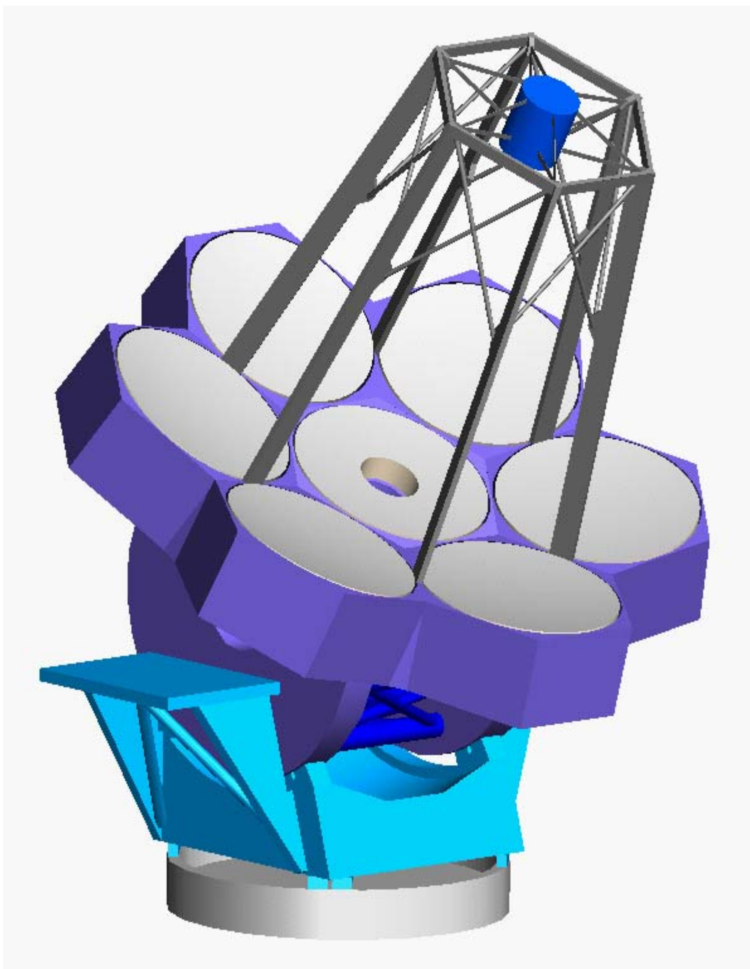
The Magellan 20 Telescope

Science Goals



Preliminary draft, not for distribution

March 18, 2003

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SCIENCE WITH THE MAGELLAN 20 TELESCOPE

1 Astrophysics with the Next Generation of Large Telescopes

As we look ahead to the coming decades we can anticipate an evolution in our approach to astrophysics. The focus of stellar and extragalactic research is shifting from discovery to an emphasis on understanding physical processes and evolution. Cosmological parameters are now known to high precision, providing a firm landscape within which the processes of galaxy and structure formation can be examined. An exception to this view of maturing astrophysics is the study of extra-solar planets. This field is arguably in the early discovery phase and will undergo a revolution in discovery space and physical studies over the next several years.

In this context the Magellan partners are preparing for the development of the next generation optical/IR facility. We aim to strike a balance between proven technology and new experimental techniques and technologies that offer the prospect of dramatic gains in sensitivity, angular resolution and multiplexing capabilities. The Magellan 20 telescope meets these goals and provides a vehicle for maintaining and extending world-class science within the Magellan consortium, and likely a wider user community, for the coming decades. In this document we give an overview of the scientific drivers that shape the design of the Magellan 20 telescope and its instrument complement.

2 The Capabilities of the Magellan 20 Telescope

The Magellan 20 primary mirror is composed of 6 segments, each of which is an 8.4m diameter off-axis hyperboloid of 18m focal length surrounding a center 8.4m mirror. The effective collecting area is that of a 21.5m filled-aperture and the resolving power is equivalent to a 24.4m diameter aperture. One configuration under consideration is an f/10 Gregorian, as shown in Figure 1. The secondary mirror in this configuration is 3.5-m in diameter and is composed of seven adaptive segments that map onto the primary mirror segments.

The telescope can be operated in a number of modes encompassing a range of fields of view and angular resolutions. The optical aberration at the raw Gregorian focus is small (< 0.2”) over a 15’ diameter field of view. This mode is well suited to multi-fiber spectroscopy and IMACS-like multi-slit spectrographs. Current designs for multi-slit imaging spectrographs cover fields of 7’ to 15’ in diameter (appendix A).

A thin-shell Gregorian adaptive secondary will conjugate to a level 150m above the ground and will be used to correct a wide-field for ground-layer seeing up to 300m. Detailed measurement of the ground layer wave-front distortions should be possible nearly anywhere in the sky using natural guide stars in the field. Rayleigh laser beacons may be used if higher photon rates are required. The potential scientific gains are large. For point sources in the background-limited regime, and for the J-band and longer wavelengths, the expected improvement of ~30% in the seeing FWHM of any 5 minute field from ground-layer correction gives the same signal/noise improvements as a 70% increase in telescope collecting area (e.g. a 27m diameter aperture). This mode will be well suited to deep multi-object spectroscopy and low-surface brightness integral-field unit (e.g. 0.2" apertures) work.

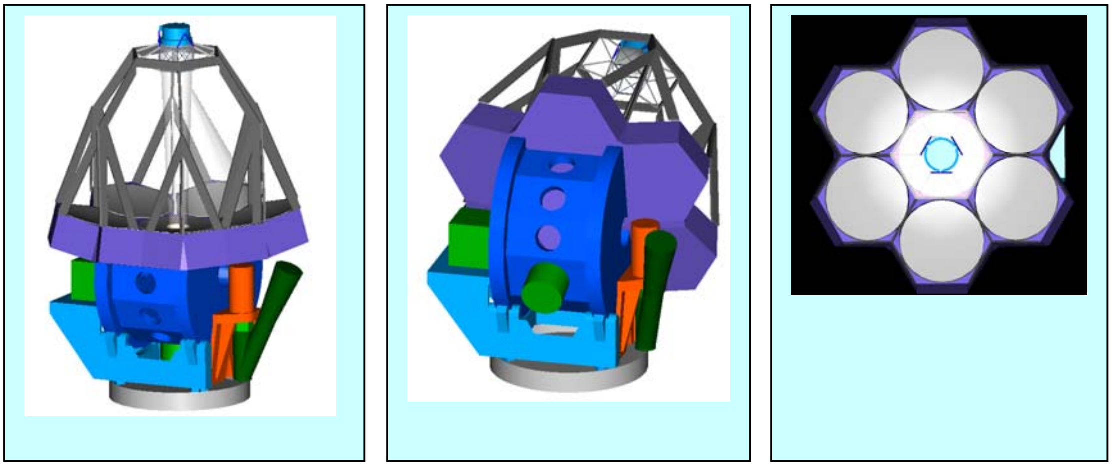

Figure 1. Three views of the Magellan 20 telescope with a Gregorian secondary. From left to right: zenith pointing, rear view and as seen from a star. Three instrument ports, two Nasmyth, and one Cassegrain, are shown.

We envision that the first-light operational configuration of the facility will include a high-order single-deformable-element adaptive optics system. This system will operate primarily in the near and mid-IR and will feed integral-field-units and high-resolution imaging systems over fields of ~ 20". For diffraction-limited images the FWHM of the central peak is the same as for 24.4 m filled aperture, and the fraction of all energy collected placed in the central peak is 68%, compared to 84% for a filled circular aperture. The diffraction-limited resolutions are 4.6 and 18 mas in the V and K bands, respectively.

The baseline configuration is being developed with an upgrade path to a full multi-conjugate adaptive optics (MCAO) system. This should allow diffraction-limited performance over ~1.6' fields with high Strehl ratios. This mode may be best exploited with deployable IFUs or deployable high-resolution imaging modules. The details of the implementation of the MCAO system are currently being modeled. Much will be learned from MCAO systems that are currently under development for the MMT, Gemini and other telescopes.

The full potential of the Magellan 20 telescope concept can be realized by adding a second telescope on a common translation track. This allows the two telescopes to operate in concert as a Fizeau interferometer. In this "20/20" mode the effective resolution is more than 4 times that of a single 30m telescope. Unlike Michelson interferometers, the Fizeau mode allows for direct imaging observations with full interferometric resolution. The details of the 20/20 concept are discussed in Angel et al. (2001).

In Table 1 we summarize the FOVs and resolutions of the various modes discussed above. We envision a baseline configuration that includes the wide-field natural seeing mode, a single-DM small-field AO mode, and a wide-field ground-layer corrected AO mode.

Table 1. Operating modes for Magellan 20

Mode	**FOV**	**FWHM @1μm**	**Notes**
Natural Seeing	15'	0.4"	Gregorian focus
Single-DM Adaptive	20"	0.007"	Natural & Laser guide stars
Ground-layer Adaptive	5'	0.25"	Natural guide stars
MCAO*	1.6'	0.007"	Natural & Laser guide stars
20/20 Interferometer*	1'	0.0017"	Requires 2nd telescope and track

* upgrade paths

3 Science Priorities for Magellan 20

In this section we layout the core science case for the Magellan 20 telescope. This is not intended to be a complete overview of all science areas in which this facility will have a significant impact. Rather it is meant to present a broad view of science issues that will impact critical design choices for Magellan 20 and its instrument complement.

3.1 *Origin and evolution of galaxies and structure in the Universe*

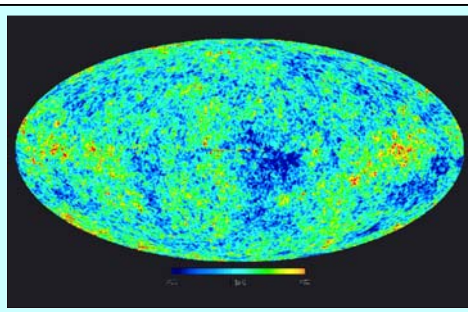

Figure 2. The WMAP image of the CMB (from Bennet et al. 2003). The last scattering surface reveals the seeds from which galaxies and large-scale structure evolves. Polarization measurements show that the first ionizing sources appeared at redshifts near 20.

Galaxies are the fundamental building blocks of the baryonic Universe. As such a deep understanding of their origin is an essential part of our overall view of the cosmos. The basic framework on which an understanding of galaxy and structure formation can be built is well in hand. Gravitational instabilities amplify tiny primordial density fluctuations and drive the hierarchical growth of structure. The amplitude and power spectrum of the initial fluctuations have been revealed by recent images of the cosmic microwave background. The mix of baryonic and non-baryonic matter and dark energy, and the fundamental geometry of the Universe are now reasonably well determined. The challenges facing galaxy and structure formation studies center on understanding how galaxies form as a function of environment, the impact of galactic feedback on the distribution of baryons, and the populations and processes responsible for the reionization and enrichment of the IGM. In simple terms we seek to understand both the history of star formation and galaxy assembly as a function of time and environment.

