APPENDIX 2.C

STELLAR POPULATIONS

Report of the Stellar Populations Panel, September 2000.

STELLAR POPULATIONS

The members of the Stellar Populations panel were Rosemary Wyse (chair; JHU), Knut Olsen (vice-chair; NOAO/CTIO), Michael Rich (UCLA), Robert O'Connell (UVa), Jay Frogel (Ohio State), Ralph Wijers (SUNY Stony Brook); Mario Mateo (UMich) and Caty Pilachowski (NOAO/KPNO). All except R. Wijers attended the panel meeting in Tucson in mid-September. Brent Ellerbroek (NOAO/Gemini) was available by telecon at that meeting. Arjun Dey (NOAO/KPNO) also participated in the panel meeting, providing scientific and technical input. This report was drafted by R. Wyse and K. Olsen with input from other panel members, in particular from M. Rich and R. O'Connell.

Overall Summary

The panel was very enthusiastic by the possibilities offered by a very large optical-infrared telescope to extend detailed study of resolved stellar populations beyond the Milky Way and its immediate satellites. The major science thrust we identified is to use the fossil evidence of resolved stellar populations in galaxies over a representative sample, covering as broad a range of Hubble types as possible, to decipher the formation and evolution of galaxies – what is the star formation history, the chemical enrichment history, the mass assembly history? Resolved population studies, coupled with high signal-to-noise integrated light observations of the same objects, will provide fiducial calibrations to extend integrated light population analysis to the very distant universe. This research will also place constraints on the nature of the ubiquitous dark matter, setting the scale of gravitational instability, through, e.g., measurements of potential well depth and faint stellar IMFs.

The distribution of galaxies in the nearby Universe is non-uniform, and 'cosmic variance' requires that we study a significant sample of each morphological type of galaxy. While the nearest dwarf galaxies are only tens of kpc removed, the nearest large spiral, M31, is ∼850 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. Large numbers of elliptical galaxies, including giant ellipticals, are not found until the Virgo cluster is reached, at a distance of $\sim$ 15 Mpc. For reference, Table 1 gives the distance moduli of galaxies and clusters, and the angle subtended by 1pc at those distances. For comparison, the diffraction limit of a 30m telescope is $0.002''$ at 300nm, $0.006''$ at 800nm, $0.018''$ at K-band (2.2μm.)

For the science goals, the required observations are color-magnitude diagrams down to a magnitude below the oldest turnoff, which will be used to derive age distributions, when combined with metallicity distributions from spectroscopy of stars on the lower red giant branch. Further information can be obtained from the detailed elemental abundances which may be obtained by higher resolution spectroscopy of the brighter giant stars. In the opinion of the panel, **the real quantum leap in our understanding of stellar populations will come with observations of the resolved stellar populations of the entire Hubble sequence, including giant elliptical galaxies**. This sets a real threshold for the minimum requirements of the telescope, since it must allow accurate photometry of faint main-sequence stars in the target elliptical galaxies in the Virgo cluster, to an apparent magnitude of $m_V \gtrsim 36$. **As we describe below, this requires at least the resolution and sensitivity of a 100m telescope, with full Adaptive Optics in the optical.** We recognise that this science goal is extremely ambitious, and detail subsidiary science goals with less technically challenging requirements.

Table 1 : Examples of Stellar Systems for Study

object	$(\text{m–M})_o$	angle corresponding to 1pc
LMC	18.5	$4''$
M31	24.3	$0.3''$
Sculptor Group	26.5	$0.11''$
M81	27.8	$0.06''$
Cen A	28.5	$0.04''$
NGC3115	30.2	$0.02''$
Virgo Cluster	30.9	$0.014''$
50Mpc	33.5	$0.004''$
Perseus Cluster	34.5	$0.002''$
Coma Cluster	35.0	$0.002''$

Why the optical? A significant driver 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) combined with the fact that the high terrestrial sky background

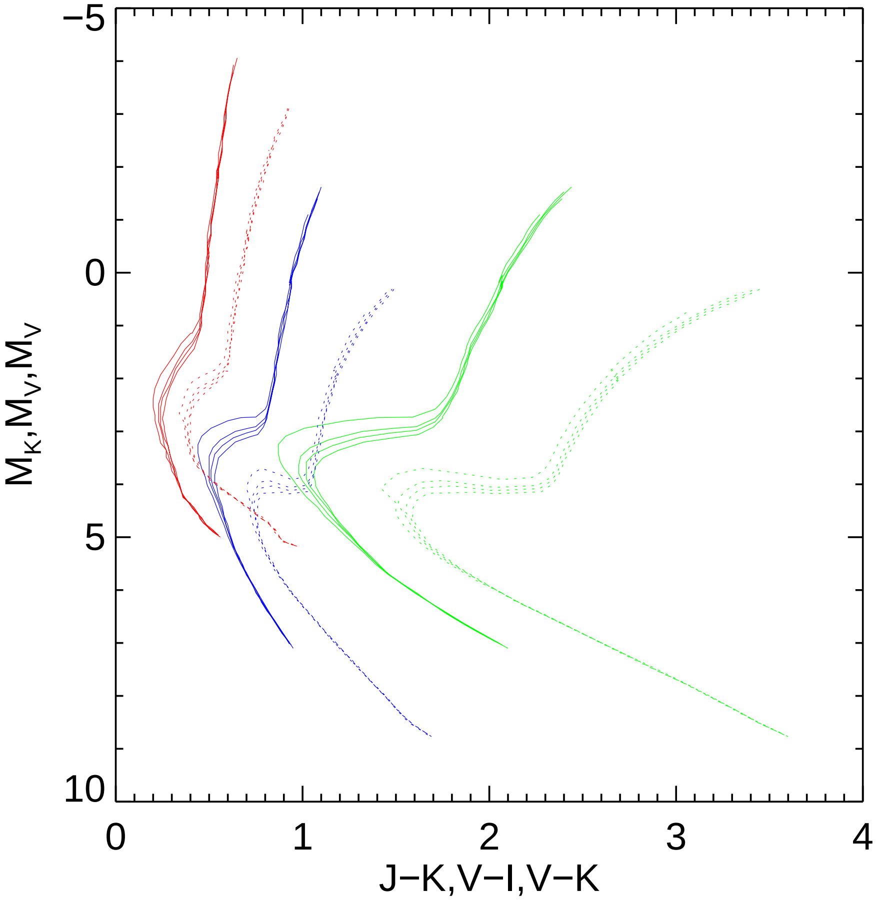

Figure 1: Bertelli et al. (1994) isochrones showing a comparison of optical with infrared colors. Red lines show $J - K\, vs.\, \mathrm{M}_K$, blue lines $V - I\, vs.\, \mathrm{M}_V$, and green lines $V - K\, vs.\, \mathrm{M}_V$. The solid lines show low-metallicity (Z=0.0004) isochrones while the dotted 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.

in the infrared severely limits the depth for imaging; 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 (as noted below in section V), 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$2. However, should it prove possible to control the photometry in the near-IR to 1$-$2%, then for science not do-able with NGST, JHK colors will be useful, especially if AO is restricted to these and longer wavelengths. However, in evolved populations AGB stars can be 4-5 mag brighter in the IR than in the optical, and the scattered light from these stars may also limit the practical depth of any imaging program.

Indeed, the achievable photometric performance of the future large telescopes is rather uncertain, and in Tables 4 and 5 we have provided our estimates of limiting magnitudes etc. based on two different assumptions about the photometric accuracies. We believe our numbers to be realistic, but as noted below in section V, we also believe that a detailed study of photometry with AO systems should be undertaken.

