlensing, such as planet searches around lenses, or resolved stellar surface spectroscopy of bulge stars, to be performed.

Microlensing surveys of other galaxies are possible provided sufficient angular resolution is achieved - in order to detect stars which brighten by a small factor it is necessary to keep the number of other stars per resolution element as small as possible.

If a galaxy could be monitored continuously, microlensing events can be detected at a rate given by (Gould 1995 Apj 455,44)

$$\Gamma \approx 0.01 \tau N_{res} \Gamma_{\overline{M}}$$

where τ is the optical depth (typically 10^{-7}), N_{res} is the number of resolution elements that are monitored, ($4\,10^6$ for a 20" field at 5mas resolution) and $\Gamma_{\overline{M}}$ is the photon arrival rate at the fluctuation magnitude $\overline{m}$ of the galaxy ($\overline{V} = 31$ for Virgo). For M87, this would translate into hundreds of events per day for a 100m telescope. For fixed detector size but diffraction-limited images the rate scales as the square of the telescope diameter, and the inverse square of the source distance. Typical timescales for brightening and fading of individual events are a week, so a microlensing campaign would have to last on the order of months. Sparser sampling in time reduces the event rate in proportion to the sampling frequency.

Even if τ is lower than 10^{-7}, as is the case for dwarf galaxies and globular clusters, monitoring experiments are still feasible. A 100 m telescope will therefore allow the baryonic dark matter distribution of our Galaxy, the Local Group and even the Local SuperCluster to be accurately mapped out. It will probe differences in the baryon content of dark haloes of galaxies along the Hubble sequence and of clusters.

Experiments such as these pose challenging requirements on the stability of the PSF, as variations are detected through image subtraction techniques.

2.3.3 Stars as distance indicators

The star-resolving power of ELT allows the traditional distance ladder to be shortened considerably, thus tightening the accuracy of astronomical distance measurements. In particular, it enables the link from astrometry-based distances to the Hubble flow to be made with only one intermediate step. GAIA will calibrate, ELT will implement.

Massive variables, such as Cepheids or red supergiant long period variables are the brightest candidates for this kind of work. Their contrast remains high even though, being massive stars, they tend to be found in high-background environments, such as star-forming regions of spiral disks. Further, the RSG LPVs are particularly bright in the near IR, minimising the effects of dust (e.g. Pierce et al 2000). Distance measurements based on such stars will be able to be pushed to well beyond the Coma cluster, and potentially to cosmological distances, $z \sim 0.5$, with an ELT. This will enable distances to many SN Ia hostgalaxies to be determined on the Cepheid/SGLPV scale.

The tip of the RGB ($M_V = -2$, $M_K = -6$) provides a good standard candle for old stellar populations; it is particularly suited to the (low surface brightness) outskirts of galaxies, where crowding is not an issue. Even given the need to determine the luminosity function down to several magnitudes below the tip to get a good identification of the tip, the Coma cluster is well within range of a diffraction-limited 100m telescope (but not of a 30m).

3 Resolving galaxies into stars II. The Merger Sequence

Also at the present epoch, galaxies are still interacting and evolving along the Hubble sequence. Examples of galaxies in many different stages of interaction/merger may be found in the local universe, and they allow us to study the detailed effects of such mergers. Comparison with the local quiescent Hubble sequence galaxies, and with systems at high redshift, allow a many-faceted picture of galaxy formation and evolution to be developed. We can study systems as a function of the mass ratio in the merger, or as a function of time elapsed since first closest approach (roughly), or as a function of environment such as relative velocity, etc.

Local starburst/interacting systems such as the M81/M82 group, and Cen A, can be studied in detail, using the unevolved old stars. (maybe should have image of that amazing HI map that covers the entire system M81/82?) Even out to redshift $z \sim 0.1$, is possible with an ELT, through optical imaging, to identify TRGB/AGB stars in the low-background outskirts ($M_V = -2.5$ stars are at $V = 36$) and mors massive stars out to larger distances and/or higher surface brightnesses. Thus faint stellar tails can be detected as well as some constraints on their stellar population derived, e.g. through detecting long-period variables. In the inner regions of merging galaxies young star clusters can be studied in great detail, and near-IR spectroscopy performed to derive ages. Characteristic sizes of starforming regions can be measured with high resolution optical imaging (at z=0.1, 1mas corresponds to 3pc), and combined with spectroscopic velocity dispersions to yield M/L and hence IMF constraints. (See section on young star clusters above.)

[FIG of Toomre sequence, and antennae clusters]

3.1 Polar Ring Galaxies

Polar ring galaxies are a peculiar class of interacting galaxies, which find themselves in a rather long-lived intermediate state where one galaxy is tidally shredded but not yet absorbed by the other; the mass ratio, gas content and initial orbital inclination are important parameters in determining whether or not a polar ring will form (e.g. Bekki 1998). This class of incomplete merger therefore allows both the post- and pre- merger star formation to be viewed clearly [RW: How, if both systems form stars?] . How much star formation is happening in polar rings now? What was the star formation history? What was the initial metallicity of the polar ring material? With ELT this question can be addressed through a stellar population analysis (CMDs as well as intermediate-resolution spectroscopy of the R/AGB) of the polar rings' stellar populations.

Further, polar rings provide a unique opportunity to determine rotation curves in two perpendicular planes, and constrain the shape of the underlying dark halo (e.g. Sackett and Sparke 19xx). With HII regions in both the polar ring and in the disk one can such an analysis can be pushed out to beyond the Coma cluster.

[FIG of some polar rings - 4650A?]

3.2 Minor Mergers: Elliptical Galaxies with Shells

Many elliptical galaxies show faint shells in their surroundings. These are thought to be stars associated with tidally shredded satellites in the process of being assimilated into the larger elliptical. A complete census of these shell systems, together with a study of the dynamics of the stars in them, will allow the minor-merger rate onto elliptical galaxies to be determined very well. Because of their particular dynamical state (phase wrapping), shells also offer a unique opportunity to determine the gravitational potential at very large distances from an elliptical galaxy. With ELT deep images and R$\sim$10000 spectroscopy of shell systems, at surface brightness levels less than 1% of sky, becomes possible (in the optical.)

[FIG of shell galaxy, and some of Dantes CenA results?]