3.1.1 First Light

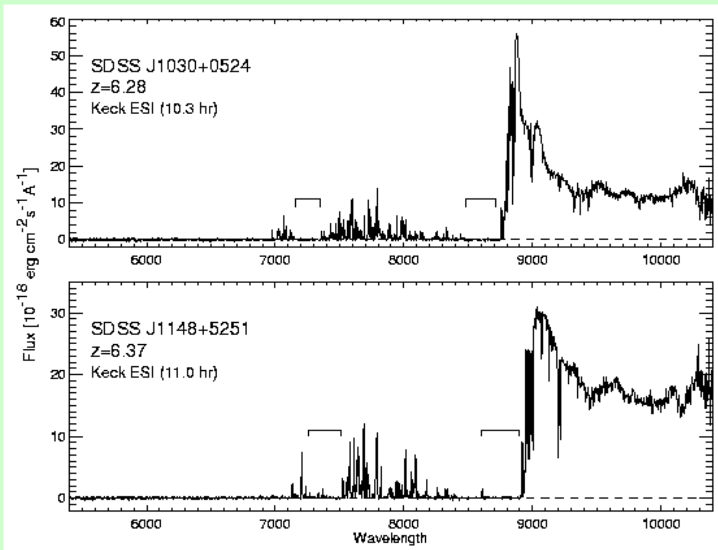

Figure 3. Two z > 6 Quasars from the SDSS (Fan et al. 2003). Deep Gunn-Peterson troughs are seen in a fraction of the z > 6 quasars, showing that reionization was not complete at this epoch. The large collecting area of Magellan 20 will allow unprecedented studies of the evolving IGM at high redshifts.

The formation of the first generation stars and black holes, the end of the cosmic dark ages and the process of cosmic reionization is one of the most important unsolved problems in modern cosmology. Recent detections of polarization in the CMB by CBI and WMAP suggest that the epoch of reionization began at redshifts near 20. The detection of Gunn-Peterson troughs in the spectra of several distant SDSS quasars suggests that z ~ 6 marks the end of the reionization epoch, or perhaps a secondary reionization event. The "first light" ionizing radiation may arise from nucleosynthesis within stars or it may be dominated by accretion onto compact objects. While it is believed by some that "first light" studies are primarily the domain of the JWST, 20m class ground-based telescopes will make unique contributions to our understanding of the detailed process of early galaxy formation and reionization, primarily through deep spectroscopy.

Figure 3 shows deep (10 hour) Keck/ESI spectra of the two most distant quasars known to date, the only two objects that show complete Gunn-Peterson troughs in their spectra. Detailed comparison of these two troughs begins to reveal subtle differences of the IGM properties along these two lines of sight. Furthermore, these deep spectra begin to reveal IGM metal absorption lines, and can be used to probe the metal enrichment history of the IGM at z>6, which might be the most powerful tool to date to study to properties of the first stars during the reionization epoch. Even for these relatively luminous quasars we are at the limit of our current telescopes for probing the universe at z>6. While they are adequate (only with 10 hours of Keck time) to probe HI, the sensitivity of even the largest telescopes is simply not enough to detect weaker metal lines in the spectra. We are already at the limit of the current generation 6-10m class telescope, even a 20m class telescope without AO will be a major and critical improvement in this regard.

Combining the power of JWST, a 20m-class optical/near IR telescope, CMB measurement from Planck, as well as the submm observations from ALMA and 21cm observations from SKA, we can expect to be able to map out the reionization process and the end of the cosmic dark ages in the next decade. A 20m-class telescope will play a critical role in this endeavor. The redshift range of $6 < z < 10$ is an epoch when the first generation galaxies and quasars are assembled and the reionization process ended. The most efficient way to probe them is through deep spectroscopy and imaging of high-redshift sources in the far optical and near IR, and a 20m-class telescope, especially with AO, is the most powerful probe in this redshift range especially when spectroscopy is needed.

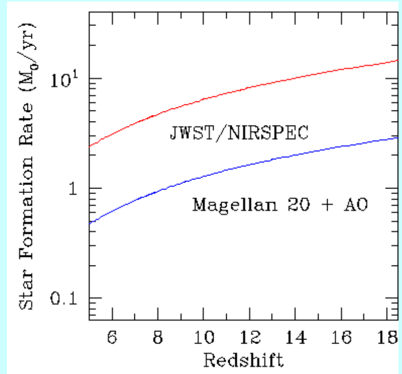

Figure 4. Limiting detectable star formation rates from Ly alpha emission-line spectroscopy with an AO-fed near-IR spectrometer on Magellan 20 and NIRSPEC on JWST. Both are for 10 hour integrations.

Lyman alpha emission from forming galaxies at $7 < z < 18$ will be redshifted into the traditional near-IR bands. Spectroscopy with large-format low-noise IR detectors on Magellan 20 should reach deeper than similar observations with the 6m JWST. In Figure 4 we show the limiting star formation rates derived from Ly alpha fluxes after 10 hours of exposure with an AO-fed near-IR spectrometer on Magellan 20 and NIRSPEC on JWST. The smaller image size and large collecting area of Magellan 20 leads to substantially high sensitivities in the $5 < z < 15$ range.

3.1.2 Evolution of the Galaxy Distribution

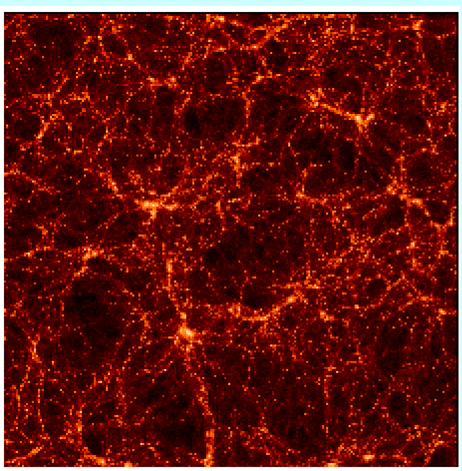

Figure 5: Structure in the dark matter distribution at z=1 in a Lambda-CDM model form the Virgo consortium.

The evolution of clustering and structure as traced by galaxies and intergalactic gas is an effective tool for gauging the galaxy assembly process. The redshift range of interest spans from $z \sim 6$, the end of reionization, to $z \sim 1$ when galaxy formation appears to have essentially halted. This time span encompasses the major epochs of galaxy, star and black hole formation. Deep spectroscopic surveys are required to probe the galaxy distribution at these redshifts and large samples are needed to provide robust determinations of the evolving luminosity functions, clustering scales and amplitudes. Very ambitious spectroscopic surveys are currently underway, or soon will be, with 8m class telescopes and wide-field imaging spectrographs. One may reasonably ask if such capabilities will remain vital in the era of

20m apertures. We believe that aggressive multi-aperture spectrographs will be an essential feature of the Magellan 20 facility. The current generation of telescopes does not have the light gathering power to reach intrinsically low luminosity galaxies at z ~ 1 and do not adequately sample even typical galaxies at z > 3. The practical limit of continuum spectroscopy with 8m class telescopes appears to be I(Vega) ~ 25. Deeper spectroscopy requires integration times in excess of one million seconds, making it impractical for statistically significant samples.

A wide-field spectrograph for Magellan 20 will allow us to reach I ~ 26, corresponding to 0.01L* at z = 1, 0.1L* at z = 3 and star formation rates of 10M/yr at z = 5. Reasonable design goals include fields in the ~15' range and hundreds of simultaneous spectra at intermediate (e.g. R = 4000) resolutions. This would allow for surveys sufficient to sample the galaxy distribution on 10 x 100Mpc volumes in a practical amount of observing time. Redshift surveys that sample a range of volumes and intrinsic luminosities that are comparable to the LCRS survey, but at redshifts well in excess of unity are essential if we are to be able to trace the evolution of galaxies and structure from early epochs to the present.

At this time the optimal approach to multi-aperture spectroscopy is uncertain. Multi-slit spectrographs offer higher throughput and possibly better sky subtraction. Fiber systems, on the other hand, are more economical and, with the use of Nod & Shuffle, may allow for sky subtraction that is competitive with slits. Design studies are currently underway (see Appendix A).

3.1.3 The Intergalactic Medium

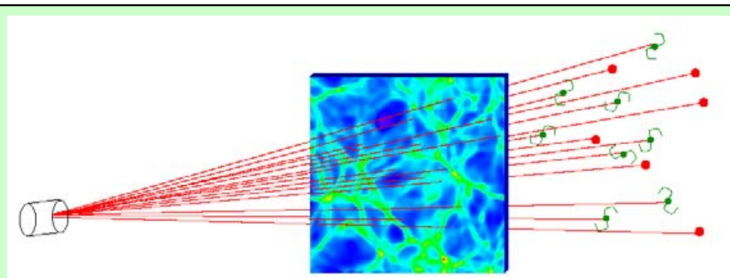

Figure 6. Lyman-break galaxies can be used as background sources to probe structure in the IGM on spatial scales relevant to galaxy formation.

Stars contain only a tiny fraction of the total cosmic mass density and a minority fraction of the baryons. The bulk of the atoms in the Universe are in the hot intergalactic medium. Recent advances in numerical hydrodynamics and high-resolution spectroscopy have fundamentally altered our view of the Lyman alpha forest and the IGM. Our present understanding of the IGM is limited by the surface density of background probes: bright quasars are simply too sparse to adequately sample the intergalactic gas.

The Magellan 20 telescope will enable a new approach to IGM studies through the use of *galaxies* rather than quasars as background UV sources. This will allow the sampling of hundreds of sight lines simultaneously, providing the same amount of detailed information on the IGM as individual QSO sightlines but now with a dense 2D sampling in the plane of the sky. A 3D tomographic reconstruction of the mass distribution and kinematics of the IGM becomes possible, mapping tenuous structures with densities down to the mean density of the universe. A combination with a traditional galaxy redshift survey of the same volume sampled by the lines of sight to the background galaxies would allow us to correlate the properties of gas with the positions of the galaxies embedded in it.