In principle, the infrared permits high resolution spectroscopy just as is possible in the optical. In practice, there are considerable difficulties. The very large number of terrestrial absorption and emission lines requires perfect sky subtraction and precise division by a featureless standard star. Although $S/N = 50 - 100$ spectra are routinely obtained in the optical, high-resolution spectra of this quality are hard to get, in practice, in the infrared. The second problem is the lack of laboratory *gf* values. Practical abundance measurements require the use of Solar or calculated *gf* values (Melendez & Barbuy 1999). This is likely to remain true, as the effort to make the laboratory measurements is unlikely to be expended. While there are many molecular OH lines in the infrared at 1.5 μm, these lines are useful only for relatively metal rich stars. If one seeks to measure oxygen in the most metal poor stars, one is forced to use lines at 3μm and to suffer a much higher background. Further, although the list of Melendez & Barbuy gives r- and s- process lines, the lines are not strong enough to be identified in infrared Arcturus atlas (Hinkle, Wallace, & Livingston 1995). As the heavy elements are of great importance as a diagnostic in the chemical evolution of stellar populations, this could be a problem. Although an adaptive optics fed echelle spectrograph would be a very powerful instrument for a 30m telescope, we conclude that it would be a serious loss not to have a high resolution optical spectrograph.

Preserving the optical performance of the next-generation telescopes is of the utmost importance for the study of stellar populations. The same conclusion has been reached by previous panels.

0. Context: After the 10m-era

The era of 30m-class telescopes and NGST will come after a decade of operation of several 10m-class telescopes, and one must consider what will have been achieved. Complementarity with future space missions, such as NGST, SIM and GAIA, is also an important issue for the next generation ground-based telescopes.

For native-seeing, ground-based observations of the stellar populations in nearby galaxies, source confusion sets the limiting magnitude, as has been clearly demonstrated by the great advances made by HST in producing color-magnitude diagrams of Local Group galaxies. Even with seeing as good as $\sim 0\farcs3$, photometry to the oldest main sequence turnoff will be limited, with 10m-class telescopes, to galaxies closer than M31. HST, with $0\farcs1$ resolution in the optical, will still be better suited for studying the crowded regions of nearby galaxies than will a seeing-limited GSMT. Thus, imaging studies will be dominated by HST (optical and IR; WF3 and ACS) and AO systems on 10-m ground-based telescopes (IR and perhaps I-band; SOAR, a 4.2m telescope, intends AO in the R-band). These will be able to obtain CMDs down to within a magnitude of the older turn-off in the outer regions of the bulge and disk of M31, and the low surface brightness regions of dwarf satellite galaxies.

Given that source confusion already limits ground-based imaging of stars in nearby galaxies, a more plausible niche for a seeing-limited large telescope is optical and IR spectroscopy. However, for observations of objects fainter than the background, the gains in S/N grow just linearly with telescope aperture. Thus, the availability of several 10m-class telescopes in the next decade should mean that many problems will have been tackled by simply integrating for a very long time on a 10-m. Given the difficulties and costs associated with the large size of native-seeing spectrographs—indeed, a 30m telescope is a reasonable upper limit for which one should consider conventional native-seeing instruments as feasible—a GSMT dedicated purely to seeing-limited spectroscopy is not a high priority for the astrophysics of stellar populations.

10m Science

A good illustration of the typical capabilities of Keck and HIRES (native-seeing) is provided by the investigation by Shetrone et al. (2001, ApJ 548, 592) of the elemental abundances of bright ($M_V \lesssim -2$, close to the tip) RGB stars in the companion dSph galaxies of the Milky Way, at distances of ~ 80 kpc. The project analysed spectra with $\mathcal{R} = 34,000$, $S/N \sim 20$. A combination of longer integration times and more efficient spectrographs might enable such work on stars as much as 1.5 mag fainter, but $V = 18.5$ is a reasonably firm limit for the determination of stellar elemental abundances, with a 10m-class telescope.

Keck/HIRES has also been used to measure the kinematics (to ~ 2 km/s) of red giant stars in Andromeda II, a companion galaxy to M31, at distance ~ 500 kpc (Cote et al. 1999). These bright upper RGB stars are at $V \lesssim 22$, or $M_I \lesssim -3$. Acceptable radial velocities can be obtained with $S/N \sim 2$ spectra (1 hour integrations). Lower resolution (LRIS, $\mathcal{R} \sim 1,000$) spectra have been used to determine the chemical abundances in this galaxy, based on Lick indices (Cote, Oke & Cohen 1999), to ~ 0.3 dex.

Moderate resolution (LRIS, 1200 lines/mm grating, 0.62Å/pixel; $1''$ slit) Keck spectra of candidate bright RGBs ($I = 21 \pm 1$, $M_I \sim -3.5$, 4hr integrations) in M31 outer bulge/halo have been obtained (Guhathakurta et al, astro-ph/0004371). These provide kinematics with uncertainty $\sigma \sim 40$ km/s and metallicity to $\sim \pm 0.3$ dex. The advent of the Echelle Spectrograph Imager (ESI) gives $\mathcal{R} = 5,000$ resolution spectra with a factor of 2-3 greater efficiency. The resolution is low, but usable for stellar abundances, but ideal for velocities. ESI may permit such measurements to $V = 23$, although gains are smaller as one is limited by the sky background.

We conclude that one should be able to get kinematics to ~ 20 km/s, and rough metallicities using moderate-resolution spectroscopy ($\mathcal{R} \sim 5,000$) for large samples of giants in at least the outer regions of M31 bulge and disk with the present generation of 8m–10m class telescopes, in native seeing mode. Adaptive-optics fed spectrographs will probably push into higher surface brightness regions, and may be able to get low-resolution spectra of some of the brightest giants in the outer regions of the bulges of M31 and M32.

Subgiants in the nearer ($\lesssim 100$ kpc) Local Group dSph are around V $\gtrsim 23$ and, comparing to the Cote et al. kinematics for And II, again one should be able to derive metallicities, and kinematics to a few km/s, for subgiants across the face of at least the nearer dSph with existing (native-seeing) capabilities. This will allow us to decipher the chemical evolution in these systems, for which HST and 8m-class telescopes have revealed complex star formation histories, by determining age-metallicity relations by studying the subgiants corresponding to a given turn-off. One can also map fully the radial velocities across the face of these galaxies; this is of great importance since these are among the most dark-matter dominated systems known, based on central internal velocity dispersions. A more robust determination of the dark matter content comes from analysis of the radial variation of the internal velocity dispersion. The nearer dSph are certainly accessible to 10m telescopes. The more distant dSphs are discussed below, in section I.3.1.

Although the specifications for the NGST remain under review (early 2001), one expects that it will in general provide superior performance, compared to a 30m with near diffraction-limited PSF in the K-band, in terms of IR imaging and low-resolution IR spectroscopy, simply due to the lower sky background in space, although the spectroscopy will be limited to lower-surface brightness regions (as discussed in previous MAXAT reports).

We shall now consider several science questions that we consider will not be answerable by current telescopes, NGST, or other intended future missions (GAIA etc), and the capabilities required to achieve them. We start with the overall theme, that of the origins of the Hubble sequence, and then specific projects targetting aspects of that theme.

I. Core Science Questions and Requirements

I.1 Is the Milky Way a Typical Spiral?

Background

The fossil record of galaxy formation and evolution is written in the distributions of age, chemical composition, kinematics, and spatial distributions of the stars, as well as the stellar initial mass function. These are the defining characteristics of a stellar population that we desire to study. We do not yet have a full characterization of the stellar populations in the Milky Way, throughout the main stellar components of disk, thick disk, bulge, and stellar halo. For example, even the star-formation history of the local region of the disk, the solar neighborhood, has only recently been determined to high precision using *Hipparcos* data (Hernandez, Valls-Gabaud & Gilmore 2000).

The well-known degenerate effects of age and metallicity on the positions of stars in color-magnitude diagrams (CMDs) frustrates any effort to learn the detailed star formation history from integrated spectra, or color-magnitude diagrams, alone. The more detailed the analysis, the greater the potential information to be gleaned. Iron abundance alone gives an indication of membership in a stellar population. If 'alpha'-elements (O, Si, Mg, etc. mainly produced in massive stars) can be measured, then the timescale of metal enrichment in a stellar population may be constrained (e.g. Wheeler, Sneden & Truran 1989, ARAA), and constraints placed on the massive-star IMF that pre-enriched the low-mass stars under study (e.g. Wyse & Gilmore 1992, AJ 104, 144). The alpha elements are the first metals to be produced and enrich on timescales of 10^6 yr, while iron is produced in Type I SNe that are thought to be related to white dwarfs, and contribute iron on timescales of around 10^8 yr. The neutron-rich s-process elements, produced in the envelopes of AGB stars, can probe enrichment timescales of order 10^9 yr and may give interesting insights into the form of the primordial initial mass function. The r-process elements are produced in all supernovae, but are especially enhanced in some of the most metal poor (ancient?) stars known (McWilliam et al. 1995; Burris et al. 2000). The abundances in these stars of nuclear chronometers such as U, Th and Nd may provide important constraints on the ages of the oldest stars in the Galaxy (cf. Butcher 1987, Nature).