3.3 Minor Mergers and Interactions: Connectons between Satellites and Disks

Large galaxies like the Milky Way tend to have many satellites, and interactions between them take many forms, ranging from complete assimilation of a satellite by the larger system, to perhaps stimulating periodic star formation 'bursts'. Indeed, it may be that the majority of star formation in disk galaxies is tied to interactions with satellites (e.g. Lacey and Silk 199x). There are suggestions that the star formation of the local disk is influenced by the closest passage of the LMC (e.g. Rocha-Pinto and maciel etc), which itself is clearly being tidally distorted (e.g. Putnam et al 1999). There are clearly interactions between the satellite galaxies of M31, with a tidal connection from NGC205 to M31 (e.g. Guhathakurta et al), and a large tidal stream detected in the outer halo (Ibata et al 2001). As noted above, there is an extensive HI envelope connecting all the galaxies in the M81/82 group.

As noted above, the high spatial resolution and sensitivity of OWL will allow the detection of low surface brightness galaxies as an over-density of resolved stars. Thus our inventory of the members of galaxy groups will be greatly augmented, especially for more distant groups. Assuming properties like those of the satellites in the Local Group, i.e. strong intermediate-age populations, with luminous AGB stars, detailed kinematics will be possible out to 50 Mpc. Thus we will have data to undertake analyses of group dynamics. The intermediate-age stars in the disks of the larger group members can be used to determine the recent star formation history, and see if that is correlated with the population of satellite galaxies.

3.4 Major Mergers

The closest examples of the on-going major mergers of the Toomre (1977) sequence are the Antennae galaxies. Photometry and spectroscopy of the numerous super star clusters that are forming, together with HII regions and individual very massive stars, will provide kinematics and chemical abundance estimates. Also as discussed above, the ages of the SSCs will provide further insight into the star formation and merging process. Can this form a system like the giant ellipticals in the Virgo Cluster?

3.5 Starbursts

Starbursts form a fundamental mode of galaxy evolution. In a starburst, a galaxy undergoes within a short period of time (less than 10^8 years) major changes in morphology, colour, stellar population, gas and dust content, and metallicity. Starbursts are thus central to our understanding of the Hubble sequence and the evolution of galaxies as a whole. In addition, starbursts often go hand-in-hand with the phenomenon of active galactic nuclei (AGNs); however, the relation between these phenomena is unknown.

Starbursts are generally obscured systems, with tens of magnitudes of visual extinction, forcing observers to go to near- or mid-infrared wavelengths. Since stars form inside dusty molecular clouds, this is hardly surprising. However, there exist also low-metallicity and relatively unobscured starburst galaxies that can be probed optically. These are generally small irregular galaxies. Interestingly, these objects serve as local laboratories in which we can study processes occuring in their (much more luminous) high-redshift cousins, the Lyman break galaxies at z 3. In general, although extinction is always a caveat, it appears that starbust phenomena can be studied at all wavelengths accessible to OWL. This can be illustrated by the prototypical starburst galaxy M82, where evolved star clusters can be studied optically (De Grijs et al 2001), while the ongoing starburst can be probed in the near-infrared (Foerster Schreiber et al 2001). For more obscured regions, mid-infrared data are indispensible.

1) Optical studies

The young, massive stars formed in starbursts produce copious UV-radiation, which will be redshifted into the optical regime at high redshifts. Spectroscopy of the rest-frame UV-emission of these young star clusters is of great value as a diagnostic: the stellar wind lines are sensitive to cluster age for the youngest clusters, while the absorption lines probe metallicity. Emission lines from clusters with a modest star formation rate (1 Msun/yr) will be detectable up to z 3 for a 100m OWL. The highest resolution will be critical in order to separate the cluster from its environments. This argument pushes for a 100m OWL with full optical capability.

2) Near-infrared studies

Near-infrared observations are necessary to probe the ongoing, young (and therefore dust-enshrouded) starbursts. The near-infrared region is rich in bright and highly diagnostic spectral features: hydrogen and helium recombination lines (probing the upper main sequence), the [FeII] 1.26 and 1.64 micron emission lines (shocks from supernovae and superwinds), H_2 vibrational lines (probing the hot molecular gas in the starburst region) and spectral features of bright red supergiants (principally the CO absorption bands). Since these features all probe a different phase of starburst activity, they are excellently suited for disentangling starburst properties and evolution (see Foerster Schreiber et al 2001 for a case in point).

The power of OWL in this field lies in its high angular resolution. The K-band light of starbursts and young starclusters is dominated by red supergiants which are so bright that they can be observed over large cosmological distances. The limiting factor will be crowding, since starclusters are very compact. For instance, the starburst core of M82 contains in total about 5.10^5 red supergiants. Given the size of this region, a 100m OWL would be able to resolve an M82 starburst into individual red supergiants out to the distance of the Virgo cluster, if the stars are approximately uniformly distributed (for a 30m OWL, this would only be possible in M82 itself). In real starbursts however, star formation takes place in clusters as well (although the relative proportion of clustered and diffuse starformation is acually a subject of debate). A typical starcluster in the M82 starburst contains about 10^4 red supergiants, and given the size of these clusters, a 100m OWL would be able to separate these stars in the nearest starburst galaxies (distances less than 6Mpc). This offers the opportunity to do dynamics of starbursts and starclusters based on individual red supergiants (using the CO absorption bands), thus addressing issues such as mass segragation, virialization, dynamical mass, properties and universality of the Initial Mass Function, etc. An integral field spectrograph with R 10000 would be required for this project. This project is ONLY possible with a 100m OWL, due to the angular resolution requirement.

An important fraction of star formation occurs in gigantic episodes, possibly involving substantial fraction of the host galaxy: the starbursts. The closest galaxy where a starburst is currently going on is M82, the companion of M81 at a distance modulus of $(m\text{-}M)_0$=27.8. While starbursts seems to be excited by galaxy-to-galaxy interaction, mechanisms are far from being clear. There are in particular three topics of extremely high interest:

(i) Observations of M82 indicates the presence of bright, very dense regions of star formation (O'Connell et al. 1995, ApJ, 446, L1). Some of them are likely proto-globular clusters. The mechanism of formation of such dense aggregates of stars are far from being understood. OWL offers the opportunity to study such regions at unprecedented high resolution. The large dust absorption suggests that such observations should be carried out in the infrared; with OWL it is possible to study such objects at a resolution of a few hundredths of a pc, similar to the resolution achieved by current AO techniques at the distance of the MC's, and at a spectral resolution high enough for a detailed kinematical study of these superclusters (errors of $\sim$1 km/s). hence get internal dispersions – are they bound?