As a concrete example, we consider a deep study of the IGM in the $2 < z < 3$ epoch using Lyman-break galaxies. Spectra covering the 3600-5000A range will sample the Ly alpha forest. To reach a surface density of 1 object per square Mpc at $z = 3$ requires an angular density of ~5000 objects per square degree, or a depth of AB ~ 24. A spectral resolution of R ~ 5000 does not quite resolve the width of the Lyman alpha forest lines, but it is sufficient to obtain the velocity centroid to within a few km/s, for a signal-to-noise ratio of ~30. Exposure times of 6 hours will be required for each setting. A multi-object (fiber or slit) spectrograph with 1000 simultaneous spectra spread over a 25 arc-minute diameter field would be well suited to this experiment and could exhaust all the background galaxies in a one square degree field in 5 nights. If we take 100 physical Mpc at z=3 representative of the largest scales to be investigated the field must be as large as 3.8 x 3.8 or 14.4 square degrees. To survey such a field would then take 72 nights. This science emphasizes the importance of large fields of view and high degrees of multiplexing for the Magellan 20 faint object spectrograph.

3.1.4 Galaxy Structure and Formation History

Integral Field spectroscopic observations of nearby galaxies are about to revolutionize our understanding of the kinematic and spectral properties of stellar populations in nearby (V <~ 1000 km/sec) galaxies (see de Zeeuw et al. 2002). The Magellan 20 telescope could extend the volume of the Universe available for study currently by a factor of over 300,000 in the single-DM adaptive mode. The vast increase in volume is critical in being able to define large samples of galaxies with particular properties (for example environment, luminosity, or isophotal characteristics).

The current state-of-the-art produces measurements of high order moments of the line-of-sight stellar velocity distribution. These moments are necessary to break the degeneracy between mass profile and orbital anisotropy that plagues every stellar dynamical analysis. One can determine the intrinsic shape of galaxies, the orbital structure, the age and metallicity of the stellar population, the frequency of kinematically decoupled cores, and the kinematics around nuclear black holes. The relative populations in different orbital families is a signature of different formation mechanisms. In some striking cases observers have found evidence of mergers in galaxies that otherwise appear normal (for example, the disk galaxy NGC 4550 which has one half of its stars orbiting in one direction and half in the other; Rubin, Graham, & Kenney 1992 and Rix et al. 1992). A census of the stellar kinematics of a large sample of galaxies that probes a range of properties will provide an entirely new view of the formation history of galaxies. In an era where we hope to probe the physical processes involved in the evolution and

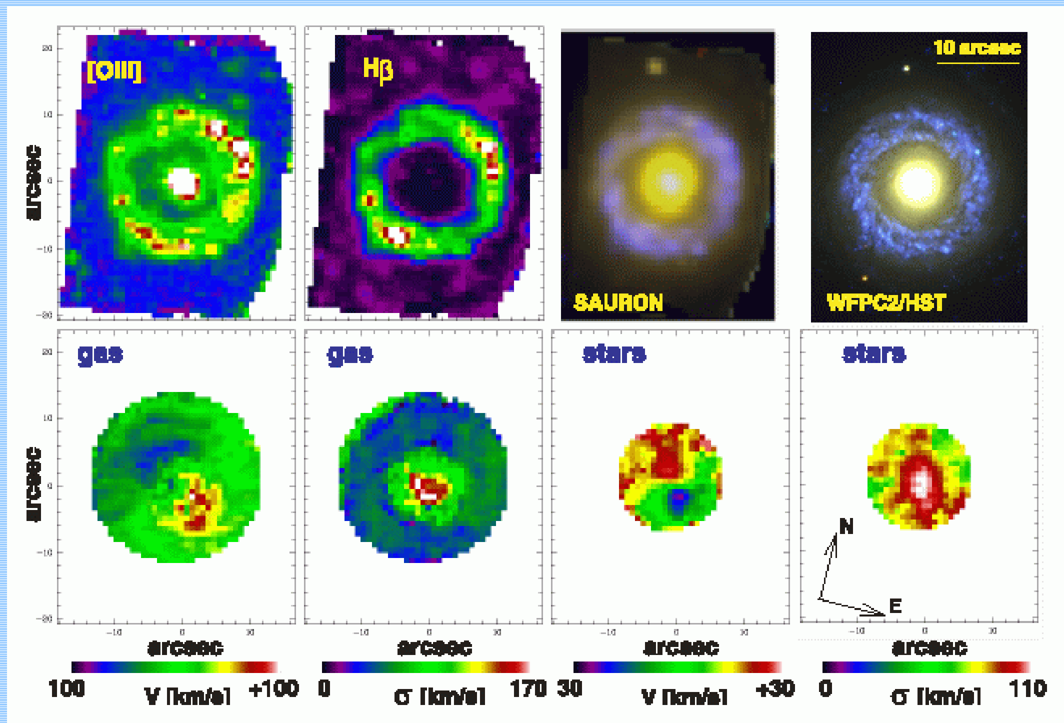

Figure 7 Sauron images of NGC 7742 (de Zeeuw et al. 2002). The distribution of gas and stars, kinematics and line-stengths, can be mapped simultaneously with integral field units. AO-fed IFUs on 20-m class telescopes will allow detailed internal investigations over a wide range of galaxy types and luminosities.

formation of galaxies in detail, this type of data on large numbers of galaxies will be critical.

3.2 The Nature of Dark Matter and Dark Energy

The existence of dark matter, first postulated in the mid 1930's, is now a well established astronomical fact. The concept of a vacuum energy, or Cosmological Constant, dominated Universe has recently evolved from an interesting alternative cosmology to the standard model.   The most recent measurements suggest that dark energy and dark matter compose 73% and 23% of the universe, respectively. Some limits on the nature of dark energy and dark matter have been set by recent investigations; there are presently no acceptable theories as to the nature of dark energy or dark matter.

3.2.1 Dark matter

Galaxy clusters are likely the best astronomical venue to gather information about the nature of dark matter. They are large, readily identified, and have the largest mass-to-light ratio of any observable bound objects in the universe. The detailed nature of CDM, for example, whether it has even a small self-interaction cross-section, will be reflected in the details of the distribution of dark matter in galaxy cluster cores. However, accessing detailed information on these length scales is extremely difficult.

There are two obvious generic approaches. The first is to use some form of baryonic dynamical tracer, such as the stars in the extended halo of cD galaxies, or intra-cluster planetary nebulae, to measure the projected dynamical structure of the cluster. The second is to use information from strong-lensing. We consider each case below.

Given a sufficient number of "test particles" (typically 1000 or more) one can in principle recover details of the density distribution. Recent observations using Subaru find approximately 40 intracluster PNe in 0.2 square degrees in the Virgo cluster in a total observing time of about 4 hours; a similar observation in the Coma cluster requires a further 4 magnitudes of depth over a field about 4 x 4 arcminutes. This increase is achievable using a ground-layer AO system on a 20m-class telescope, if an image quality of 0.2" is possible at Hα. A better approach is likely to use a wider field imager in natural-seeing mode (assume 0.3") to cover a much larger area and hence boost the number of objects significantly. With either strategy, a complementary spectrograph is needed to make velocity measurements.

The outer regions of cD galaxies also provide dynamical probes of the dark matter distribution in clusters. Typical surface brightness limits at which useful velocity information can be recovered are about 26.2 magnitudes per square arcsecond in the V-band. This projects to a 50 kpc radius for the systems studied to date. Long-slit observations are non-optimal in part because of the limited spatial sampling, and because uniform sky subtraction is very challenging across a very long slit. A better approach would be to use a large IFU in a nod and shuffle observing mode (perhaps more appropriately in this case a "chop and shuffle" mode) on somewhat more distant targets. A 1 x 1 arcminute fully filled IFU with 0.33" sampling requires 32K fibers operated in a nod and shuffle mode requiring a bank of 60 2K x 4K detectors. At three times the distance to the Coma cluster, and assuming a total throughput of 25%, such a system could readily address cD dynamics with adequate S/N for a large set of cluster cD galaxies.

Quite apart from their obvious applications for studying a range of very distant objects (c.f. cB58), strong-lensing galaxy clusters provide unique insight into the core mass distribution of the cluster lenses. For such applications, the most attractive targets are clusters with one or more bright arcs, since these are the most readily studied. For mass modeling the lenses, the most important piece of information is redshifts for the arcs, and secondarily redshifts for the individual galaxies along the cluster core line-of-sight. The best approach to studying the mass distribution (indeed the only approach since clusters with arcs are a biased subset of clusters) is to globally compare large lensing simulations to the global statistics of a large sample of lensing clusters. Such samples will be forthcoming in the near future; an effective comparison to detailed models requires the ability to gather redshift information about a large set of objects which are densely distributed on the sky, and which often have extremely distorted morphologies. This is again likely most effectively done using an approximately 1 x 1 arcminute fully filled IFU operating in a natural seeing mode, though in this case a somewhat smaller area could be usefully traded against better seeing using, for example, a ground-layer-AO fed IFU.

3.2.2 Dark Energy

Supernovae are the closest thing that astronomers have to standard, or calibratable, candles with sufficient luminosities to be seen at cosmological distances. The first evidence for a non-zero cosmological constant was provided by the type Ia SNe Hubble diagram. While most of the impact of dark energy on the Hubble diagram is at modest redshifts, distant SNe studies are essential for understanding the role of evolution and selection effects. Late time light curves require accurate host-galaxy correction and may best be done from space, but spectroscopy will remain the domain of large telescopes. At redshifts of 1 and higher AO-fed near-IR spectrographs will sample the rest-frame visible spectra and with small entrance apertures reject the light of the host galaxy. Imaging surveys from wide-field cameras on 6-8m class telescopes or HST/JWST/SNAP will provide targets for spectroscopy with Magellan 20.

3.3 *Formation and Growth of Black Holes*

The remarkable correlation of black hole mass with bulge mass and bulge velocity dispersion points to a close connection between the formation and evolution of galaxies and their central compact objects. Today our empirical knowledge is limited to the present epoch. While the end state of bulge and black-hole mass evolution may be well calibrated (e.g. 1/5% of bulge mass is in a central black hole), the process by which stellar systems arrive at this state is not well understood. Magellan 20 opens several new avenues on black hole formation and evolution at high and intermediate redshifts.

3.3.1 The first black holes and AGN

As described in section 3.1.1, the Universe was reionized at redshifts between ~ 6 and ~20. The balance between nucleosynthesis and accretion in powering reionization is unclear at this time. The mere existence of luminous quasars at $z > 6$ implies an early black hole formation epoch and points to the possibility of periods of high accretion luminosity at very large redshifts. Extremely deep near-IR imaging can reveal a population of $z = 10$ AGN (or galaxies) through their unique photometric signature. While the JWST will probe to very deep levels (e.g. a few micro-Jy), the large field available with Magellan 20 will sample a region of parameter space not accessible to JWST. A wide-field YJHKs imager that is matched to ground-layer AO-corrected images (e.g. FWHM ~ 0.2”) would be capable of surveying large volumes at high redshifts to depths of K(AB) ~ 26. Spectroscopic follow-up with a near-IR fiber fed spectrometer (using the same detector package as the imager) could be used to measure precise redshifts, emission-line diagnostics, including black hole masses and broad-line region abundances.