As noted above, the high-mass IMF in old systems may be constrained by the values of the different elemental abundances in the long-lived stars they enriched. The low-mass IMF is derived by direct star counts, with intermediate masses requiring information about the star-formation history. The characterization of the IMF in various environments is an important science goal.

The kinematics, and kinematic gradients within a stellar population, also should be derived, to quantify relationships between the different stellar components, and, through the determination of correlations between kinematics and other parameters, elucidate the main physics determining Galaxy formation (slow dissipative collapse with angular momentum conservation or accretion by fragments?). The kinematics constrain the mass density profile of the Galaxy, and phase space structure constrains the disruption and accretion of smaller-scale substructure, e.g. globular clusters and companion galaxies.

The fascinating smaller-scale physics of star formation and the inventory of planets and brown dwarfs are discussed in another panel.

While we acknowledge that filling in the above roadmap to characterizing the Milky Way's stellar populations involves a tremendous amount of further work, we do expect that much of it will be done before the era of the next generation (30-m and larger) ground-based telescopes. Some obvious exceptions are the proper motions and parallaxes of distant Galactic stars, but that is the science mission of GAIA and of SIM. The densest regions of the Galaxy are often the dustiest, e.g. the Galactic bulge, and NGST with its IR capability has the science goal to determine the IMF down to the brown dwarf regime here.

Given the characterization of the Milky Way, one approach to understanding disk galaxy formation and evolution is to adopt the Copernican view and assume that the Milky Way is typical, and compare the stellar populations with as detailed as possible predictions from theories. However, given the inherent 'cosmic variance' of modern theories, one really needs to have a *sample* of large disk galaxies with the same level of information.

A crude measure of cosmic variance may be derived by comparing the properties of M31's stellar populations with those of the Milky Way. We already know from study of the colors of RGB stars (both HST and Keck) that the bulge/halo of M31 is more chemically enriched at large distances from the center of that galaxy than is the typical Milky Way star at the analagous location, and have data on the gradients and limits on the spread of metallicity at different locations. The 'halo' of M31 has a much higher surface density in the outer parts, compared to the Milky Way, due either to a different density normalisation or scale-length (Pritchet & van den Bergh 1994; Holland, Fahlman & Richer 1996). The available kinematics of the satellites of M31 suggest that despite its higher luminosity, it has lower mass than does the Milky Way (Evans et al. 2000).

It should be noted that bulges do follow a similar relation between surface brightness and size as do ellipticals (the 'Kormendy relations'; Kormendy 1977), in that larger bulges tend to be lower surface brightness at their effective radius, but there is a large scatter in this relationship (de Jong 1996; see also M31/Milky Way!).

Thus, for a clear understanding of the principles of galaxy formation and the factors that lead to variance among galaxy properties, we need to go beyond the Local Group to obtain a statistical sample of spiral galaxies. Specifically, this sample of spiral galaxies will allow us to address the following questions:

I.1.1 Do all spiral galaxies have stellar halos? – are they related to bulges?

The stellar halo of the Milky Way contains the oldest and most metal-poor stars in the Galaxy, and thus the science questions here relate to the earliest stages of galaxy evolution. A small, but not insignificant, fraction of the Milky Way halo is apparently younger than the dominant population, and may have been accreted as part of the merging/interactions with satellite dwarf galaxies (cf. Unavane et al 1996, MNRAS; Mateo 1998 ARAA). The central bulge of the Milky Way is also apparently very old (Ortolani et al; Feltzing & Gilmore 2000), but is rather metal rich (McWilliam & Rich 1994). The angular momentum distributions of halo and bulge are consistent with a collapse and spin-up of gas in a smooth fashion, forming the halo initially and the bulge subsequently (Wyse & Gilmore 1992). Hierarchical clustering models of galaxy formation combine elements of monolithic collapse (cf. Eggen, Lynden-Bell, & Sandage 1962) and merging fragments (cf. Searle & Zinn 1978), with the mix perhaps determining the Hubble type.

A corollary to this question is whether all galaxies contain a very old component; was the first star formation simultaneous over a wide range of environments? Indications from globular clusters suggest that indeed all Local Group galaxies contain a very old component (e.g. the LMC, Olsen et al 1998, Johnson et al 1999).

The data required to address these questions are kinematic, metallicity and age distributions for the outer regions of 'bulges', complemented with similar data for regions closer to the center. Note that it is important to use field stars, not globular clusters alone (see below for studies of the globular clusters), since apart from possible problems of small number statistics, there are well-known differences between globular cluster populations and the field – for example the 'halo' globular clusters of M31 have a dominant population with metallicity of ~ -1.5 dex, similar to that of the Milky Way (Barmby et al 2000 AJ), while the field halo of M31 apparently has a mean metallicity of ~ -0.7 dex (e.g. Holland et al 1996). Further, it is becoming clear that the globular clusters we observe now are the survivors of an earlier larger population (e.g. Fall & Rees 1977; Gnedin & Ostriker 1998; Zhang & Fall 1999). Indeed, we do not understand the conditions under which globular clusters form (discussed below).

In summary, the science needs CMDs down to the oldest turnoff – ideally at least a magnitude fainter than the turnoff – at several key locations within the target galaxy. These need to be complemented by low-resolution spectroscopy of tracer stars, such as the lower red giant branch, in order to break the age–metallicity degeneracy in the CMDs. These spectra will also provide kinematics, through radial velocities, of accuracy good enough to discriminate between different stellar populations (tens of km/s). Kinematics will decompose the CMDs into separate subcomponents, provide a database in which to look for phase-space structure, and probe the potential well of the galaxy. To determine detailed elemental abundances (and hence trace relative contributions of Type Ia and Type II supernovae to the enrichment, date the duration of enrichment, and constrain the massive-star IMF), higher-resolution spectroscopy should be obtained, of stars at least as faint as a magnitude below the tip of the RGB (tip RGB is at $M_I \sim -4$) to avoid complications in the interpretations of the elemental abundances due to possible internal mixing and dredge-up.

Spectroscopy suitable for overall chemical abundances and for kinematics to $\lesssim$ 20 km/s, assuming the optical, requires $\mathcal{R} \sim 4,000$. Detailed elemental abundances require $\mathcal{R} \gtrsim 40,000$. Thus adopting the telescope requirements (aperture, resolution) for imaging (CMDs) down below the turnoff, to given S/N in given time (in Table 2 here S/N = 10 in 10^4s), kinematics and metallicities can be obtained for stars some ~ 3.5 magnitudes brighter, or the lower RGB, while detailed elemental abundances can be obtained for stars some ~ 6 magnitudes brighter, or the upper RGB. This is an appropriate combination of observations, keeping to lower stellar luminosities than would raise concerns about internal mixing processes and hot-bottom burning etc. perhaps affecting the surface abundances.

Requirements for M31

First consider analysis of the CMDs: M31 has a distance modulus of 24.3, and its bulge half-light (effective) radius is at a minor axis projected distance of ~ 1.3 kpc, and surface brightness of $\mu_B \sim 22.2$ mag/sq arcsec (uncorrected for extinction; Walterbos & Kennicutt (1988); Pritchet & van den Bergh (1994); adopting extinction of $A_B = 0.756$ (cf. Renzini 1998) this is an intrinsic surface brightness of $\mu_{B,0} \sim 21.5$).