(ii) Powerful winds from the numerous early type stars, and explosion of core-collapse SNe inject into the ISM huge amounts of kinetic energy and momentum: this may originate galactic winds, causing significant fraction of the stellar gas to be lost into the intergalactic medium. While it is not clear that this will be the fate of M82, the chemical composition of the interstellar medium in this galaxy is crucial to our understanding of chemical evolution of galaxies, and of the intergalactic medium in cluster of galaxies: are O/Fe and alpha/Fe ratios abnormal? Is the (high-velocity) O-rich gas preferentially lost? This requires a detailed study of the composition of very young stars and of composition and kinematics of ISM in star-bursters, both from observations of HII regions and SN remnants. The high space resolution and large collecting area of OWL are crucial for such observations

(iii) In order to explain chemical composition of the intracluster medium in clusters of galaxies, peculiar stellar initial mass functions have been claimed for starbursts, truncated at masses above 3 Mo (Elbaz et al. 1995, A&A, 303, 345). Direct estimates of the IMF in star forming regions in M82 may allow us to test this hypothesis. This requires a very good resolving power, in order to appropriately derive the luminosity function in the very dense regions of star formation: diffraction limited observations with OWL in the near IR at the distance of M82 should provide data of a quality similar to that obtained for star forming regions in the MC's using HST (see e.g. Marco et al. 2000 AAS 197, 4122; Sirianni et al. 1999, IAU Symp. 190, p. 254) or current day AO: this is adequate to study IMF's down to about 1 Mo, just enough for the present purpose.

OWL also offers the opportunity to trace the evolution of the starburst and its feedback on the host galaxy - i.e., the detailed astrophysics of galaxy evolution by starbursts. Relative age-dating of starbursts can be performed by observing the equivalent widths of hydrogen and helium recombination lines, which measure the turn-off point on the upper main sequence, especially in comparison with the CO index which measures the red supergiant proportion. Feedback can be studied directly in the [FeII] 1.64 micron line which traces shocks (i.e., mechanical energy input = feedback) from supernova remnants and superwinds. Again angular resolution is the driving force for a 100m OWL. At an observing wavelength of 2.2 micron, HII regions of size of those in the M82 starburst can be resolved out to z 0.2. Compact HII regions can be resolved out to 60 Mpc distance (reaching the nearest ULIGs), and ultracompact HII regions out to 6 Mpc (i.e., again in only the nearby starburst galaxies). Sizes of individual supernova remnants in active starbursts are a few pc or more (as shown by high-resolution VLA data of M82 by Huang et al 1994) and will be resolvable in the luminous [FeII] lines out to 100 Mpc, and thus be accessible out to the nearest ULIGs such as Arp220.

3) Mid-infrared studies

The mid-infrared spectral region is not only necessary to overcome extinction in the most obscured regions, it also provides a totally different view of the universe compared to the optical/near-IR region, since it is probes hot dust in star forming regions, and not (directly) photospheric radiation. The importance of the mid-infrared is best illustrated by the ISOCAM 15 micron images of the Antennae (NGC4038-4039) by Mirabel et al (1998), where an impressive complex of obscured star formation is revealed in a region that is quite inconspicuous at shorter wavelengths. Interestingly, the clusters involved are also visible in the near-infrared, and thus available for near-infrared spectroscopy (Gilbert et al 2000); however, their significance for the energetics of the starbursts only becomes evident with mid-IR data. Here again angular resolution is what drives OWL to 100m. The fundamental reference point is here not NGST but ALMA, which will have an angular resolution of 0.01 arcsec in its widest configuration and at its highest frequency. A 100m OWL reaches a comparable resolution: 0.02 arcsec at 10 micron. Hence OWL provides the necessary information at the short wavelength (Wien - hot dust) side of the Planck curve, that ALMA probes at the long wavelength side. In spectroscopy, a 100m OWL will also be able to outperform NGST (at least in the available atmospheric windows) in both sensitivity and resolution, and gives access to the highly diagnostic fine-structure lines such as [NeII] (12.8 micron), [ArIII] (9.0 micron) and [SIV] (10.5 micron) which provide the effective temperature of the UV radiation field produced by the ionzing clusters. The detectability of these lines from typical star clusters is then only limited by atmospheric windows. A 100m OWL is thus the perfect complement to ALMA in the mid-infrared.

4) A challenge: Ultraluminous infrared galaxies

The ultraluminous infrared galaxies (ULIGs) are of fundamental importance as the most extreme starburst galaxies. While locally these objects are rare and of little importance in the overall star formation budget of the universe, this was fundamentally different at high redshift. Indeed, recent submillimetre surveys have revealed a rich population of high-z ULIGs, which are plausibly the progenitors of present-day spheroids. ULIGs are obsevationally challenging since (being rare) even the nearest ones are at considerable distance, and since they are compact, and highly obscured. What can OWL do in the field of ULIGs? Again, angular resolution will be the key to everything. The nearest ULIG, Apr220, is at a distance of 75 Mpc, and even for a limited sample we must go to distances of 200 Mpc. At 200 Mpc, a 100m OWL has resolutions of 10 to 50 pc at observing wavelengths of 2 to 10 micron. This will reveal unprecedented detail in the nuclear region. For instance, in the nearest ULIGs, a 100m OWL will be able to resolve individual supernova remnants, superstarclusters and HII regions, and thus directly address the long-standing issue of the power source: starburst or AGN (this will not be possible with a 30m OWL). In addition, the transition to elliptical can be traced dynamically, by near-infrared integral field spectroscopy (at R 3000) of the CO bands. Comparison with the gas kinematics (from ALMA) will shed light on the origin of kinematically decoupled cores. OWL will thus be able to produce key information (stellar kinematics) on ULIGs that can never be obtained with ALMA. The combination ALMA-OWL will provide a fundamental breakthrough in our understanding of the role of ULIGs in shaping the Hubble sequence.

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3.6 Stars outside galaxies

Galaxy merging is a messy process, liberating many stars from the ultimate merger remant. Indeed, in clusters of galaxies, where the relative velocities between galaxies is generally much larger than their internal velocities and thus a merger is not a likely end-point, the many high-speed encounters (aka 'harassment' Moore et al 1998) can cause substantial mass loss from the victim galaxy, perhaps ultimately creating the many 'dwarf elliptical' galaxies in clusters out of normal disk galaxies. Indirect evidence for these free-flying stars has been available for many years in the form of diffuse light from clusters. More recently the individual stars have been detected: Ferguson, Tanvir & von Hippel (1998) showed that there is an excess of unresolved HST sources in fields in the Virgo cluster, consistent with what one would expect for the brightest stars (TRGB, $M_I \sim -3.4$) in such a population.