3.3.2 The faint-end AGN luminosity function at high redshifts

The broad emission lines, short variability time-scale, and X-ray through radio emission of AGN are the signatures of black holes at large and intermediate redshifts. Recent studies of volume-limited samples have provided a firm census of the local AGN population. Our knowledge of the faint end of the AGN luminosity function becomes progressively weaker with increasing redshift. At the peak of the "quasar era" ($z \sim 2$) we know very little about the weak AGN population and at $z > 3$ our knowledge is limited exclusively to high luminosity quasars. The black hole – bulge mass correlation shows that *all* massive galaxies harbor black holes. Thus there should be a large population of low luminosity, or perhaps inactive, AGN at high redshift.

At even very modest redshifts the signatures (e.g. broad lines) of weak AGN are lost in the light of their host galaxies. Magellan 20 operating in the single-DM AO mode with a matched entrance aperture (e.g. 0.005" slit) can be used to isolate the nuclear light of galaxies at intermediate redshifts, dramatically improving the contrast between the stellar and AGN light. An imaging survey can be used to screen for objects with high surface brightness nuclear sources. The J, H, and K windows are the appropriate place for this experiment as they sample H alpha at redshifts of ~ 1, 1.4, and 2. The large collecting area and superior image sizes give Magellan 20 an advantage over JWST/NICSPEC in the spectroscopic mode as the bulk of the pixels are likely to be detector noise-limited for either instrument. With Magellan 20 we will observe in a high resolution (e.g. R~ 4000) mode, mask the strong telluric OH emission features and then rebin the spectra to R ~ 500 to achieve maximum sensitivity to weak broad-lines. Stellar template subtraction may be required for the faintest nuclei. A clean measurement of the faint-end AGN luminosity function will lead to a better understanding of the growth of black holes and will aid in discriminating between conventional and advection dominated accretion modes. This technique will be particularly powerful when used in combination with deep observations at other wavelengths with facilities planned or under construction in the southern hemisphere (e.g. ALMA, SQA).

3.3.3 The black hole bulge mass correlation at intermediate redshifts

While AO-fed spectroscopy may aid in the determination of the faint-end AGN luminosity function, and by extension the black hole mass function, at $1 < z < 2$, this alone will not complete our empirical understanding of the AGN-galaxy connection. The recent discovery of a tight correlation between black hole mass and bulge velocity dispersion in nearby galaxies strongly indicates that the growth of black holes must be closely linked to the formation and evolution of their host galaxies. Exactly when and how this was accomplished, however, remain a central unresolved problem.

Our present understanding of the black hole-bulge mass correlation is based on a single epoch snapshot of galaxies that span a limited range of environments. An important gauge of the coeval evolution of galaxy bulges and central black holes would be provided by extending the dynamical investigations to higher redshifts over a range of environments. Models of early-type galaxy (and possibly bulge) evolution suggest little activity beyond passive evolution since z ~ 1, just as our understanding of the bright AGN luminosity function shows dramatically declining activity to the present epoch. Both AGN activity and the dynamical evolution of galaxies proceed at different paces in different environments. The rate of merging and, possibly, AGN fueling are significantly different in small groups than they are in rich clusters or voids.

The most direct way to tackle this issue is to obtain measurements of black hole masses and bulge velocity dispersion as a function of redshift. Direct dynamical detections of central black holes are not feasible for galaxies much beyond ~100 Mpc, even with the next generation of large telescopes. Significant progress can be made, however, using "secondary" methods to estimate masses, such as through the use of broad emission lines in AGNs. Virial masses calculated in this fashion for local AGNs appear to be relatively robust, and this method in principle can be easily extended to AGNs at progressively larger redshifts.

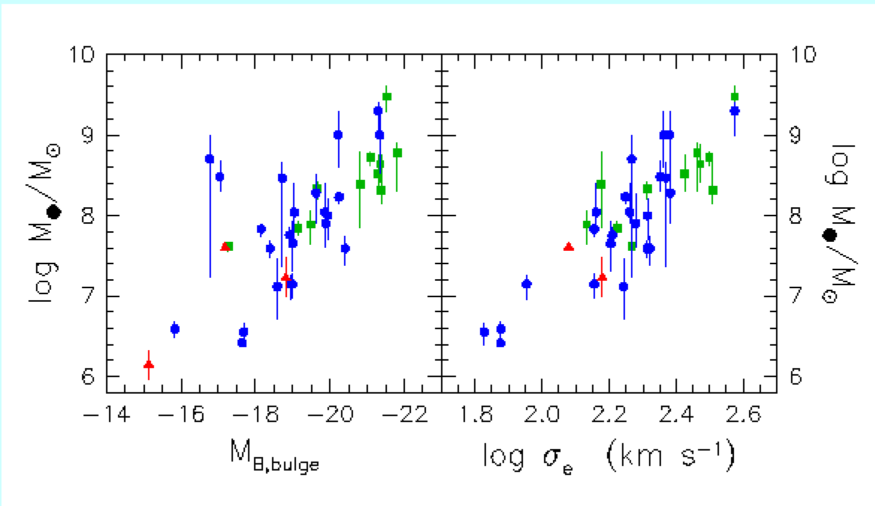

Figure 8. The black hole mass correlations with bulge mass and central velocity dispersion (from Kormendy). The Magellan 20 telescope will allow us to extend this work to a wider range of environments and to earlier epochs.

A greater challenge is to constrain the mass or velocity dispersion of the AGN host galaxies, because the stellar absorption features are heavily diluted by the dominant non-thermal emission. This difficulty, however, can be overcome by obtaining sufficiently deep spectra, as has been demonstrated for nearby AGNs. A key goal for the 20m telescope is to extend similar measurements to higher redshifts. The CaII infrared triplet (rest wavelength ~ 8550 A), the spectral features of choice for velocity dispersion measurements in AGNs, can be tracked out to redshifts of ~1.7 in the NIR bands, thereby permitting a direct probe of the host galaxies over the critical period during which the AGN population underwent dramatic evolution.

3.4 *Resolved Stellar populations*

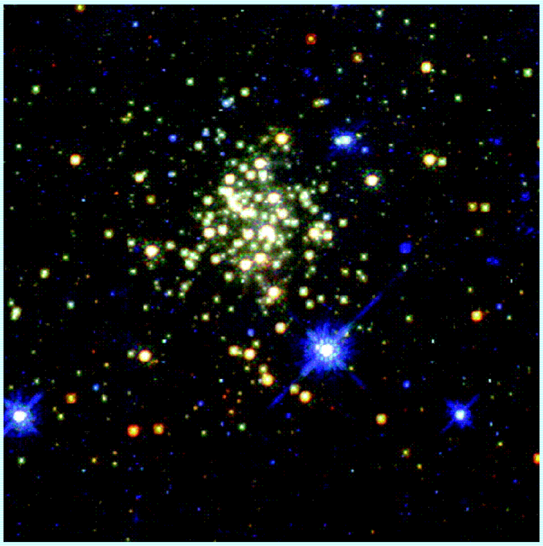

Figure 9. Near-infrared image of the Arches cluster in the galactic center obtained with the NICMOS camera on HST. Figer et al. reach limits corresponding to the expected luminosity for 1 Myr old post-main-sequence 1.0M stars. However, only post-main sequence evolution is considered in converting the LF into an IMF that extends only to 5M.

One of the pivotal moments in modern astronomy came when Baade used the Mt. Wilson 100 inch telescope to resolve the bulge of M31. The concept of two distinct stellar populations that grew from this fundamentally changed our thinking about galaxy formation and evolution. Studies of resolved stellar populations continue to play a key role in astronomy. The advent of large aperture diffraction-limited telescopes promises to extend the study of resolved populations to a range of environments and galaxy types beyond the reach of current facilities. With a resolution of 7 to 15 mas in the near-IR, Magellan 20 will probe confusion-limited stellar environments well beyond the local group and will have the light-gathering power to extend galactic center and LMC work to lower mass stars.

A southern hemisphere sited 20m telescope would be well placed to study the nearest stellar systems, the MW and the Magellenic Clouds. The closest elliptical galaxy (Cen A) and several of the closest dwarf spheroids are also southern hemisphere objects.

3.4.1 The galactic center

The center of our galaxy has received considerable attention in adaptive optics and speckle studies. This intense activity is driven by a number of considerations, the dynamics of the central compact object, the availability of numerous bright natural guide stars, and the apparently unusual central star clusters near the GC. Recent studies have revealed young star clusters in the galactic center. These star clusters offer a close laboratory for the study of star formation in environments that may be germane to both starburst and primeval galaxies. A key issue is the shape of the IMF in these environments. Present IMF determinations become confusion-limited at ~ 2-3 M_0, Magellan 20 will extend IMF determinations in the galactic center region to ~ 1 M_0.

The additional resolution and light-gathering power of the 20m will not only improve IMF studies, it will also increase the number of dynamical probes in the immediate environs of the central compact object. It is possible that the luminous sources directly associated with accretion onto the central object will be detected with Magellan 20.

3.4.2 Local group galaxies

The local group provides us with a small number of local laboratories for fundamental stellar physics and stellar dynamics. A southern hemisphere 20m would allow unprecedented detailed studies of the Magellanic Clouds and the local group dwarf spheroidals (e.g. Sculptor, Fornax, Carina) and the Sagittarius dwarf. Much of the information needed to understand the star formation history in these object is contained in stars well below the limits of current techniques, or in subtle differences in giant-branch morphology. Magellan 20 will be able to distinguish between bursts of different ages and metallicities by probing down to, and below, the main sequence turn-off for ages up to a few Gyrs. High precision photometry of the RGB should allow us to differentiate between fairly subtle (~ 0.4 dex) abundance differences.

3.4.3 Beyond the local group

While the local group provides a number of relevant stellar systems, it is ultimately limited in the range of luminosities and Hubble types that it contains. Magellan 20 will allow resolved stellar population studies in several systems between the local group and Virgo (e.g. Sculptor group, Cen A) and will probe bright giants in Virgo. Of particular interest are the most massive star clusters discovered in HST and the relationship between these star clusters and MW globulars.

3.5 *Stellar Populations and Chemical Evolution*

Stellar atmospheres contain a fossil record of the material from which they formed as well as the products of internal nucleosynsthesis that may have been brought to the surface. High spectral resolution abundance studies of stars of differing populations (e.g. AGB stars, metal-poor giants, supergiants etc.) provide insight into the chemical evolution of galaxies and their interstellar matter. Stars also carry fossil records of the dynamical processes that shape stellar systems. Distinct kinematic subsystems can be the signature of recent accretion events (e.g. Sagittarius dwarf) or the remnant of early dynamical processes (e.g. the thick disk). Stars also provide test particles for detection of dark matter within galaxies, particularly in systems with very low stellar masses (e.g. dwarf spheroids).