Considering the IR first, a 10m telescope with AO in the K-band, with diffraction-limited performance, would barely reach the old turnoff, even in the lowest surface brightness regions (isolated turn-off stars). Note that Renzini (1998) argues that even for the outer regions of the bulge of M31, at surface brightnesses of $\mu_B = 23$ mag/sq arcsec, $\mu_V \sim 22$, to get two magnitudes below the turnoff would require a diffraction-limited 80m telescope operating in the K-band (set by the required resolution to have enough pixels per target star). Our calculations in Table 4 agree with this, assuming that we require only 20% photometry two magnitudes below the turnoff. For 2 Gyr age resolution of old populations, i.e. ~2% K-band photometry at the turnoff, even a 100-m telescope can probe only surface brightnesses below $\mu_V \sim 25$.

The higher resolution of the diffraction-limited *optical* allows one to obtain CMDs to the turn-off in higher surface brightness regions for a given aperture size, and the sensitivity and (V-band) resolution of a 50m class telescope with full optical AO would provide the required CMDs for at least the outer bulge of M31, (3% photometry), and, with 10% photometric accuracy, into the half-light radius. The innermost regions would still require the higher resolution of a larger telescope (see Table 4, entry under 'center of E-galaxy').

Thus, if we have optical AO – and indeed optical is favoured for stellar population diagnostics, and the panel **urges** that optical AO be a design requirement for any next-generation ground-based telescope – then a 50m telescope would provide CMDs suitable for constraining the ages of the oldest populations into around the half-light radius of M31. A 100m telescope, diffraction-limited in the optical, would provide the same for the more central regions.

The FOV requirements for the imaging are not stringent, being set by the surface density of targets on the sky, with the worst case being study of the lowest surface brightness regions. Even at several bulge half-light radii from the center of M31, at projected distances of around ~ 10 kpc, HST WFPC2 $(3 \times (80'' \times 80'') = 5.3$ sq arcmin) contains many hundreds of lower RGB stars (Holland et al. 1996), and presumably tens of thousands TO stars. For the realm of interest, a field of view of perhaps $1' \times 1'$ should suffice.

As noted above, the requirements in terms of sensitivity and resolution set by the proposed analysis of the CMDs provide adequate spectroscopy for the science also. FOV requirements again are set by the necessary sample size, the surface density of targets on the sky, and here by the need (and capability) for MOS; as mentioned above there will be, say, 100 lower RGB stars per square arcmin in the outer regions of M31's bulge. Brighter giants are more rare, but again we expect that a modest FOV (several tens of sq arc sec) with some MOS/IFU capability, with several tens of simultaneous spectra (some for sky) would suffice, without too many pointings being required to build up a large enough sample.

High-resolution spectroscopy of samples with sizes of $\sim$100 are required to identify patterns of elemental abundances (e.g. Edvardsson et al. 1993; Burris et al. 2000) and also to define means and dispersions of metallicity and kinematic distributions. A more detailed analysis, looking at the tails of the distributions and evidence for phase space structure, require sample sizes in the thousands for statistical significance (e.g. the 2dF star survey of Gilmore, Wyse, Norris & Freeman).

Note that native-seeing spectroscopic capabilities will be restricted to low surface brightness regions, and there, as noted above, we expect that the large number of 10m-nights that will be available in the next decade will have largely completed the spectroscopy of M31 red giants in the outer bulge/halo, which might otherwise have been identified as 30m native-seeing science in this category.

Requirements for the large spiral galaxies beyond M31

In the Northern hemisphere, the next large spirals are in the M81 group, and in the Southern Hemisphere, they lie within the Sculptor Group, each with distance modulus ~ 27. Following the discussion above, the *requirements* for study of these systems to answer the science questions are a 70m telescope for the outer, lower surface brightness regions, and a 100m telescope for the inner regions, in both cases diffraction-limited in the optical.

I.1.2 Are bulges related to disks? Are bulges old?

Recent surface photometry has shown that low-luminosity bulges tend to have exponential surface brightness profiles, while large bulges have more 'classical' $r^{1/4}$ laws (see e.g. Wyse, Gilmore & Franx ARAA 1997). The scale-length of the exponential bulges correlates with the scale-length of the disk (Courteau, de Jong & Broeils 1996). The suggestion has arisen that the exponential bulges could arise from a disk instability. While predictions are not yet very detailed or robust, there should be a signature of this in the stellar kinematics, and perhaps in the age and metallicity distributions. These bulges are perhaps best studied in the IR, due to their small scale-length, but again one needs CMDs, and complementary spectroscopy.

The Milky Way Galaxy is interesting in that the central bulge indeed appears to be better fit by an exponential than by a de Vaucouleurs profile, suggestive of an association with the disk, but the stars in the bulge are dominantly old (e.g. Feltzing & Gilmore 2000). Are all bulges old?

The statistical samples of galaxies studied in terms of surface brightness so far have been fairly distant, set by the requirement of reasonable angular size (typically $\sim 2'.5$) for efficient profile measurements and sky subtraction with standard detectors. A study of the age distributions, and the relation between bulges and disks across the disk Hubble sequence, would begin the elucidation of the physics of galaxy formation.

Requirements: As above, with the additional proviso that perhaps one would need to use the IR to probe dusty regions, but it may be that these regions are of too high a surface brightness even for 100m telescopes. Thus, the deep optical CMDs and moderate- and high-resolution optical spectroscopy demands at least a 70m telescope to get beyond the Local Group.

I.1.3 When did disks start to form stars?.

A significant constraint on current models of disk galaxy formation is the epoch at which large disks initiated cooling and star formation. Hierarchical-clustering models, such as those based on the CDM cosmogony, find that proto-disk material suffers significant angular momentum loss during the merging processes inherent in the formation of large galaxies, and the result is disks that are too small and centrally-concentrated. The solution proposed has been to delay disk formation until after the epoch of most merging, or to redshifts less than unity (e.g. Weil, Eke & Efstathiou 1998). Extracting the age distributions of disks as a function of radius is an obvious test of this solution. Again, one needs deep CMDs and complementary spectroscopy. The reasonable assumption that the older thin disk stars will have a larger scale-height, as in the Milky Way (through well-established mechanisms such as the Spitzer-Schwarzschild scattering by GMC-analogs (1953)) suggests that one target edge-on disks, above the disk plane, to avoid active star formation. Again, to obtain a radial gradient one will have to be able to decompose the inner regions into bulge and disk, so kinematics are necessary.

The requirements are essentially as above.

I.1.4 What are the properties of thick disks?

The spiral galaxies that have had their surface brightness distributions studied in most detail have been those for which good sky subtraction could be achieved, and hence they are restricted in angular size. The best two examples of extra-Galactic thick disks, NGC 891 and NGC 4244 (van der Kruit & Searle 1982; Morrison et al 1998) are at distances of around 10 Mpc ($m-M$=30). Note that if thick disks are heated thin disks, they can also be used to probe the early stages of thin disk formation. Again, from Table 2, detailed study of the resolved stellar populations, through CMDs to below the turn-off plus complementary spectroscopy requires optical AO and a 100m telescope.

I.1.5 Is there a floor in chemical abundance?

An important aspect of the question of the early evolution of galaxies is how quickly do they enrich with metals? There appears to be a lack of extremely metal-poor stars in the halo of the Milky Way (Beers et al. 1990s) below [Fe/H]~ -4; we do not know if this is unique to the Milky Way, or why this is not higher, given the detection of metals at about [Fe/H]~ -2.5 in the Lyman-α forest at high redshift (Cowie 1998). As in the Milky Way, the approach would be to use low resolution spectroscopy to identify candidate extremely metal-poor stars, and then obtain high-resolution spectroscopy to determine the actual abundances.

This requires an efficient means of identifying the rare extremely low-metallicity candidates; the extant method uses objective prism techniques to measure the strength of the Ca H&K line, and hence requires wide-field MOS $\mathcal{R} \lesssim 5,000$ capability with good sensitivity at $\sim$ 3900Å. However, candidates could also be selected photometrically with multi-slit follow-up at the Ca triplet. The final high-resolution ($\mathcal{R} \gtrsim 30,000$) spectroscopy would probably not need to be MOS, but would need to be in the optical for sensitivity at low metallicity (the superiority of the optical over IR in terms of stellar diagnostics is very clear in the case of low metallicity). Further, all of the nuclear chronometers are near 4000Å.