With OWL, it will be possible to construct a CM diagram for intergalactic stars in Virgo all the way down below the oldest main sequence turnoff. The age and metallicity distributions from such an analysis could discriminate between an origin for the stars predominantly from interactions between cluster ellipticals (in which case one might expect most to be old), or whether there is a significant contribution by stars stripped from relatively recently infallen spiral galaxies (in which case some fraction would be significantly younger). Indeed, with OWL one will be able to do a direct comparison between the CMDs of the intergalactic stars and those of the stars still associated with the outer parts of cluster galaxies.

Further, the brighter stars already detected ($m_I \sim 28$) would be accessible to spectroscopic observations ($\sim$ hour integration with OWL). These data would yield metallicities (further clues to the stars' origins), and would also provide kinematic data to allow a systematic search for the star streams that one would expect if the population arose from a relatively small number of major star-liberating events.

To estimate the source density that OWL would detect, we note that the observed space density of intergalactic PNe in Virgo is 0.06-0.25 PNe per square arcmin (Feldmeier et al. 1998, ApJ 503, 109). There are roughly 10^4 RGB stars and 10^7 MS stars per PN, and hence the expected densities are $\sim$100 intergalactic RGB stars and $\sim 10^5$ intergalactic MS stars per 20"x20" OWL field. The distribution of intra-cluster stars appears to be very non-uniform, consistent with expectations for a dynamically poorly-mixed population - the nature of this non-uniformity is a powerful diagnostic of the dynamical origin of these stars.

[FIG of harassment simulation]

4 Intermediate-distance galaxies - a fair sample of the present-day universe ??? is this necessary?

Out to redshifts of 0.1 it becomes very hard to detect individual stars. HII regions, star clusters, and planetary nebulae are still visible at such distances, because they are brighter or (in the case of PNe and HII regions) because they can be observed with narrow-band techniques. This regime of distances does not yet probe a useful range of look-back time. But it does include many galaxies with globular cluster systems, the full Hubble sequence, galaxies in all stages of merging and interaction, galaxy groups and clusters, etc. This opens up the possibility to extend current 10m-based efforts to understand these galaxies to complete statistical surveys. Observing young star clusters in formation can, through kinematic mass measurements, yield important constraints on the IMF of the populations formed in them.

ELT studies of starbursting galaxies should reveal much more detail than is currently available on the way in which star formation is triggered, and its consequences on the galactic environment.

4.0.1 The intergalactic medium

It is now clear that the intracluster medium in galaxy clusters is multi-phase e.g. the Perseus cluster, Ezawa et al (2001; astroph/0105241). Observing the cooler phases will allow the link to be made between the IGM and the galaxies, and requires sufficient angular resolution to resolve pc-scale clouds. The nearest cooling flows are at distances of 70Mpc, thus requiring mas resolution.

In absorption, cool material may be studied at much lower column densities, though obtaining angular sizes is always limited by the availability of bright background sources. With ELT it is possible to perform high-resolution ($R \sim 10000$) spectroscopy of sources as faint as $V = 25$, increasing dramatically the density of background sources (to tens per arcmin), and hence of the spatial scales that can be probed (down to 100pc scales).

[FIG of Perseus cool knots - Rosie]

5 Distant Galaxies - Observing Evolution

Once we reach 'cosmological' distances ELT opens up a range of possibilities. In this regime look-back time is significant and we see a considerably less-evolved galaxy population than nearby. Evolutionary processes of which we have thus far only been able to observe the remnants, can then be observed directly while they are taking place. For example many low-luminosity elliptical galaxies are known to contain intermediate-age stellar populations: ELT will show such stars' formation and allow spectroscopy of the HII regions for measurements of abundances and physical characteristics.

5.0.2 Spatially-resolved dynamics to $z \sim 1$ - see cosmology panel

With 8m telescopes it is now possible to study internal dynamics of bright galaxies out to redshifts ~ 1, with a few resolution elements per galaxy. With a 30m the spatial resolution can be extended, and the work pushed to higher redshifts (in the IR) and more typical galaxies. Even higher redshifts will require IR as that is where the spectral lines will be; the largest possible aperture is then required to catch sufficient photons for the medium-resolution spectroscopy.

These vague words to be turned into numbers - galaxies/cosmology panel?

Science drivers include evolution of M/L with redshift, kinematic signatures of asymmetries, minor axis rotation (shape evolution), dynamics of bars as probes of halo dynamics. Integral-field spectroscopy gives the complete picture of a galaxy's dynamics, experience is teaching us that this is often full of surprises.

5.1 Evolution of the Tully-Fisher Relation

Evolution of rotation curves provides an interesting tool for studying the evolution of spiral galaxies. Unfortunately, rotation speed and luminosity evolve along the zero-redshift Tully Fisher relation, almost irrespective of formation theory. However, the shape of the inner rotation curve does depend quite strongly on the formation scenario for $z \gtrsim 1$. If the bulge forms early, then in the inner scale-length of the disk the rotation curve will rise steeply to close to its asymptotic value. As more disk material is acquired later, the amplitude of the rotation curve at larger radii will rise, creating a more gently rising rotation curve. If bulge and disk form together, via dynamical instability, there is little evolution with time. Typically, these phenomena have an impact on the shape of the rotation curve in the inner scalelength, which corresponds to ~ 0.1 arcsec at $z \sim 1$. This scale must be well resolved with integral field spectroscopy – one cannot simply deconvolve a rotation curve as the light is likely to be dominated by localized regions of star formation, whose locations will not be known a priori.

5.2 Spatially-resolved abundances to $z \sim 1$ -TBD

Use Wolf-Rayet stars, RSGs, OB stars and HII regions to determine the radial gradients in disk galaxies, and do two things : first how extended are galactic disks at redshifts of 1, very relevant for angular momentum etc, and how chemically evolved are they? Look for evolution in the abundance gradients – this constrains models of disk build-up by accretion of gas.

Can also get kinematics of these. Note Kudritski luminosity–wind velocity relation..

Check whether this is just the lower redshifts..

5.3 Gravitational lensing masses of galaxies

There is some text on this in NOAO extragalactic case - can develop this more. Not clear 100m really advances this much. There are technical problems with PSF stability - wide field, 0.1" resolution would be OK. IR or optical are both adequate. Anyway, here is an attempt:

The gravitational field of individual galaxies peturbs the light rays that pass through it. This manifests itself to us as a weak gravitational shear, which causes systematic alignments of galaxies behind a massive foreground object. A shear measurement gives a rather direct measure of the projected mass distribution of a galaxy.