Our current understanding of chemical evolution and the origin of the elements has been greatly influenced by high resolution chemical abundance studies of stars. From these studies the trends of element abundance ratios with overall metallicity, and the metallicity function, for stars in the Galactic disk, halo and bulge have been revealed to various degrees. The astrophysical sites of nucleosynthesis, and enrichment timescale, for various elements have been identified and embodied into the chemical evolution paradigm. It is clear from these studies of Galactic stars that chemical composition depends upon environment; distinct components of the Galaxy have taken a chemical enrichment path dependent on local physical conditions. Recently, abundance studies of a handful of the brightest stars in the closest dwarf spheroidal galaxies have revealed a great variety in their chemical composition, with important implications for chemical evolution of these systems and constraints on the origin of particular elements.

High dispersion stellar spectroscopy is traditionally a source-photon-limited technique. Efficient echelle spectrographs on 8m class telescopes, however, have pushed stellar abundance work into the sky (in bright time) and detector noise limited regime. Adaptive optics has the potential to extend the reach of echelle spectrographs by concentrating the source photons against the fixed sky background. AO-fed echelles have the additional advantage of requiring smaller optics and dispersing elements.

In Appendix A we review design considerations for echelle spectrographs for the 20m telescope. In the natural seeing mode R=25,000 spectra with S/N sufficient for abundance work can be obtained to V ~ 22.5 in practical exposure times, while radial velocity work can be carried out to V ~ 24.5. Adaptive optics will allow one to work in crowded regions in the I and z' bands and to work quite faint (e.g. K ~ 19.5) at wavelengths for which high order adaptive optics is most effective.

The Magellan 20 telescope will open a wide range of fundamental astrophysics to high resolution spectroscopy. In this section we consider a few examples of areas in which the 20m can address problems that are beyond the reach of current facilities.

3.5.1 Abundances of Red Giants in the Local Group:

Red giant stars are particularly useful for measuring the history of chemical evolution of nearby galaxies: Their high luminosity makes them accessible at great distances, their low temperatures result in the presence of lines from many elements and molecules, and their progenitors have ages up to 14 billion years. Indeed, the chemical composition of red giant stars provides a fossil record of the history of galaxy evolution.

The Magellan 20 telescope will allow abundances to be routinely measured for RGB stars in members of the Local Group of galaxies, visible from the Southern hemisphere. This includes nearby galaxies such as the irregular galaxies LMC, and SMC, a host of dwarf spheroidal galaxies (e.g. Sculptor, Carina, Fornax, Leo I), and objects like Leo II (dSph-E0p). High resolution spectra of RGB stars in more distant Local Group galaxies, such as NGC 6822 (IBm IV-V) at 495 Kpc, IC~1613 (IBm/Irr V) at 725 Kpc, Tucana (dSph-dE5) at 890Kpc and M33 (Sc,cd II-III) at 795Kpc would require considerable effort, up to 35 one-hour exposures for S/N ~ 30. But this would be worthwhile if the spectrograph is equipped with a multi-object capability; in a 5 night run one might obtain S/N ~ 30 spectra for several hundred RGB stars in one of these galaxies.

For crowded regions of Local Group galaxies the natural seeing will be insufficient to isolate individual stars, so we will be limited to the outer regions, such as the halo of M33. An AO system would be most useful for probing the more crowded regions, but would limit spectral coverage to the near-IR wavelengths.

3.5.2 Detailed Chemical Composition History for Galaxies beyond the Local Group

A natural step in understanding the evolution of galaxies, using the chemical composition of red giant stars as fossil record, will be to study and inter-compare results from all galaxy morphological types. Unfortunately, the Local Group of galaxies contains a very limited census of galaxy morphologies, so it will be necessary to make detailed chemical abundance studies of RGB stars for galaxies beyond the Local Group.

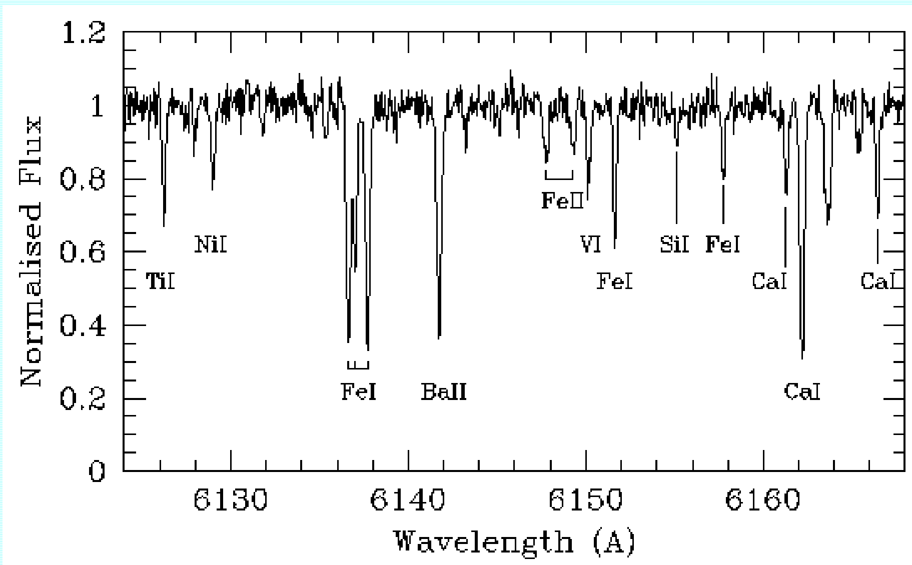

Figure 10. A typical high resolution spectrum anticipated for individual RGB stars in the halos of Local Group galaxies (S/N~30, R~25,000). For M33 halo RGB stars this would require approximately 35 one hour exposures. The same quality spectrum could be obtained for RGB stars in galaxies at 2Mpc by combining 40 multi-object spectra, each comprised of 24 one hour exposures.

The Magellan 20 telescope will allow us, for the first time, to measure the history of chemical enrichment for galaxies outside the Local Group, including several spirals and dwarf elliptical galaxies; regrettably RGB stars in giant elliptical galaxies will not be accessible. This feat will be accomplished by combining low S/N, multi-object, spectra of carefully selected RGB stars.

Even with the Magellan 20 telescope it will not be possible to acquire a high resolution spectrum of single RGB stars outside the Local Group with sufficient flux for detailed chemical abundance analysis; to do this would require a telescope with a diameter in the 70-80m range.

With 24 one hour exposures it will be possible to obtain S/N ~ 5 per pixel for a V=24.4 star. This would permit radial velocity measurements to a precision of about 3Km/s, and be sufficient for crude metallicity estimates.

If the Magellan 20 is equipped with a high resolution multi-object spectrograph we may obtain high S/N high resolution spectra by combining large numbers of the individual low S/N spectra. It would be desirable to select program stars from photometric studies which indicate similar stellar parameters and metallicities; velocities from the low S/N spectra will permit appropriate shifting of the spectra before combining.

For V=24.4 stars at least 40 multi-object spectra must be combined to produce a single S/N ~ 30 spectrum suitable for detailed abundance analysis. If a multi-object capability of 500 objects per exposure is available, then with three nights at the telescope we may obtain suitable spectra for a dozen groups of the brightest RGB stars in a galaxy at a distance of 2.0Mpc.

The technique of combining very low S/N spectra is not fully explored, and significant difficulties with systematic errors may arise. However, this method provides one of the only ways in which the systematic measurement of the detailed chemical history of galaxies outside the local group might be accomplished.

This method will be useful for studying the most luminous RGB stars in the halos of galaxies within 2Mpc. Crowding will present a problem for inner regions of these galaxies, and will require the use of Adaptive Optics technology. In this regard, the fields of several nearby galaxies outside the Local Group contain suitably bright natural guide stars (see Table 2).

Since a major benefit offered by Magellan 20 will be spectroscopy of stars in galaxies far beyond the Local Group it is useful to know whether sufficient natural guide stars exist for a useful sampling of candidate galaxies. Estimates of the faintest useful natural guide stars range from R=14 to 15. The table below shows the number of potential natural guide stars (from the USNO catalogue) located within galaxies of the Sculptor and Cen A groups. These natural guide stars will enable near IR spectroscopy of objects within ~ 30”. The tables show that there are many fields within numerous galaxies which could best studied; each 30 arc second field likely contains many thousands of stars suitable for study.

Table 2. Natural AO guide stars for Sculptor and Cen A group galaxies

Galaxy	D(Mpc)	Diameter(‘)	N(<14)*	N(<15)**
NGC 55	1.3	32	21	49
NGC 247	2.1	21	15	24
NGC 253	3.0	27	16	31
NGC 300	1.2	22	19	35
NGC 7793	2.8	10	1	3

NGC 4945	5.2	20	49	108
NGC 5128	4.9	26	5	145

* # of potential natural guide stars with R < 14^{th} magnitude, ** # with R < 15^{th}

3.5.2. Abundances of Supergiant Stars to 6Mpc (m - M ~ 29 magnitudes):

The chemical composition of supergiant stars reveal details of the relatively recent (a few million years) star formation history and gas in spiral and irregular galaxies. With many supergiants in a galaxy the homogeneity of the gas and the presence of radial abundance gradients can be probed, and the results compared to nebular abundances. Additionally, the supergiant spectra contain lines from elements which cannot be measured from nebular studies. Recent work in this area includes Venn et al (2000, ApJ, 541, 610) who measured the composition of four A to F supergiants in M31 with the Keck echelle spectrograph. With the 20m telescope and R=25,000 spectrograph similar detailed abundance studies could be carried out to ~ 6Mpc, including spiral and irregular galaxies far beyond the Local Group, and into nearby groups.

3.5.3 Super-High S/N Spectra of Extreme Metal-Poor Stars:

Extreme metal-poor stars ([Fe/H] < 2.5) are thought to precede the main halo population, possibly from a pre-Galactic era; some stars are so metal-poor, and have such unusual compositions that they are thought to contain the composition of individual supernova events. These objects are profoundly important for understanding the first step in chemical enrichment, and provide important constraints on the yields of type II supernovae. However, because they are so metal-poor (the most metal-poor with [Fe/H] ~ -5) lines from interesting elements are too weak to measure in normal high dispersion spectra with S/N ~ 100. With Magellan 20 it will be possible to obtain spectra with S/N ~ 1000 in a few hours; this would enable the detection of very weak lines (~ 0.1mA) from various elements. The resulting abundance patterns would be critical for identifying nuclear reaction processes and understanding the earliest phase of chemical evolution.