Requirements: For M31 the candidates could be identified by 10-m class telescopes, at least in the outer regions, with follow-up using optical spectroscopy on a 30m; presumably the low surface brightness, outer regions of the bulge/halo could be targeted, and so this could be a native-seeing project. Sample sizes of at least 100 stars are needed. Again, to investigate the lowest metallicity stars in the halos of the spiral galaxies of the next groups of galaxies (M81 and Sculptor; distance moduli $\sim$ 27), requires a 70m telescope, and even modest AO capability helps.

I.2 The Origins of the Hubble Sequence: Ellipticals vs Spirals

The testing of theories of galaxy formation and evolution needs the inclusion of elliptical galaxies, rather than the sample being restricted to just the spiral sequence. The nearest normal giant elliptical galaxies are in the Virgo cluster, at distance modulus of almost 31. Again following the discussion of bulges/halos/disks, one wishes to answer questions such as *'Are bulges and ellipticals of the same luminosity the same*, apart from the addition of a disk, as predicted by some merger models (e.g. Kauffmann 1996), and seen in integrated kinematics (Davies et al. 1983)?' A more general question is '*What is the age distribution of stars in ellipticals (and bulges)?* (cf. Renzini 1999).

Again following the discussion above, the deciphering of the fossil record requires deep CMDs, and complementary spectroscopy. The requirements are set by the usual combination of resolution and sensitivity needs. A comparison between bulges and ellipticals is the more stringent requirement, since the surface brightness at the half-light radius of an elliptical goes up as the luminosity goes down (Kormendy 1977). The surface brightness at the half-light (effective) radius for ellipticals varies from $\mu_V \sim 23$ mag/sq arcsec for giant ellipticals, to $\mu_V \sim 20$ mag/sq arcsec for low luminosity (compact) ellipticals (not to be confused with the second elliptical family, that contains the extremely low surface brightness dwarf spheroidals; Wirth & Gallagher 1984).

As can be seen in Tables 4 and 5, even a 100m will reach the oldest turnoff only in the outer regions of ellipticals in Virgo. Of course, younger turnoffs will be reached, and hence the age distribution of intermediate-age stars, and limits on ages, will be obtained. With a 100m, one can also obtain kinematics and metallicities in these outer regions, and start to understand ellipticals in detail.

It is obviously very technically challenging to initiate the investigation of the resolved stellar populations of ellipticals, and it is extremely important to have a detailed study of the photometric capabilities with AO. Our estimates in Tables 4 and 5 should not be taken as definitive at this stage.

I.3 How do Dwarf Galaxies Form and Evolve?

I.3.1 Dwarf Spheroidals

As noted earlier, HST photometry has revealed complex stellar populations in many of the dSph companions to the Milky Way and M31, with star formation histories that are varied but usually contain a strong intermediate-age population. Detailed study of representative RGB stars (as opposed to upper/tip RGB) in the nearer examples will be possible with 10m-class telescopes, in both native-seeing and AO-modes. These systems are of low surface brightness, with central values $\mu_V \sim 24$ mag/sq arcsec. Detailed elemental abundances of bright red giant stars and deep CMDs will be available for the nearer examples from HST + 10m telescopes (see earlier discussion of Keck data for LG dSph). The more distant examples will require a larger telescope.

Age-Metallicity Relationships and Chemical Evolution: As noted above, these systems often have had extended star formation episodes, forming many generations of stars. Did the mean metallicity increase smoothly, or are the effects of gas outflows important? Spectroscopy of subgiants corresponding to a given turnoff age will provide age-metallicity relationships; this will tie down the chemical evolution of these systems, which may be analogs of the first systems to form, and perhaps contribute to the chemical enrichment of the IGM. Even with the low surface-brightnesses of dSph, targeting old subgiants (see Table 5) requires a diffraction limited system. The dSph companions to M31 are just beyond reach of a 10m telescope for this project; a 30m is required, again diffraction-limited in the optical.

Internal Dynamics: The velocity dispersions of these systems are around 10km/s, high enough that significant amounts of dark matter are inferred. A full spatial map of the radial velocities, with few km/s accuracy across the face of the galaxy (thus several degrees on the sky), is required for detailed modelling of the underlying mass distribution. This analysis for these smallest galaxies provides unique constraints on the nature of the dark matter, since the smallest scales constrain the 'temperature' of the dark matter. The targets could be bright RGB stars, which for high-resolution spectroscopy are just accessible out to M31 with Keck, native seeing (see earlier; Cote et al 1999). The outer fringes of the Local Group will require a 30m, but again native seeing should suffice.

Requirements: native seeing 30m, moderate resolution MOS, FOV perhaps several arcmin.

I.3.2 Dwarf ellipticals in Virgo

Numerous low surface brightness, 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 suggest that indeed the dEs are associated with infalling galaxies (Conselice, Gallagher & Wyse 2001). Detailed stellar population information would allow the determination of ages, metallicities and kinematics. Determination of the radial profiles of velocity dispersions and streaming motions – either from integrated spectra, or preferably from star-by-star samples – constrain the underlying potential well, revealing whether or not dark matter is indeed dominant. This in turn provides a strong constraint on e.g. models whereby dEs in clusters are formed through harrassment, since the central regions of spirals have a significantly lower dark matter content than the local dSph.

Requirements: The internal kinematic gradients, which are necessary for a robust determination of the potential well, require a 100m for both the spatial resolution and sensitivity. Determining a simple line-of-sight central velocity dispersion should be possible with a 10m telescope.

I.3.3 Intergalactic stars in Virgo

Intergalactic stars and PNe have been detected in the Virgo cluster, e.g. Ferguson, Tanvir and von Hippel (1998) used HST to discover a population of TRGB stars ($M_I \sim -3.4$), while Freeman et al (2000) have identified a population of planetary nebulae not associated with individual galaxies. These populations were perhaps produced as a result of the galaxy harassment that has been postulated to form the numerous dEs in Virgo (e.g. Moore et al 1999, MNRAS 304, 465). Kinematics and metallicities for these intergalactic tracers will constrain their origins, by identifying streams (should they exist) and estimating the means and spreads in metallicity within a stream. The PNe are accessible for further study with 10m class telescopes (e.g. planned VLT use, Arnaboldi et al 2000). Moderate-resolution spectroscopy to determine the kinematics of the more numerous intergalactic TRGB stars requires a diffraction limited 30m telescope, but in this application using the IR would probably be fine; if the stars are truely isolated, then native-seeing is possibly also sufficient (Table 3).

I.4 Globular Clusters

The kinematics, abundances, ages and spatial distributions of globular clusters provide important information on star formation and chemical evolution, not only at very early times, but apparently during episodes of enhanced star-formation rate, such as associated with mergers between host galaxies.

I.4.1 What are the internal spreads in age? metallicity? elemental abundances?

The extant studies for Milky Way globular clusters have shown the fascinating result that a few globular clusters show real internal spreads in metallicity. In the case of ω Cen, there is also a possible correlation between age and metallicity (based on Stromgren photometry; Hughes & Wallerstein AJ March 2000). Is this an indication that this globular cluster is the remnant nucleus of a dwarf galaxy? How common is this? In native seeing, limited by resolution, optical CMDs below the turnoff (and hence low resolution spectroscopy of lower RGB and high resolution spectroscopy of bright giants) are possible for the outer regions of Galactic globular clusters only, to distances of $\sim$ 4 kpc. Adaptive optics, in the optical, on a 10-m class reaches out to M31, and indeed includes the outer parts of all globular clusters in the Local Group. A 30m telescope (optimistically) would include the outer regions of globular clusters in the M81 group. The requirement for study of the (outer regions) of the globular clusters associated with the giant ellipticals in Virgo is a 100m (to resolve the clusters) plus optical AO. The inner regions of globulars will not be studied beyond M31, even with a diffraction-limited 100m.