The accuracy of a weak shear measurement is set by the intrinsic shape variations of galaxies, which necessitates averaging measurements of many galaxies in order to yield a systematic alignment. A dark halo with a velocity dispersion of 100km/s (Einstein radius $\sim$ 0.16arcsec) can be detected at 5σ significance from 10,000 galaxies in a 1arcmin field (shear=0.5%) surrounding the lens. This corresponds to several sources per square arcsec!

Strong lensing masses might be more useful. The fact that the Einstein radius is routinely resolved for $z \sim 1$ galaxies allows many optical rings to be detected. With IFU spectroscopy the background galaxy can then be cleanly separated from the lens, and a lens model made. Such models are currently the best way to derived shape parameters for gravitational potentials. Unfortunately the Einstein rings probe the mass distribution quite far into the galaxy, and not the dark halos. Also none of this is very strong argument in favour of a 100m over a 30m telescope.

5.4 The (dis-)appearance of the blue horizontal branch -TBE/Gerry

Stellar evolution provides several timescales which can be used as cosmological clocks. One such feature is the blue horizontal branch. $\sim$ 1-Gyr old stellar populations are dominated by the AGB, and hence appear very red; but after about 8Gyr the integrated colour evolves back to the blue as BHB stars begin to dominate. If bulges formed at very early times, within a time span of a Gyr or less, then this systematic colour change should be observable. The redshift at which the BHB appears can then be linked to the cosmic age at that epoch.

Show colour evolution from some spectral synthesis model...

[I do not understand why this is not an ACS project for instance - is the bulge surface brightness dimming at z=1 already too severe?]

5.5 Intermediate-age populations in early-type galaxies -TBE/Roger/cosmology panel

Intermediate-age populations, with ages of 2-8Gyrs, are commonly found in early-type galaxies. This population tends to be more important in low-luminosity ellipticals, suggesting that star formation is more short-lived in the more massive galaxies. This obviously makes ithard for large ellipticals to be made of many smaller ones.

The details of how, in what circumstances (Hubble type, location in the galaxy, relation to merger, typical size of HII region...), and how fast these (presently) intermediate-age populations form are not clear. A very direct way to test this would be to observe HII regions in galaxies at redshift 1–3, and measure abundances and star formation rates spectroscopically. At these redshifts the important diagnostic lines (OII, OIII, Balmer series) move to the near-IR. Such a project may allow us to see directly the formation of disks – are they inside spheroids?

A particularly efficient method would be to observe galaxies at these redshifts with an IR IFU-fed spectrograph (field of view 1–5 arcsec).

6 Studying the monsters in galactic nuclei

It is becoming increasingly clear that super-massive objects, presumably black holes, are common in the centers of galaxies. Moreover there appears to be a strong physical link between the mass of this nucleus and the type of galaxy it inhabits, suggesting an intimate relation between the formation of the galaxy and its nucleus.

Thus far galactic nuclei can be studied in nearby galaxies (out to Virgo cluster distances), whereas active nuclei are among the brightest objects known, and may be seen to cosmological distances. The capabilities of an ELT would allow also quiescent nuclei to be studied out to cosmological distances, allowing a direct link to be established between active and dormant nuclei. How fast do they grow, what happens meanwhile to the surrounding galaxy, why was nuclear activity more common in the past... etc.

The radius of the 'region of influence' of a massive galactic nucleus determines where the gravitational field of the black hole dominates the dynamics. It sets the scale for dynamical processes such as density cusp formation. Spatially resolving this region is necessary to be able to study the nucleus and its surroundings dynamically. A typical value for a radius of influence if 7pc - rather independent of nuclear mass as larger bulges also tend to host larger nuclei. Currently with HST the region of influence may be observed out to Virgo cluster distances, and most of our knowledge on galactic nuclei demographics has been gathered from within this distance. With ELT this range will be extended to ALL redshifts.....

For a baseline of 100 m the resolution obtained at 10 micron will be 20 mas, improving to a few mas at 1-2 microns, where the adaptive optics system can deliver high Strehl imaging performance. Note that this is indeed more than an order of magnitude better than NGST at these wavelengths. This resolution is ideal for studying the inner part of the accretion disks around active galactic nuclei. For the famous Seyfert galaxy, NGC 1068, at a distance of about 20 Mpc, this resolution corresponds to a few pc, the expected size of structure. Even at cosmological distances (figure in intro from Bruno) at $1 < z < 6$ the physical resolution is of order 300 down to 30 pc, clearly sufficient to resolve these objects spatially for the first time. Thus an ELT will allow investigation of the physics of accretion disks, full mapping of the velocity fields around the black hole and hence a derivation of the black hole mass, for AGN at all redshifts at which they are now known to exist – and beyond.

6.1 The nucleus of the Galaxy

The nucleus of our own galaxy is the largest event horizon on the sky (in terms of projected size). ELT will therefore automatically probe a scale not seen before. CHECK what OIR yields cf radio VLBI - Falcke work at nIR wavelengths. The Schwartzschild radius is 6E9m=0.04AU=0.005mas at 8000pc. Probing 5mas thus reaches to 1000AU radius. Though this is considerable poorer than what can be achieved with VLBI (sub-mas resolution), it is still unique.

6.2 Massive Black hole demography

Detecting nuclear black holes is best done through dynamical analysis of circumnuclear regions. Very often these contain small emission-line disks whose kinematics can be measured. High velocities imply high enclosed mass, which, sufficiently close to the nucleus, in turn imply mass-to-light ratios well in excess of what is realistic for a stellar population.

These measurements need to be made in the region where the gravitational field from the nucleus dominates the dynamics. The radius of this *region of influence* is set by

$$r_i = \frac{GM_\bullet}{\sigma^2} = 4.3pc\left(\frac{M_\bullet}{10^7 M_\odot}\right)\left(\frac{\sigma}{100km/s}\right)^{-2}$$

for a black hole mass $M_\bullet$ and a stellar velocity dispersion of σ. The angular size subtended by the region of influence is around 300mas at the distance of Virgo (Kormendy & Gebhardt 2001; their table 1).

6.2.1 Nuclei in Local Group Galaxies

Here how can get proper motions and radial velocities for fainter stars then now in the MW central regions.

A census of galactic nuclei in the local environment, to the distance of Virgo, would establish whether the relation between black hole mass and the host bulge holds also for dwarf galaxies. An ELT would probe the mass function 1-2 orders of magnitude further down than existing facilities can. Angular resolution is the key limitation here.