3.5.4 M/L Studies in Distant Dwarf Spheroidal Galaxies:

Extant studies of red giant stars in Local Group dSph galaxies (e.g. Mateo et al. 1993, AJ, 105, 510) have demonstrated high mass to light ratios, M/L, consistent with the presence of large quantities of dark matter. It would be interesting to investigate the M/L ratio in other dwarf systems. Since high precision velocities, $\sigma(v)$ ~ 3km/s, require only a modest S/N ~ 5 the requisite spectra can be acquired of red giant stars in dwarf galaxies to a distance of about 2.5Mpc, (m – M = 27). This includes a volume of space encompassing a number of galaxies in the Sculptor group.

3.6 Origin of stars and planets

Figure 11. NICMOS JHK image of a circumstellar disk seen edge-on. Magellan 21 will have 10 times the angular resolution of HST/NICMOS.

The detection of extra-solar planets captivated both the public and scientific community with its far-reaching implications. No other area of astronomy stands to gain so much from the next generation of large telescopes as does the field of extra-solar planets. The anticipated gains both in light-gathering power and spatial resolution will yield order-of-magnitude increases in both the number and diversity of stars in which planetary systems can be discovered and characterized. In this section we give an overview of the capabilities of the Magellan 20 telescope in the discovery of extra-solar planetary systems.

3.6.1 Circumstellar debris disks

Planets are believed to form via gravitational instabilities in proto-stellar disks. Numerical simulations of planet formation are gaining sophistication and theory is now faced with both the challenge, and the benefits, of making predictions rather than simply reproducing the properties of our solar system. A deep physical understanding of the planet formation process must be grounded in a firm empirical understanding of proto-stellar and circumstellar disks.

The near-infrared and mid-infrared, where the Magellan 20 telescope is likely to actually perform at its diffraction limit with the help of adaptive optics, is the most interesting region for studying the dust and gas rich disks that are the sites of planet formation. This spectral region contains important composition diagnostics, such as water and methane ice absorption bands, features due to gases such as hydrogen, carbon monoxide and methane, and emission features of silicates and polycyclic aromatic hydrocarbons.

The closest site of recent star formation to the Sun, defined by the presence of a classical T Tauri type star, is the TW Hydrae Association at 60 pc. Using our own Solar System as a guide, we need to probe scales smaller than 10 AU in extra-solar disks in order to obtain information on regions where planet formation is likely to take place. To distinguish between regions where terrestrial, gas giant, and ice giant planets form, we would like to probe scales of 1 or 2 AU. The Magellan 20 telescope is large enough to achieve this goal. The diffraction limit at 1.6 microns (0.015”), where there is a deep water ice absorption feature, subtends 1 AU at TW Hya. We could potentially detect the "snow line"; the location where water ice condenses, in a planetary system. It has been suggested that this region marks the boundary beyond which giant planets must form by enhancing the accretion of planetesimals. Water is the most commonly detected material on surfaces in the outer solar system and, of course, is critical for the development of life. Finding its location in forming systems would help explain how it can be delivered to terrestrial planets.

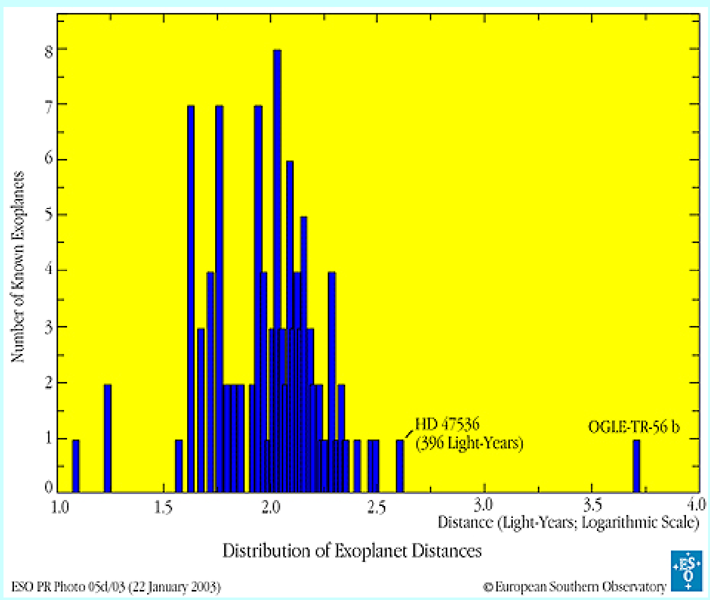

Figure 12. The distribution of extra-solar planet distances in light years. Magellan 20 will increase the volume available for radial velocity searches by two orders of magnitude.

The diffraction limit of the Magellan 20 at 12 microns, where crystalline silicates and PAHs have emission features is 0.12 arcsec, or about 7 AU at TW Hya, or just enough to distinguish the compositions of the inner versus outer planetary system. We could potentially look for the distribution of crystalline material with distance as a probe of where amorphous silicates are annealed. Competing theories today place the location of annealing at the disk-star boundary or in shocks at several AU from the star. Finding enhanced crystalline silicates in the outer versus the inner disk would strengthen the idea that gravitational instabilities are generated in disks and could be responsible for giant planet formation.

3.6.2 Radial velocity detection of massive planets

Even without using adaptive optics to exploit the resolving power of the Magellan 20 telescope, its large collecting area will advance radial velocity searches for extra-solar planetary systems. The radial velocity search technique can be extended to fainter stars allowing study of planet frequency in new environments compared to the solar neighborhood. The current limit of radial velocity searches with 8m class telescopes is V

~ 15, corresponding to a distance of 30pc. We anticipate a gain of 1.5 magnitudes, increasing the accessible search volume by a factor of 200. This will bring a number of open clusters within reach, allowing one to probe the frequency of extra-solar planets as a function of metallicity and stellar age.

In addition to searching for planets in nearby open clusters, the Magellan 20 would enable extension of planet searches to the M dwarf regime. This will allow study of the relationship between stellar mass and planetary companions and provide key constraints on planet formation theories. Current facilities only probe the very brightest M stars. Most of the 200 M-type stars currently being monitored are nearly all in the M0 to M2 range, with a strong bias toward M0. The 20m telescope will extend our reach to M5 and later, and thus enable planet searches around stars of 0.2 solar masses. Short-period Earth-mass planets in the habitable zones (temperature suitable for the existence of liquid water) of late M stars could be discovered.

3.6.3 Direct detection of young planets

All of the planets discovered to date (except one from Macho) have been found via the radial velocity method, but the hunt is on for planets from which light can be detected directly. Since young planets are quite hot, the first results are likely to be direct detection of Jupiter-mass objects by infrared observations at high spatial resolution and high dynamic range around nearby young stars. The optimal wavelength range for such a study is 1-5 microns: the shorter wavelengths provide higher spatial resolution and important photometric diagnostics, such as the presence of a methane atmosphere, while the longer wavelengths provide higher contrast between the star and planet. Magellan 20 has a uniquely favorable geometry for directly detecting such planets very close to the star. Apodization and nulling interferometry methods will allow very high dynamic range measurement in the key range of angular separations (60 – 120mas in the J-band; see section 4.1). In Figure 14 we show a simulation of a 60msec exposure with Magellan 20 in the J-band with aggressive AO and apodization of the six unobscured outer primary segments. A planet with a contrast of 10-6 compared to the central star is detected at an angular distance of 80mas from the star. Given longer integrations (e.g. 8-20 hours) even old planets at ~ 1 AU should be detectable at 60-120mas separations with predicted contrasts in the 1 – 2 x 10-8 range.

3.7 *Physical processes in extra-solar planetary systems*

The last three years have seen a remarkable increase in the number of very young stars discovered near the Sun. There are now approximately 100 known stars of age 8--40 Myr within 100 pc. For the closest young stars, the 12 Myr old members of the Beta Pictoris association at ~30 pc from us, the 0.021” diffraction limit at 3 microns projects to 1 AU resolution. Combined with a coronagraph, it is reasonable to expect that planets might be detected directly at separations from the star of 5 AU (the location Jupiter). Even for young stars further away, Magellan 20 could image Jupiter-mass planets at distances comparable to those of the ice giant planets. In addition to determining the temperature and hence atmospheric environment of such objects, quantifying the flux directly will constrain planet evolution models that are degenerate in age and mass.

3.7.1 Physical studies of "hot Jupiters"

Magellan 20 will also be used as a nulling interferometer to study extra-solar giant planets (EGPs) in close proximity to their central stars, where stellar illumination is important. For the closest in, the so-called "roasters", there are numerous diagnostic spectral and broad-band features in the accessible 0.6-1 micron region that reveal their compositions and character. The Na-D and K I resonance lines determine the overall spectral shapes and water absorption around 0.93 microns can announce the presence of this distinctly planetary molecule. Hence, low resolution (R ~20) CCD spectra can collectively constrain the atmospheric compositions, radii, and cloud properties of roasters such as 51 Peg B and Tau Boo.

In addition, and perhaps more importantly, for less extremely placed EGPs even low-resolution spectra of in the near infrared can provide radii, water abundances, and estimates of mass and age. The latter are possible because the intrinsic luminosity of the planet props up the flux in the near infrared at values far in excess of the reflected component if the distant planet is massive and/or young. This effect can amount to factors of 2 to 100, depending upon the system.

For both close-in or far-away irradiated planets, the brightness as a function of orbital phase will reveal the sizes and character of atmospheric particulates, as well as the effects of jets streams and planetary circulation currents on the planetary thermal balance and structure. In particular, a phase shift between the planetary orbit and the brightness curve (phase function) is diagnostic of weather on EGPs. Apodization and nulling interferometry methods will be exploited to investigate these spectral and phase phenomena, breaking wide open the study of extrasolar planets (see section 4.1).

Observations of scattered or thermally emitted light from the planet itself are the only way to learn about 'old' planets' physical properties. These kinds of observations are showing to be just beyond reach of existing large ground-based telescopes Magellan, Keck, and VLT. A 20-m telescope without adaptive optics but with visible and near-IR capabilities would enable characterization of extra-solar planet properties for the "hot Jupiter" class of planets that can be studied in the combined light of the planet plus parent star. Albedos, spectroscopy, and temperatures from transiting extra-solar planets can be studied. In addition optical and near-IR spectroscopy of other relatively high-inclination orbit extra-solar planets will also be possible.

3.7.1 Physical diagnostics from transiting planets

Transiting planets (of which 2 are currently known and large numbers are expected to follow) can be very well characterized via the time domain. A 20-m telescope without adaptive optics but with a very short read-time detector, will allow the planet radius to be derived to high accuracy from a photometric light curve, even for faint stars. In addition transit timing can reveal perturbations to the transit light curve caused by Earth-mass moons or presence of other nearby giant planets in the same planetary system.