I.4.2 Metallicities and Ages from Integrated Light of Globular Clusters

Recent results from HST (where spatial resolution allows good globular cluster/star/galaxy separation) have revealed that the globular cluster systems of many galaxies have bi-modal color distributions. The inferences from colors alone in terms of ages and metallicities are rather weak, and one would like at least integrated spectra, which have the bonus of kinematic information. The current state-of-the-art with LRIS on Keck is crude kinematics (errors about 100km/s) and Lick-index-based metallicities ([Fe/H] to ±0.4 dex) for globular clusters at NGC3115 distances (see Puzia et al. 2000), closer than the Virgo cluster. The globular cluster systems of elliptical galaxies in the Virgo cluster (e.g. M87) and beyond (e.g. NGC 1700; Brown et al. MNRAS 2000) will be within reach of a 30m. Indeed the integrated light of globular clusters in the Virgo and Coma clusters could be studied down below the peak in the globular cluster luminosity function, with a 30m, native seeing, allowing investigations of e.g. metallicity versus luminosity and kinematics for the globular clusters of elliptical galaxies, in particular those with a bi-modal color distribution.

Requirements: Native seeing, low-resolution spectroscopy, 30m telescope, most efficient with MOS with reasonable (several arcmin) FOV.

I.4.3 Internal velocity dispersions of Globular 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 and velocity dispersions. The present state-of-the art outside the Milky Way are central dispersions for 21 luminous globular clusters in M31 (Djorgovski et al. 1997), using Keck with HIRES ($\mathcal{R} \sim 35,000$). Combination of these kinematic data with HST imaging leads to the conclusion that these clusters follow the same scaling relations as the Milky Way globulars, and also have no evidence for dark matter. But can we extend this to other galaxies? Can we measure internal kinematic gradients within a globular cluster in M31? The requirements are for high-resolution spectroscopy, to measure radial velocities to a few km/s, of red giant stars, at least into several core radii. From Table 4, this requires a minimum of a 50m telescope, diffraction-limited in the optical. As a bonus, elemental abundances could also be obtained (cf. McWilliam, priv. comm. to Rich).

I.4.5 Mass segregation and IMF of Globular Clusters

In the Milky Way, star counts within globular clusters are consistent with a fixed underlying low mass IMF, but with some internal dynamical evolution having produced mass segregation and preferential evaporation of low-mass stars. Is this the same in external galaxies? This project requires deep star counts, down to a few tenths of a solar mass, some ~ 4 magnitudes in the V-band below the turnoff, or ideally down to the brown dwarf limit of $\sim 0.1\ M_{\odot}$. These counts should be done in the outer regions and into at least several core radii of the globular clusters; from Table 4, to study the globulars in M31 at these surface brightnesses requires a 100m telescope, diffraction-limited in the optical.

II. Other Science

II.1 Massive Stars and Star Formation

The distribution, kinematics and chemical elemental abundances of bright stars are also important tracers of galactic evolution, the OB supergiants for recent star formation, and the AGB for intermediate ages.

Key science issues include:

II.1.1 What are the present-day elemental abundances, and how homogeneous is chemical enrichment?

Detailed study of the OB, A and F stars in the Orion association (Cunha & Lambert) has shown that reliable chemical elemental abundances can be derived from OB stars, and that the nebular and stellar abundances are on the same scale. Further, there are spreads in the elemental abundances, correlated with age across the Orion OB association, suggesting internal contamination by Type II supernovae. The existence of scatter in the local F-star age-metallicity relationship is fairly well-established (e.g. Edvardsson et al 1993) but the intrinsic amplitude is still uncertain (e.g. Binney 2000), although at least some part may also reflect inhomogeneous chemical enrichment. Can one quantify this? Supergiants in the LMC are within reach of 4m-class telescopes (Venn 1999). Venn et al. (Oct 2000, ApJ) have analysed KECK HIRES ($\mathcal{R} \sim 35,000$) spectra of three A-F supergiants in M31 (S/N $\sim$ 80 per resolution element, after only 2×45 min exposures), demonstrating that one can obtain reliable oxygen abundances, and as for OB stars, with larger uncertainties, iron-group and other elements that are inaccessible through HII region analyses.

Given these results for M31 with short exposures using Keck, the whole of the Local Group (low surface brightness regions only) is within reach even with native seeing on a 10m-class telescope. Indeed, massive OB stars are within range of 8-10m telescopes out to distances of 3-4 Mpc, primarily in dwarf irregular galaxies and the outer parts of spirals. However, very distant supergiants, fainter than $V = 18$, require one or more nights per star. A 30m telescope would vastly increase the sample and quality of data. A large sample is required if one wants to identify scatter in chemical enrichment/gradients, since one needs some tens of stars at each radial location. Further, identifying radial gradients and measuring their amplitudes requires probes in the higher surface brightness, inner regions. From Tables 4a and 5a, a diffraction-limited 10-20m-class telescope could, operating in the optical, obtain moderate-resolution spectroscopy of massive stars in the spiral arms of disks out to the Sculptor group. A 30m telescope would extend moderate-resolution spectroscopy to blue compact dwarf galaxies, such as the extremely metal poor system I Zw 18 ($m - M \sim 30$; Ostlin 2000). However, routine elemental abundances of massive stars beyond the Local Group will require a 50m telescope, again diffraction-limited in the optical.

II.1.2 What Fraction of OB stars are born in bound clusters?

We know that most OB stars are born in loose associations that dissolve through internal and external effects. The high-resolution spectra discussed above for elemental abundances will also provide high precision kinematics to ~ 2 km/s (see Cote et al 1999), that will provide limits on possible past associations.

II.1.3 Super Star Clusters – when and how do they form?

HST has recently shown that formation of massive, globular star clusters with $M > 10^5 M_\odot$ has continued to the present day in some galaxies. These "super star clusters" (SSCs) are found preferentially in disturbed systems in the aftermath of strong tidal interactions or mergers. Some galaxies contains hundreds of SSCs, for example the merger remnant NGC7252 contains some 500 candidate SSCs more luminous than $M_V \sim -7.4$ (Schweizer & Seitzer 1998). They are common in starbursts. They are important in a number of ways. Because they are luminous and nearly coeval systems, they are highly valuable tracers of the history of star formation and chemical enrichment in galaxies. With some SSCs as luminous as $M_V \sim -12$ to -15, their integrated properties can be determined at large distances; 4-m class telescopes have produced moderate-resolution ($\mathcal{R} \sim 1,000$) optical spectroscopy of a small number of relatively isolated (low background) SSCs out to $m - M = 34$ (e.g. NGC7252, Schweizer & Seitzer 1998), allowing rough age and metallicity estimates. Higher resolution optical spectra ($\mathcal{R} \sim 3,000$) have been obtained for the nearer starburst M82 ($m - M = 27.8$; Table 1), allowing a more robust determination of ages and metallicities (Gallagher & Smith 1999). The youngest SSCs, still embedded in the dusty gas clouds in which they form, are best studied in the IR, even though the stellar diagnostics are not as well-suited to determinations of age and metallicity. As an example, Gilbert et al (2000) have obtained moderate-resolution ($\mathcal{R} \sim 1,900$) near-IR spectroscopy of a young (derived age ~ 4 Myr) embedded SSC ($M_K \sim -18$) in the Antennae galaxies, at a distance of 19 Mpc. With a 30-m telescope, native-seeing integrated optical spectroscopy of the brightest SSCs, at low-moderate resolution, could be extended as far as $z = 0.3$ ($m - M = 41$; Table 3), allowing us to trace star formation to cosmological distances–provided they can be isolated from their parent galaxy.