6.2.2 Nuclei at large distances

The peak of the nuclear activity of galaxies ocurred near redshift 2, and in present-day galaxies we see a high frequency of dormant nuclei. With ELT it is possible to link these two directly, and observe the evolution of the mass function of dormant nuclei. This is needed to understand why nuclear activity switched off, how fast (and why) galactic nuclei grow, and what the relation is between the mass of a nucleus and the host bulge.

The mass function can be measured provided the radius of influence can be resolved. At a redshift of 1 (and higher), 1 mas corresponds to 8pc, which is the size of the radius of influence of a few times $10^7 M_\odot$ in a massive bulge. Therefore the demographics of massive black holes can be studied back to the epoch where quasar activity was at its peak, provided sufficient angular resolution can be attained - a few mas resolution is required.

6.3 Near-IR radiation sources

The wavelength region from 1 to 20 micron is very rich in diagnostics for a wide range of physical conditions (e.g. van Dishoeck 1999). In table 2, we provide a simple summary of the radiators, their radiation mechanisms and what physical conditions are being probed by observing in the near to thermal infrared. Simplifying, gas and dust with temperature in the range of 10 - 10,000 K and relatively high (gas-) densities of > (>) 100 cm^{-3} are probed. We note that one of the important advantages of observing in this wavelength region is that one physical mechanism is not, or hardly operating. This is dust extinction. A low redshift object that might be obscured by dust by an amount of 100 mag in the optical will have an extinction close to zero at 10 micron, indeed allowing for an un-obscured view.

Table 2: Important species that can be studied in the near-mid-infrared

Species	Observables	Derivable Physical Parameters
Molecules	Rotational and vibrational lines	Temperatures, densities, kinematics, chemistry
Ions	Forbidden fine-structure lines	Temperatures, densities, kinematics, Abundances, excitation mechanisms
Dust	PAH features, continuum shape	Composition, temperature
Late type stars[a]	Continuum	Spatial scales

[a] Note that for high redshift galaxies, the stellar emission shifts towards the mid-infrared.

Active galaxies have compact nuclei that can be so luminous that they can outshine a whole galaxy. These cosmological beacons are so bright that they have already been seen out to the earliest 5 % of the age of the Universe. At early times ($1 < z \lesssim 5$) these active objects are a factor $100 - 1000$ more common than in our local universe. There is much evidence that they contain massive black–holes, the central engine of the physical processes that give rise to a large number of energetic phenomena. The most important questions in this area undoubtedly include the relation of the AGN phenomenon to galaxy formation, and the physics of the formation and evolution of the massive black-holes. A recent clue to answering these questions is the strong indication that a large fraction of local galaxies contain massive black-holes, and that the mass of the black-hole directly scales with the mass of the spheroidal component of the hosting galaxies, with the galaxy mass being measured by either the stellar mass of the bulge, or by its stellar velocity dispersion (e.g. Kormendy & Richstone 1995; Ferrarese & Merritt 2000; Kormendy & Gebhardt 2001).

The now canonical view of AGN is that they are powered by the exchange of gravitational energy for thermal energy in a compact accretion disk surrounding a massive black-hole (e.g Rees 1984; Gallimore

Figure 1: A cartoon of the heart of an AGN, indicating several of the components. Note the scale interior to the torus, which is also of the same order as the region of influence where the black hole dominates the dynamics, around 30mas at a distance of 20Mpc, well-matched to a 100m telescope.

Figure 2: Greyscale presentations of the morphologies at 10 micron according to the model for NGC 1068 of Granato et al. (1997). The optical depths vary with visual extinction $A_V = 30$ and 150 mag and the orientations vary with theta = 60° and 90°.

1997). In the currently popular and attractive "unified" model of active galactic nuclei, all AGN host an optically thick obscuring torus; its orientation with respect to our line of sight determines whether we see the object as a Type I (Seyfert 1 or quasar) or Type II (Seyfert 2 or radio galaxy – for reviews see Antonucci 1993 and Urry and Padovani 1995). A cartoon of the unified model for the heart of the AGN is presented in Figure 1. The inner accretion disk feeds the massive black-hole directly, probably supplemented by direct stellar infall, which will be preceded by a luminous flare during tidal destruction of the star. This inner disk is expected to be warped, precessing, and to show complex, time-dependent radiation-feedback induced structures (Maloney, Begelman & Pringle, 1996; Stone & Pringle 2001).

The inner disk is surrounded by the "broad-line region". In this region dense compact clouds move at a high speed through a more tenuous medium giving rise to broad optical emission lines. The broad-line region is surrounded by an optically thick torus composed of dust and molecular and neutral gas. If the torus hides the central region from our view, the direct high energy phenomenon associated with the very central part of the region is more difficult to observe. The object does not show broad lines and is classified as a Type II object. If the object is observed sufficiently close to its polar axis, a very bright nucleus is observed and the optical spectrum will exhibit broad lines. It will be classified as a Type I.

Although this picture is capable of explaining a large number of the differences between the various classes of AGN (e.g. Antonucci 1993), there is still a vigorous debate as to whether other mechanisms contribute to, or even dominate over, the scenario in which orientation and a putative torus play such a major role. It has even been argued that in a subset of AGNs, the main power-source is not a black-hole, but supernovae explosions produced within a central starburst region (cf. Heckman 2000). Another interesting suggestion is that time variability plays an important role in understanding differences between AGN. In the sources that show a bright nucleus the AGN is being actively fed, whereas in the sources that do not show such a bright nucleus, the feeding has been (temporarily) stopped. Alternatively, perhaps the flow is advection-dominatd and low luminosity does not necessarily imply a low accretion rate (e.g. Narayan 1997).

A number of models for obscuring tori have been proposed (e.g. Pier and Krolik 1992; Efstathiou and Rowin-Robinson 1994; Krolik and Begelman 1988; Granato et al. 1997). The models range from extended 100 pc-scale tori having a moderate optical depth to much more compact tori with very high optical depth. Also several geometries have been investigated, including structures with a warped disk (Sanders et al. 1989). It must be stressed however, that there are a number of serious difficulties with these models. For example, it is generally assumed that the tori are composed of dusty molecular clouds with a large cloud velocity dispersion. How such an assembly can be maintained is an unsolved theoretical problem (e.g. Maloney 1998).