4 Magellan 20 in the Context of other Proposed Facilities

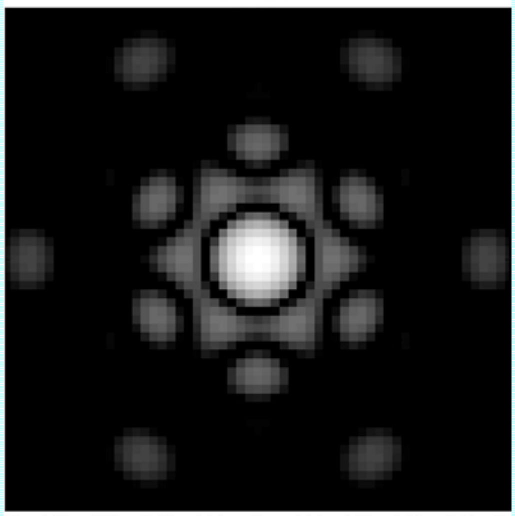

Figure 13. With adaptive-optics the PSF of the Magallen 20 has 68% enclosed energy in the first dark ring and the resolution of a 24m filled aperture.

A number of different extremely large telescope concepts are under consideration throughout North America and Europe. The principal distinguishing characteristics are the size, focal-length and number of segments that compose the primary mirror. While the present document is focused on the science drivers for a 20 meter telescope, we believe that our science aspirations are to a significant degree constrained by engineering and financial realities. In this section we give a brief overview of a number of technical considerations that have led us to the present baseline design.

4.1 Primary mirror design and optical performance

The hallmark of the Magellan 20 telescope concept is its use of 8m borosilicate mirror segments. Within the Magellan consortium there is a deep reservoir of experience in the use of large, borosilicate-honeycomb mirrors to build large telescopes. These mirrors are structurally rigid, their temperature can be controlled to closely follow the changing ambient temperature during the night, and their surfaces are accurate and smooth. The large monolith mirrors in operation today have smaller wave-front errors than the smaller segment systems and hence better PSFs.

A telescope made with large segments will have a pupil which is relatively unstructured at small scales and which can be apodized at large scales to produce relatively benign, and controllable, diffraction-limited point-spread functions. The large monolith segments are supported with 6 axis positioning and high order shape control, so they can be very accurately fitted to the parent 25 m surface. Small segments on 3-point supports with warping harness are much more limited in their ability to conform to their parent surface.

The Gregorian configuration that is currently under consideration as the baseline focal

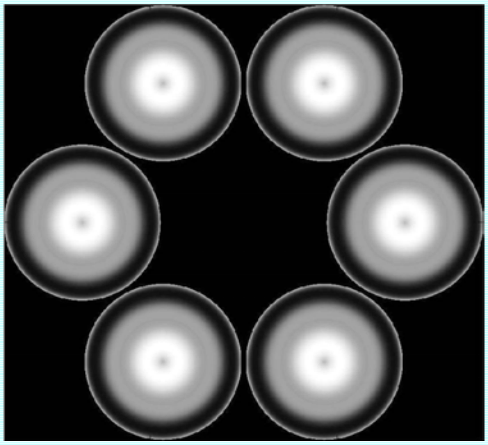

Figure 14. The layout of 7 large mirrors can be well apodized for low diffraction at 60 – 100 mas where giant exoplanets are expected to be found.

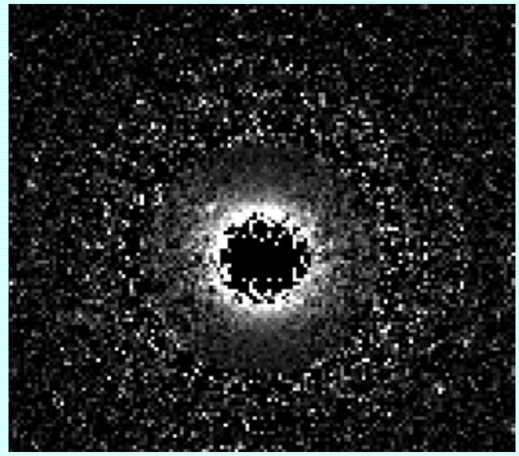

Figure 15. Simulation of a 4.6 msec exposure with Magellan 20 in the J-band with AO and apodization of the primary as shown on the left. A planet with 10-6 of the flux of the center star is detected at 80 mas from the star (at 10 o'clock). A 1.4×10-8 planet will require 8 hours of integration.

configuration allows for straight forward ground-layer adaptive optics. The thin-shell Gregorian adaptive secondary when used with the very short focus primary conjugates to a level only 150m above the ground. It can thus be used to correct ground-layer seeing up to 300m over a wide field of view. Detailed measurement of the ground layer wave-front distortions should be possible nearly anywhere in the sky using natural guide stars in the field. Other telescope configurations allow for ground-layer AO but Cassegrain configurations with slow primaries would require a deformable element that is not the secondary mirror, and additional wide field relay optics. The adaptive secondary approach allows for AO without additional thermal background or throughput losses.

4.2 Mechanical performance of mount and mirror support

Advances in mirror support technology allow the current generation of large telescopes to maintain figure in the presence of large and variable gravity loads. Similarly, improvements in mechanical modeling (e.g. FEA) have allowed the design of very stiff telescope mounts that maintain pointing and image quality in the face of strong and variable wind loading and gravity deflections. The next generation of large telescopes will face enormous challenges as masses, wind cross-sections and image quality requirements all increase by large factors.

The honeycomb structure of the borosilicate mirrors is intrinsically rigid and effectively resists wind deformation of the optical surface. The thermal performance of 6.5-8m mirrors is now well understood. The thermal time constant for 8.4m segments is less than 1 hour.

The design for the Magellan 20 mount builds on the heritage of the Magellan and LBT programs. These compact structures have high resonant frequencies and perform well in the wind environments appropriate to sites under consideration for Magellan 20. The current mount design is expected to have a lowest resonant frequency of ~ 5 Hz. The control frequencies and disturbance rejection will be comparable to those for the current generation of 8-m telescopes, even though Magellan 20 will be much larger.

4.3 Upgrade paths – Multi-Conjugate Adaptive Optics

The baseline configuration of Magellan 20 takes advantage of mature technologies with modest risk exposure. The facility is being designed with sufficient flexibility to ensure that we can take advantage of advances in adaptive optics that are anticipated in the coming years. In particular we have identified upgrade paths toward multi-conjugate adaptive optics over wide fields of view. A more ambitious, but high payoff, upgrade involves the addition of a second telescope operating in concert with the first as an interferometer.

4.3.1 Multi-Conjugate Adaptive Optics

MCAO is an important upgrade, because the field of view is increased by an order of magnitude in area. This is valuable not only for the bigger selection science targets, but for the greater availability of guide stars necessary for tip/tilt correction. At the expected limit of 18^{th} magnitude, the wider field of MCAO will permit the diffraction limited imaging of AO to be realized virtually anywhere on the sky, including the galactic poles.

A preliminary MCAO design for M20 has been developed and analyzed by Lloyd-Hart and Milton. It uses 10 sodium beacons placed in two pentagons at 60 and 72 arcsec radii. Performance has been modeled using a 7 layer atmosphere, with integrated r0=0.9 m at k band, typical of the Magellan site. Correction is taken to be at 3 conjugates, with the deformable secondary and additional mirrors conjugated to 3.8 and 12.8 km. The correction is limited to 500 modes/mirror.

At this stage the model does not included photon noise or latency losses. These will depend on the laser power and detector speed and noise. Give moderate advances in the next decade, these losses could well be small.

The results which include the errors made in the tomographic reconstruction, the limitation to 3 conjugates and 500 modes are very encouraging. In the K band the Strehl is 0.79 on-axis and 0.49 at 50 arcsec off-axis.

We expect the concept to evolve as experience with MCAO is gained. Early results will come from the MMT MCAO system, which is being built with 5 Rayleigh laser beacons in a single pentagon with 1 arcminute radius. The MMT system will be a good test for the M20 system, because the geometry and tomographic reconstruction details are similar. Rayleigh beacons at 25 km with a 6.5 m telescope sample the layers with the same offsets as 95 km sodium beacons at the 25 m M20 telescope.

4.3.2 The 20/20 Interferometer

The M20 concept allows for later incorporation of the telescope as one of two mounted on a 100 m diameter track - the 20/20 concept. When track-mounted, the full MCAO-corrected fields of two 20 m telescopes can be combined for a x 4 increase in resolution with virtually no loss of point source sensitivity or field of view. The higher resolution images are reconstructed from exposures taken with different baseline lengths and orientations.

The reason to move the telescopes (rather than with beam trains and path length compensators, like the VLT and Keck) is that the full field is preserved, instead of being restricted to an arcsecond or less. Just as in MCAO, the wide field is important both for better science, and for the ready access to phase reference stars in the field. These allow for long integrations, with similar sensitivity as for a 30 m filled aperture.

The tracked telescopes can also be very efficiently combined in the Bracewell nulling configuration, with low thermal background maintained. In this mode the sensitivity for thermal emission from extra-solar planets will be very high.

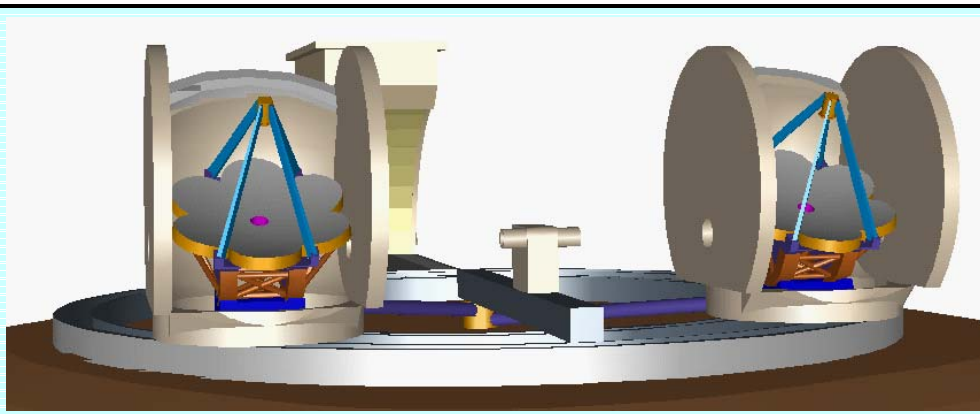

Figure 16. The 20/20 interferometer, a potential upgrade for Magellan 20. The two 20m telescopes travel on a common track as they follow an object across the sky with a constant projected baseline.

The M20 will not initially be built on a track, or with a mount with the added degree of freedom. But it will compact and stiff to allow for such an upgrade, and a site will be chosen with room.

To make the upgrade, the track and second telescope will be built and tested, and then the first telescope will be moved and re-erected on the track, with an addition to the mount.