The effective radii of SSCs are measured by HST to be typical of globular clusters, or ~ 10 pc (refer to Table 1 to compare with diffraction limits). If limited by seeing, CMDs would only be available for the nearest rich clusters, those populous young clusters in the Local Group, which are already accessible with *HST*. With optical AO, a 30-m could produce color-magnitude diagrams of the outer parts of isolated, young SSCs which we may now only study through integrated light. Even for marginally-resolved clusters, we could measure shapes and internal color gradients. The effects of various destruction mechanisms on the evolution of the cluster luminosity function could be followed. Studies of the resolved stellar content of SSC systems can answer several important open astrophysical questions: for instance, the conditions which favor the formation of massive clusters, the fraction of total star formation which occurs in clusters versus the field, and the cluster IMF from which the extant, surviving clusters are produced. The interactions of young clusters with their environments in the form of ionization and winds, and the resulting "feedback" on later star formation, are also of great interest.

For the distant SSCs integrated light studies would require high S/N relative spectrophotometry (1% goal). Spatially-resolved spectroscopy with multiple slitlets or an IFU would be needed. AO in the optical would allow for the resolution of individual massive stars in many of the objects. Access to the full optical spectrum, down to 3400 Å is important to get useful age and metallicity diagnostics.

II.2 Faint Luminosity Functions and IMFs

Deep star counts in various extragalactic systems are required to determine the consistency with a universal low-mass IMF, or to see if real variations in the IMF are inferred, and whether a significant part of the 'dark baryons' in the universe are locked into objects like faint stars and brown dwarfs or stellar remnants such as white dwarfs. One can also use the WD LF in globular clusters to determine cooling ages and compare with stellar isochrone ages.

Studies down to around 6 magnitudes fainter than the turnoff in anything other than the lowest surface brightness regions a few kpc from the solar circle will require adaptive optics (see Table 4, scaling from the entry for one magnitude fainter than the oldest turnoff), and as noted earlier, the central bulge of M31 is beyond even a 100m telescope. The state-of-the art with HST is an optical LF down to $V \sim 26$, or masses of a few tenths of a solar mass, in the nearby dSph in Ursa Minor (Feltzing et al 1999), and down to the brown dwarf limit in nearby globular clusters (Cool and King 1998).

IR (NICMOS) data down to the brown dwarf limit have been obtained with HST in the central bulge of the Milky Way, at one scalelength from the center (Baade's window; Zoccali et al 2000). NGST will aim to measure the IMF in the central bulge, but more distant systems require a larger telescope.

The state-of-the art for the white dwarf LF with HST is the open cluster NGC 2420, at a distance modulus of ~ 12 (von Hippel & Gilmore 2000).

A 30m telescope, diffraction-limited in the optical, would provide LFs down to the brown dwarf regime in the Milky Way dSph galaxies, but to go beyond them, or to higher surface brightness regions, would require a 50m and larger. Similar requirements are set by the WD cooling sequence.

II.3 GRBs – Are they associated with massive stars and extreme star formation rates?

The high spatial resolution and sensitivity of diffraction-limited large telescopes will provide the answers to the identity of the progenitors of GRBs that may well remain into the next decade. The requirements are to detect, in a galaxy at redshift of order unity, a GRB afterglow (peak luminosity of $\sim 10^{16}$L$_\odot$, but very briefly) and obtain high-resolution spectroscopy of it, and detect the most luminous individual stars and also smallish open clusters; these requirements are met by a 30m telescope, diffraction-limited in the near-IR. The spatial resolution is comparable to the size of a giant molecular cloud. At the limiting threshold its location accuracy (~resolution/signal-to-noise) is significantly better.

Note that the limiting luminosity of such a telescope system at $z \sim 1$ is, at 1.25μ, $L_{lim} = (\nu F_\nu)_{lim} 4\pi d^2 \sim 5 \times 10^{39}$ erg/s $\sim 10^6 L_\odot$. It therefore easily detects supernovae and GRB afterglows.

II.3.1 What is the immediate environment of GRBs?

One may examine the GRB-progenitor relation by providing precise association of GRB afterglow with structures in its host galaxy. The location of the GRB would be identified with a smaller telescope, and the large telescope used for detailed study of the environments. This needs a large telescope because of spatial resolution considerations: typically $z > 0.5$ for the rare GRB we see, implying very high resolution requirements. Extinctions are generally small, so IR helps but is not crucial. However, on a time scale of years, we expect a signal from the heated dust in a region of several pc around the burst. It peaks in the 3-8 micron range in the rest frame, and thus requires mid-IR capability. The strength of the dust signal (detectable beyond z=5 with a diffraction limited 30-m) and its duration depend on the amount and density of ISM around the GRB.

II.3.2 What is the larger-scale environment of GRBs?

One may examine the detailed morphology and properties of the host galaxies of GRB. Are they starbursts or normal galaxies? Since GRBs are identified through X-rays or with gamma-ray satellites, there is little extinction selection. Thus, if GRBs trace star formation, then they may give an unbiased view of where (massive) stars form. An outstanding question that can be answered is whether star formation at high redshift is dominated by ULIRGs or by small, HDF-type galaxies.

II.3.3 GRBs as probes of star formation at the highest redshifts?

At 3 microns, a GRB afterglow does not decrease in brightness when viewed after 1 day of observer time, since high-z GRBs are then still just hours old in their restframe, compensating for greater distance. This means that in the 3-5 micron range, we can detect GRBs out to all plausible redshifts (z∼20). Hence, if GRBs do trace star formation, we may see the earliest star formation. We would automatically have enough signal to do decent spectroscopy. This will extend the analysis of Lyman-alpha forest systems and DLAs possibly up to redshift $z = 15$, and thus shed light on the history of early structure formation and gas to star conversion in the early Universe.

II.4 Astrometry

There are significant challenges for astrometric observations with AO and MCAO, but the potential rewards with a large diffraction-limited telescope are also significant. The astrometric space missions such as GAIA will measure positions with centering accuracy of around 150μarcsec for stars brighter than $V = 20$, increasing to around 10μarcsec for stars as bright as V=15; SIM's nominal precision is 3μarcsec at $V = 20$. For GAIA, this allows e.g. the measurement of the internal proper motions of evolved stars in satellite galaxies out to around 70kpc (assuming transverse velocities are about equal to line-of-sight velocities, and so the dispersion is around 10km/s, then at 70kpc this is 30μarcsec/yr; p.m.$(''/\mathrm{yr}) = \frac{V_T(\mathrm{km/s})}{4.74\mathrm{d(pc)}}$). GAIA will also measure rotational parallax distances to the large galaxies M31 and M33. A similar centering precision of tens of μarcsec is required to measure the internal kinematics in M31 through proper motions, but with the further requirement that the stars to be used are at fainter magnitudes than can be reached by GAIA, necessitating a larger telescope – again assuming that the transverse and line-of-sight kinematics are similar, one expects halo stars in M31 to have dispersions ~ 100 km/s, which is $\sim 30\mu$arcsec/yr at the distance of M31. One must measure this signal to better than a few μarcsec/yr for sufficient confidence, and assuming a 10-yr baseline, this gives the required precision of around 20μarcsec. The dwarf satellite galaxies of M31 that contain only old stars (e.g. And I, Armandroff et al 1998) are also inaccessible by GAIA (targets below the magnitude limit for given accuracy), but these would be amenable to study with a larger telescope, provided similar positional accuracy were possible.

The limit achieved so far from the ground is ~ 1 milliarcsec, a factor of fifty poorer than this requirement. Indeed, milliarcsec positional accuracy is the present estimate for MCAO (taken from section 3.4 of Gemini preprint 62, Rigaut et al). The challenge for AO/MCAO is to achieve significantly better than this. The science that would be achievable would be e.g. allowing the internal velocity dispersion to be measured in *all* the Local Group galaxies. Further, systemic proper motions for all the galaxies in the Local Group would allow a definitive analysis of the orbits within the Local Group, and a full modelling of the timing arguments for masses etc.

Near-IR capability opens up obscured regions such as the Galactic Center, where speckle/AO work on 4m–10m class telescopes has allowed determinations of proper motions of at the level of several milliarcsec/year (100km/s corresponds to 2milliarsec/yr at 10kpc; Genzel 2000; astro-ph/0008119); Ghez et al. 2000, Nature 407, 348). A 30m telescope with MCAO could make dramatic gains in this type of science. The presence of the black hole should deplete radial orbits (the loss cone). Unusual microlensing events may be observable, as well as the effect of the radiation environment on stars nearest to the black hole. Presently only a handful of stars near the Galactic Center have orbits determined, but a 30m could push the sample to hundreds. The compact and obscured Arches cluster near the Galactic Center has hundreds of OB stars in a small volume, and its stability is questioned. AO astrometry could give complete kinematics for these stars.