High resolution imaging at near to mid infrared wavelengths of nearby active galaxies has a crucial role to play in quantifying all these possible effects. At 10 microns the view towards the heart of the galaxy is not hampered by extinction due to dust in the galaxy and also is not confused by stellar emission. This should therefore allow the unambiguous detection of the emission from dust tori. It will further constrain a number of important physical parameters of the torus, including the inner and outer radius, its density,

Figure 3: The 10 micron luminosity and physical scale D of dusty tori as a function of redshift. The solid lines are for observed angular scales of 1, 0.1 and 0.01 arcsec. The dotted lines are for an observed 10 micron flux density of 5 and 50 μJy. The computations have been done for $H_0 = 75$ km s^{-1} Mpc^{-1} and $\Omega = 1$.

temperature and kinematical structure.

For a first indication of what structures can be expected to be observed, we use the models of Granato et al. (1997). In these models the radiative transfer through the dust is calculated for axially symmetric tori. Important input parameters are the line of sight optical depth and the orientation. The resulting IR spectral energy distribution can then be compared with what is observed. Furthermore, the morphology of the torus as a function of wavelength is predicted. As a test case we use the canonical Seyfert 2 galaxy NGC1068 for which several recent observations suggest the presence of a molecular/dusty torus with a temperature of 1500 K near the core and 600 K at 15 pc (Gallimore et al 1997, Rouan et al 1998, Marco and Alloin 2000, Tacconi et al 1997). The fit to the nuclear spectrum of NGC 1068 is obtained with a visual extinction of $A_V \sim 72$ mag along the line of sight, and an orientation of 65° (Granato et al 1997). In Figure 2, we show the resulting morphology for this particular model, but with line of sight optical depths of $A_V = 30$ and 150 and orientations of 60° and 90°.

It is very clear from these simulations that an ELT delivering a few mas resolution in the near to mid IR will be able to provide 2-D time and space-resolved spectroscopy and imaging of the nuclear tori in nearby galaxies. Robust determination of the nuclear black hole mass function will be an immediate result of this full mapping of the kinematics and physical state of the gas tori. An interesting question is to what distance tori of AGN can be mapped. To investigate this, we again will use the models of tori of AGN of Granato et al. 1997. A first thing to note is that the inner radius of these tori, $r_{\rm in}$, is set by the distance from the central source at which the dust grains sublimate due to the strong nuclear radiation. This radius is larger for more luminous AGN. For the models of Granato et al, $r_{\rm in} \sim 0.5 L_{46}^{1/2}$ pc, where L_{46} is the luminosity of the central optical UV emitter in units of 10^{46} ergs s^{-1}. As a scale size of the torus D we will use 300 $r_{\rm in}$. In Figure 3, the diameter D and the 10 micron luminosity (which are directly coupled) are given as a function of z for angular scales of 1, 0.1 and 0.01 arcsec. The dotted lines correspond to the 10 micron luminosities as a function of z for 10 micron flux densities of 5 and 50 μJy.

A relatively weak AGN such as NGC 1068 has a 10 micron luminosity of the order of 1.7×10^{31} erg s^{-1} Hz^{-1} and its modelled torus size is 60 pc. Up to redshifts of $z = 1 - 2$ such weak AGN are readily imaged, and can be studied with spatially resolved spectroscopy. Also the nominal resolution of a few to 20 mas is well matched for imaging the tori at these redshifts. Brighter AGN can basically be mapped up to redshift of $z = 10 - 20$ – if they exist; note the present redshift limit is around 6, and that the existence and population of massive systems at even higher redshifts is a powerful constraint on models of structure formation. Cold-dark-matter dominated models in which massive objects are rare at early times are already being challenged, and extending the demography of supermassive objects to higher redshifts is clearly of extreme importance.

The ELT provides a unique opportunity to investigate how the properties of tori change with redshift and when and how these tori and their associated massive black-holes are built up at an epoch when galaxies are forming.

6.4 The Nearest Galaxies

6.4.1 Central regions of M33 and M32

The extremely high resolution of OWL offers the opportunity to resolve individual bright stars in nearby galaxies down to their very central regions. For instance, AO with Gemini has revealed a population of luminous AGB stars throughout M32 (Davidge et al. 2000, ApJ, 545, L89) and OWL will obtain radial velocities and abundances of these stars, making the transition from simple detection to analysis. The nucleua of M33 will similarly become accesible for detailed analysis.

6.4.2 Asymmetric nuclei

The nucleus of M31 can today be studied in integrated light, with HST/STIS as well as groundbased AO/assisted integral field spectroscopy on 4m telescopes. The nucleus is asymmetric, and the observations provide constraints on formation of central star cluster, black hole mass, etc. Is this object unique? With OWL one can extend studies of the morphologies of nuclei out to Virgo, i.e. to about 15-20 times the distance, so that the entire Hubble sequence is accessible.

Figure 4: Bertelli et al. (1994) isochrones showing a comparison of optical with infrared colors. Red lines show $J-K\,vs.\,\mathrm{M}_K$, blue lines $V-I\,vs.\,\mathrm{M}_V$, and green lines $V-K\,vs.\,\mathrm{M}_V$. The solid lines show low-metallicity (Z=0.0004) isochrones while the dotted lines represent solar metallicity (Z=0.02). Each set of isochrones is plotted for ages of 8, 10, 11, and 12 Gyr. Note that the age and metallicity are much better discriminated if at least one optical band is utilised – such as V, I or if a $V-$magnitude is combined with an IR color. This is due to the higher sensitivity of the V band to metal-line blanketing.

7 Technical issues

The science of stellar populations is a strong driver to deliver close to diffraction-limited performance in the optical. *Why the optical?* A significant factor is the higher diffraction-limited resolution in the optical (a factor of 3–4 higher than in the infrared, corresponding to magnitudes of depth in crowded fields) – most stellar population applications are confusion-limited rather than sky-background or photon-limited and typically attainable depths are 7 magnitudes fainter in V than in K (see Table 2). While OH line cancellation may be technically feasible in the H band, thermal emission at redward of 2 microns is an insurmountable obstacle to deep imaging from the ground. Further, the derivation of stellar parameters such as age and metallicity is much more robust in the optical than in the near-IR – for spectroscopy, the resonance lines are in the optical/UV (electronic transitions are in the optical/UV, whereas it is molecules in the IR, and these are much more complicated). While the issue of ability to measure age and metallicity in the IR needs careful study, we can get a first idea from published isochrones. Figure 1 shows Bertelli et al. (1994) isochrones of J-K vs. M_K, V-I vs. M_V, and V-K vs. M_V, for metallicities of Z=0.0004 and Z=0.02 and ages of 8, 10, 11, and 12 Gyr (roughly spanning the evolution in stellar populations from redshift z=1 to z=3). Including an optical filter clearly gives better age discrimination near the turnoff and better metallicity discrimination from the RGB slope, by a factor of $\sim$2. One can see immediately the complementarity of NGST and and ELT.