Appendix A

Instrument Concepts for Magellan 20

The science case outlined above points the way toward a preliminary list of six scientific instruments. Listed very approximately in order of priority, they are:

1. Wide-field optical spectrograph.

2. High-resolution optical spectrograph.

3. Near-IR AO imager

4. Near-IR integral-field spectrograph.

5. Mid-IR AO imager.

6. Near-IR ground-layer (wide-field) AO imager.

Each of these is discussed briefly in the following sections.

A.1 Wide-field optical spectrograph.

At the beginning of the instrument-study process this instrument was identified as the most likely one to interact in a significant way with the overall optical design of the telescope. It has received the most attention in the preliminary definition of instrument concepts, although there are still many unresolved issues to explore.

It is clear that a wide-field, faint object spectrograph on such a large telescope will spend almost all of the time working on objects which are very faint compared to sky background. In the red this places a premium on achieving adequate resolution to look between the bright airglow lines. In practice this will probably translate to a resolution requirement of 4000 or perhaps 5000 through a practical slit-width in the range 0.7 to 1.0 arcsec.

In either the red or the blue, work on such faint objects will require extremely accurate sky subtraction, as well as the highest possible throughput. At the present time the most promising method for achieving accurate sky subtraction is the nod-and-shuffle technique.

There are presently two concepts being explored for a wide-field spectrograph. One is a large imaging spectrograph; the other is a bank of smaller spectrographs fed by fibers.

Both concepts have been found to be compatible with an f/10 Gregorian focus. This is a desirable secondary configuration for implementing a ground-layer AO system, as described above. The Gregorian secondary also has real foci which can be expoited for off-line testing of the adaptive actuator and control system. Plausible focal ratios for the primary and secondary foci are f/0.7 and f/10.

Both spectrograph concepts are capable of working with fields in the diameter range 10 to 20 arcmin. Toward the upper end of this range it may be desirable to add a refracting field corrector to the optical path. This is practicable using either an aspheric plate (Gascoigne) corrector or a spherical doublet. The elements will be large (1.5-m dia) but within the feasible range of sizes for transmitting optics made from fused silica. For the fibers in particular it would also be highly desirable to add an atmospheric dispersion compensator. This is probably feasible as well, using the most common optical glasses at the very upper end of the range of available sizes.

A.1.1 Imaging spectrograph.

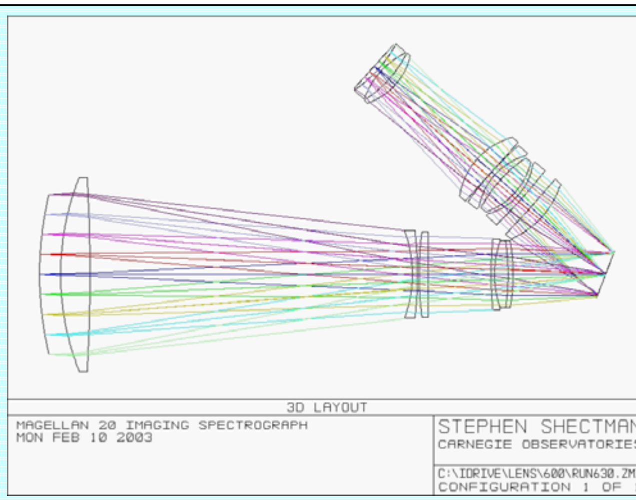

Figure 17. Optical layout for the imaging spectrograph for the Magellan 20 Gregorian focus.

At the baseline secondary focal ratio of f/10 it turns out that a very high-performance collimator can be designed, with an exit pupil diameter (grating size) of 250 mm. The field of view of this collimator is 15 arcmin, and the rms image diameter is 0.07 arcsec. This collimator is optically similar to the IMACS collimator on the exisitng Magellan telescopes. The collimator requires a very large fused-silica field lens (1.1m dia) but well within the range of available sizes for this material. It also requires one piece of either CaF2 (a crystal) or FPL51 (glass) with a diameter of 400 mm, and one piece of a more straightforward glass (like BaK2) with a diameter of 500 mm. The availability of optical materials in these sizes is currently being investigated by the project, but the sizes are comparable to some that have been encountered in other projects.

A spectrograph camera has also been designed, with a 13 arcmin field of view and an rms image diameter of 0.2 arcsec. The camera is made from fused Silica and CaF2 (again

400 mm dia) and would require a mosaic of 36 2K x 4K CCDs at its focal plane. When used with a fairly high blaze-angle reflecting grating (26.7 deg) there would be some loss (about 25%) due to vignetting as a result anamorphic beam expansion. At the red end of the spectrum, the resolution with this grating is 4000 for a 1 arcsec slit.

Small (~10%) changes in the primary and secondary focal ratios result in a Gregorian focus which is matched to a collimator which produces a 300 mm exit pupil. It seems likely that the practical upper size limit for the optical materials required to implement a spectrograph using refractive optics will be encountered at about this size.

A.1.2 Fiber spectrograph

An interesting alternative to an imaging spectrograph would be a bank of smaller spectrographs fed by fibers. Each fiber probe would in fact be a small integral-field unit or image slicer with 7 or perhaps 19 fibers. A typical fiber diameter of about 0.25 arcsec makes it possible to achieve adequate resolution in a specrograph of modest size (with 150 mm gratings, for example).

The fiber probes would use a magnifier/field lens/lenslet arrangement similar to the one described by Kenworthy et al. et al. for SPIRAL at the AAT. The output focal ratio of about f/3 is a good match for coupling the fibers directly to the input of a compact Littrow design similar to the fiber input mode of the MIKE spectrograph on the existing Magellan telescopes.

In the red it would be desirable to use an echellette grating in several orders in order to achieve adequate resolution to work between the airglow lines. The available focal-plane format for such a red spectrograph would only accommodate fibers from one or perhaps a few objects. Consequently a large number of spectrographs (perhaps between 10 and 30) would be required in order to be able to observe an interesting number of objects simultaneously. The details of the spectrograph format are currently being defined and optimized. The blue spectrographs would accommodate a larger number of objects at somewhat lower resolution, and perhaps only about one-third as many would be required.

Although the nod-and-shuffle technique has so far been used primarily with imaging spectrographs, it is also clearly applicable to observing through fibers, where the gain in consistency of sky subtraction should if anything be even greater. Work is underway at the MMT to validate the applicability of this technique for spectroscopy of very faint objects through fibers.

A.2 High-Resolution Spectrograph

The available options for a high-resolution spectrograph are to build a very large spectrograph indeed, using primarily reflecting optics (similar to the MTHR proposal for CELT) or to use fiber image slicers as input to a few smaller spectrographs (similar to the fiber input of MIKE). The MIKE fiber system should go into operation later this year, and will allow us to evaluate the merits of such a system directly. However a comparison of the size and cost of MIKE compared to other high-resolution spectrographs with similar capabilities (HIRES and UVES) indicate that the fiber system should have a substantial advantage, and is scalable (by adding more spectrographs) to either higher resolution or higher multiplex capability. Work is underway to define the properties and capabilities of such a fiber-fed system.

A.3 Near-IR AO imager

The baseline plan for AO on Magellan 20 is to use an adaptive secondary mirror. This technique has recently been demonstrated at the MMT. The diffraction limit at 1 micron is 7 mas, and the desired pixel size is about 3 mas. The required focal ratio for current detectors with 18 micron pixels is very slow -- about f/50. A 2K x 2K array will have a field of view of 6 arcsec, so either a single array or a small (e.g. 4k x 4k) mosaic is adequate to cover the isoplanatic patch. Since the adaptive surface is already provided at the secondary, reimaging optics with an internal cold stop are very straightforward to implement.

A.4 Near-IR AO integral field spectrograph

While adaptive optics has numerous applications in imaging, particularly in crowded any high dynamic range environments, AO spectroscopy offers the possibility of enormous gains in sensitivity for a wide range of astrophysical problems. In any study of compact or highly structure objects in the background-limited regime AO-fed spectrographs will have a large impact. As described in section 3.1.4, IFU spectrographs in natural seeing are having a large impact on studies of the internal structure and dynamics of galaxies.

We are developing AO-fed IFU concepts that will work in both high-order small-field AO applications and in the wider field GLAO environment. Detector area is likely to be the dominant cost driver for large AO-fed IFU systems and so we hope to maximize the use of a single detector system.

In the high-order small field AO applications the desired spatial resolution element (projected lenslet size) is on the order of 10mas. To sample a 2” x 2” area, appropriate for a faint galaxy, one needs a 200 x 200 lenslet array. Resolved objects (e.g faint galaxies) call for larger lenslet sizes, probably in the 50-100 mas range. Again modest size (e.g. 200 x 200) arrays could sample individual or small groups of faint galaxies. In the GLAO regime image sizes are expected to be in the 0.2-0.3” range and field of view as large as 5’ – 10’ may be accessible. Mulitple deployable IFUs with 200 x 200 0.1” – 0.2” lenslet arrays could sample several regions of the corrected field at any one time. A large (e.g. 8k x 8k) detector bank could serve a single spectrograph, or multiple spectrographs could be employed with a number of smaller mosaics or even single 2048 x 2048 detectors.

A.5 Mid-IR AO imager.

At mid-IR wavelengths (>5 microns) the diffraction limit will be 0.03 arcsec or larger. The desired focal ratios will be faster than f/50 but still relatively slow. Work on defining the capabilities of a mid-IR camera will need to be organized during the coming year. Mid-IR detector technology is advancing at a rapid pace. We are taking a forward-looking approach towards mid-IR imagers and will design towards the next generation of detectors rather than what is currently available off the shelf.

A.6 Ground-layer AO near-IR imager

The ground-layer AO field should be much larger (several arcmin) and designing a suitable reimager will be correspondingly more challenging. The requirement to deploy multiple (~10) wavefront sensors on either natural guide stars or laser beacons will also add to the complexity of this instrument. Work is underway at the University of Arizona to simulate the properties of a GLAO system, which will help to define the requirements for this instrument.

Even at this early stage we make a realistic estimate of the focal plane characteristics. The expected best seeing in the K-band with GLAO is ~ 0.2". This calls for 60-80 mas pixels for critical sampling. A 4k x 4k focal-plane assembly will cover the anticipated 5' field of view. The newest generation IR arrays allow for high-speed readout of arbitrary sub-pixels arrays. This may allow on-chip guiding and is particularly well suited for high dynamic range applications (e.g. extra-solar planets). If GLAO is able to deliver a 10' field with good correction, an 8k x 8k focal-plane is required. The costs of these detector assemblies is modest ($2-8M) compared to the $50M anticipated of the detector assembly for the proposed GSMT wide-field near-IR AO imager.

Appendix B

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