The investigation of astrometric capabilities with AO, including questions of the stability of the system over years, is thus important for resolved stellar populations (we note the discussions in the other panels of projects that require stringent astrometric accuracies, such as the imaging of proto-planetary disks) and the panel urges the experts to consider this a high priority.

III. Connection to Extragalactic Panel Projects

Most of the above science has involved systems in which individual stars are resolved. The panel strongly believes that the scientific return of the study of resolved stellar populations, as outlined above, is greatly superior to that obtainable from integrated light studies. However, with the telescope as we desire it, one can also look at larger distances with surface photometry of spatially resolved galaxies, a focus of the ExtraGalactic panel. With native-seeing IFU spectroscopy, one will with a 30m be able to estimate stellar age and metallicity dispersions in the high surface brightness regions of galactic bulges in Virgo and Coma, and also study obscured starburst regions. One may also study the low surface brightness regions, such as the outer halo regions, of galaxies by adding up the light in large apertures. Again, robust stellar age and metallicity diagnostics require spectroscopy down to 3400Å with 1% relative spectrophotometry. For complete sampling of Hubble types, environmental effects, etc., arguably the natural volume is roughly that within the 'Great Wall' at $v_r = 8000$km/s or $m - M = 35$. One cannot do resolved population studies for the more distant parts of that volume, but can study the integrated light with any 30-m or larger telescope.

IV. Summary Conclusions

The era of 8-10m class telescopes with AO is upon us, and much has been, and will be, achieved in the study of the resolved stellar populations of the Local Group. A true paradigm shift would come with the capability to measure directly the main sequence turnoff age of the dominant population of a large elliptical galaxy.

What of the science can be done with limited future capabilities?

Extracting the highlights from the above text, we find:

♡30m, native seeing: CMDs of evolved stars and spectroscopy of red giants in low surface brightness outer regions of M31 and satellite galaxies (but note also moderate-resolution spectroscopy science – kinematics, overall metallicity – mostly accessible with 10m telescopes). High-resolution spectroscopy of candidate extremely low-metallicity stars in M31 halo. Integrated-light study (moderate-resolution spectroscopy, kinematics and metallicities) of globular clusters in the Virgo cluster, and of super-star-clusters at great distance (if in low-surface brightness regions of host galaxies). Surface photometry of spatially-resolved galaxies in the Virgo and Coma cluster will provide estimates of e.g. age and metallicity dispersions.

♡30m, AO in the IR: Moderate-resolution spectroscopy of intergalactic stars in the Virgo cluster. High-resolution spectroscopy of GRBs out to redshift of unity. High resolution spectroscopy of luminous AGB stars in the (outer) bulge and disk of Local Group galaxies.

♡30-50m, AO in the optical: CMDs to below the TO and supporting high and medium-resolution spectroscopy of stars in the outer disk and bulge/halo of M31. Also outer regions of globular clusters associated with M31, and of SSCs. Faint star counts and luminosity function to brown dwarf limit in local group dwarf spheroidals.

♡50–70m, AO in the IR: IR CMD to below the turn-off, of the bulge of M31 at its effective radius.

♡70m, AO in the optical: CMDs to below the TO and supporting high and medium-resolution spectroscopy of stars in the low surface satellites galaxies and in the outer disk and halo/bulge of the large (disk) galaxies in the next group (M81 or Sculptor group), and perhaps into the effective radius. Faint star counts and luminosity function to brown dwarf limit in outer disk and bulges of galaxies in the Local Group. Elemental abundances of massive stars beyond the Local Group, and high precision kinematics.

♡100m, AO in the optical: CMDs to below the TO and supporting high and medium-resolution spectroscopy of stars in the outer bulge of M31. The same (deep CMDs and spectroscopy) for the outer parts of large ellipticals in the Virgo cluster, and the outer regions of dEs and globular clusters in the Virgo cluster. Any population of younger stars in the higher-surface regions will also be amenable for study. Spatially-resolved internal kinematics and hence dark matter content of dEs in the Virgo cluster.

Summarize:

A 30-50m GSMT plus optical AO allows a comprehensive study of the resolved stellar populations in all the galaxies in the Local Group, with the exception of the inner bulge of M31. One then would have fairly complete knowledge of two large spirals (Milky Way plus M31), plus many dwarf galaxies, both gas-rich and gas-poor.

The next threshold is beyond the Local Group, using a 70m telescope, diffraction-limited in the optical, providing comprehensive study of the next group of galaxies. These are also spiral-dominated groups, and are useful mostly to increase the sample of large disk galaxies; further Sculptor provides an LMC-analogue (NGC 55).

The really big science threshold is to study a large elliptical galaxy, which means reaching out to the Virgo Cluster, requiring a 100m telescope fully diffraction-limited in the optical to even begin, with a study of the oldest populations in the outer parts, and limits on younger populations in higher surface brightness regions.

Table 6 : Summary requirements

parameter	requirement
sensitivity	interesting thresholds crossed at 30-70m; core science requires 100m
wavelength range	3400Å– mid IR
FOV	native seeing several arcmin ; $1'$ AO
R	$\gtrsim 5,000$ near IR (resolve OH lines)
	$\lesssim 50,000$ optical (elemental abundances)
Astrometric accuracy	relative positions to $10^{-4}{}''$ over years
	1mas per measurement
Instrumentation	MOS and IFU + echelle spectrographs
	image slice for native seeing
	optical spectrographs for native seeing (30m)
	optical and near IR imagers
PSF quality	AO as far into optical as possible
	stable PSF across field
photometric accuracy	relative spectrophotometry of 1%
	photometry to $\lesssim$3%

V. Studies Identified

♣ The panel felt strongly in favor of the optical, but felt that one should initiate a detailed study of optical vs near-IR, in terms of both age-determinations from CMDs and metallicity and elemental abundances from spectroscopy, over a range of metallicity and age. In particular, the usefulness of the IR at low metallicities has not be tested much. How much of the core science could be achieved, and with what accuracy, if only IR AO were available?

♣: Need a study to define the IR imaging and IR spectroscopy niches compared to NGST. We think that AO on 30m and above ground-based telescopes could provide improved performance in high surface brightness regions, like central regions of globular clusters in M31 and M81 and globular clusters and field stars close to the center of M31 and M81. High resolution IR spectroscopy ($\mathcal{R} \gtrsim 5,000$) will not be done by NGST, but need this on a ground-based telescope (at least in the H-band) to resolve out the OH lines.

♣ : The science capabilities are telescope requirements are sensitive functions of photometric accuracy and spatial resolution. Need a study to determine the photometric accuracy and effective resolution possible, with a detailed model of the expected PSF, for the kinds of environments we propose to study. As mentioned in the text, our Tables here are not definitive at this stage.

♣: Need a study to determine how well one can measure relative positions of stars when return to a pointing after some time (years) using AO. Are centroids measured well enough even if the PSF is different?

♣ : What are the real FOV limitations of an MCAO system? What is the faintest possible magnitude of the natural guide star? How does the AO perform when it is cloudy?

♣ : How to do sky subtraction with an IFU? Especially in crowded fields. Major deconvolution problem, especially with the extended haloes of the AO-corrected PSF.

♣ : How easy is it to match up stars if have an AO IR image and a native seeing optical image? The wings of the AO psf may overwhelm faint stars, especially since in the IR AGB and RGB stars are 3–6 mag brighter than in the V-band.

♣ : Need to quantify what gains in terms of S/N are made with limited improvements in seeing through active/adaptive optics. How does the photometric performance vary with strehl ratio?

♣ : Need to quantify what resolution is required for the (optical) elemental abundance analyses, since makes a big difference in terms of cost whether one requires $\mathcal{R} = 20,000$, $40,000$, or 80,000.