Thus much of our science case relies on the ability to perform diffraction-limited crowded-field photometry at optical wavelengths. As much of this work is confusion, rather than photon, limited, it should be possible to work at quite low Strehl ratios. Some detailed simulations are needed to test this. Also the limitations imposed by a PSF that is unstable in time, or rapidly varies across the field, need to be understood.

Similarly, for the spectroscopy of circumnuclear regions, simulations with real PSFs are required.

Tables 2 and 3 give the optical (V) and near-IR (K) magnitudes of important classes of stars, and the surface brightnesses at which confusion sets in (for 10% photometry) at the diffraction limit of a 100m telescope.

Table 3: Photometric Limiting Distance Moduli for Imaging, Isolated Stars, Diffraction Limited (V = 36.6, K = 31.7)

Star type	M_V	M_K	10-m (V)	100-m (V)	10-m (K)	100-m (K)
Massive stars	**-2.5+**	**-1.5+**	35.1+	40.1+	28.2+	33.2+
TRGB/AGB	**-2.5**	**-6.5**	35.1	40.1	33.2	38.2
RGB stars	**-0.5**	**-2.5**	33.1	38.1	29.2	34.2
HB stars	**0.5**	**-2**	32.1	37.1	28.7	33.7
Old subgiants	**3.5**	**2.5**	29.1	34.1	24.2	29.2
Oldest turnoff	**4.5**	**3.0**	28.1	33.1	23.7	28.7
Oldest turnoff+1	**5.5**	**4.0**	27.1	32.1	22.7	27.7

Notes to Table 2: Assumed limiting magnitudes (S/N=10) are based on 10,000 sec integrations, 1e$^-$ readnoise, sky background 21.5 (V), 12.5 (K).

Table 4: Confusion Limiting Distance Moduli, Diffraction Limited, 10% Photometric Accuracy, V/K bands

	Massive stars	TRGB/ AGB	RGB	HB	Old sG	Oldest TO	Oldest TO+1
Half-light of a Bulge	33.3/26.3	33.3/31.8	31.0/27.4	29.9/26.9	27.1/22.5	26.2/22.2	25.4/21.2
Spiral arms	34.3/27.3	34.3/32.8	32.0/28.4	30.9/27.9	28.1/23.5	27.2/23.2	26.4/22.2
Interarms	35.3/28.3	35.3/33.8	33.0/29.4	31.9/28.9	29.1/24.5	28.2/24.2	27.4/23.2
Disk edges	38.3/31.3	38.3/36.8	36.0/32.4	34.9/31.9	32.1/27.5	31.2/27.2	30.4/26.2
Center of E galaxy	27.3/20.2	27.3/25.7	25.0/21.3	23.9/20.8	21.1/16.4	20.2/16.1	19.4/15.1
Half-light of E galaxy	34.8/27.7	34.8/33.2	32.5/28.8	31.4/28.3	28.6/23.9	27.7/23.6	26.9/22.6
Edge of E galaxy	39.8/32.7	39.8/38.2	37.5/33.8	36.4/33.3	33.6/28.9	32.7/28.6	31.9/27.6
Center of GC	31.6/25.5	31.6/31.0	29.3/26.6	28.2/26.1	25.4/21.7	24.5/21.4	23.7/20.4
Edge of GC	37.3/31.2	37.3/36.7	35.0/32.3	33.9/31.8	31.1/27.4	30.2/27.1	29.4/26.1

Notes to Table 3: These limiting distances are set by the requirement that the rms background fluctuations per diffraction-limited resolution element ($1.22\lambda/D$, $D = 100$m) not exceed 10% of the source brightness (fluctuations are calculated assuming the luminosity function of a 12Gyr-old solar metallicity population).

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[20] L. Tacconi, J. Gallimore, R. Genzel, E. Schinnerer, and D. Downes, “A High Spatial Resolution Study of the Molecular Gas in NGC 1068,” *Astrophysics and Space Science* **248**, p. 59, 1997.

9 Pending Issues...

9.0.3 The Interstellar Medium

Needs to be written!!

9.0.4 IR spectroscopy of massive stars

Should be moved to stars/planets report. This is what we have now:

Watson & Hanson 1997, ApJL, 490, 165 ”Near-Infrared Spectroscopy of G29.96-0.02: The First Spectral Classification of the Ionizing Star of an Ultracompact HII Region”

Hanson et al. 1998, AJ, 116, 1915 ”Near-Infrared H-Band Features in Late O and B Stars”

Hanson et al. 1996, ApJS, 107, 281 ”A Spectral Atlas of Hot, Luminous Stars at 2 Microns”

The use of the near-infrared spectral range for classification has obvious advantages over optical classification when applied to heavily reddened stars, such as in star-forming regions or deeply embedded lines of sight within the plane of the Galaxy, such as the Galactic center. Furthermore, the H band is less likely to be contaminated by infrared excess emission, which is frequently seen around massive young stellar objects beyond 2um.

9.0.5 Observing the IMF directly in young star clusters

Should be merged with bits in planets/stars report.

Stellar populations contain in general at least 50 per cent of multiple systems (cf. Kroupa et al. 2000), and this fraction will be even higher in the cores of evolved star cluster systems due to dynamical mass segregation effects (cf. Inagaki & Saslaw 1985, Elson et al. 1987, 1998, Bonnell & Davies 1998, Rubenstein & Bailyn 1999, among others). The most straightforward approach to determine the fraction of binary stars in a given stellar population is by obtain two-colour diagrams, preferably containing both optical AND near-infrared passbands (see, e.g., Johnson et al. 2001).

Although it is generally thought that binary formation acts on similar (or slightly shorter) time scales as the conventional dynamical mass segregation (cf. Nemec & Harris 1987, Bonnell & Davies 1998, Elson et al. 1998), this process is not well understood. For the further understanding of dynamical versus primordial mass segregation effects, it is therefore of crucial importance to obtain two-colour information for the youngest star cluster stars. With the currently available resolving power, one can only do so for the nearest ”super” star cluster, R136 in 30Dor, but to get acceptable statistics, a larger sample of such young (super) star clusters is required, and hence one needs to extend the observable range of individual stars in super star clusters out to at least the Virgo cluster. This requires the use of 100m-class OWL-type telescopes to keep the observation times within reasonable ranges.