Chapter 2. Scientific Motivation

2.1 Introduction

CELT will combine a nine-fold increase in collecting area over existing optical/IR telescopes with a five-fold improvement in spatial resolution (for the near-IR) over the proposed Next Generation Space Telescope (NGST). CELT will provide exciting "breakthrough" possibilities in most areas of observational astronomy from Solar System exploration (with some capabilities exceeding those of space probes), to beyond the edge of the currently-mapped universe. This chapter begins with discussions of relevant properties of sky brightness as a function of wavelength, and comparisons with current and proposed front-line facilities. The science opportunities for CELT are then discussed in detail for a subset of the areas listed below. Because of the 10-year time period between when these words are being written and the first-light of CELT, and because CELT will open unexplored parameter space, it is likely that the most exciting discoveries of CELT will be in areas we cannot anticipate at this time. Nevertheless, there are a number of forefront areas of astronomy that are currently sensitivity- or spatial-resolution-limited, for which CELT will be required for further progress. We list some of the areas where we anticipate CELT will play a major role. Those marked with an asterisk are discussed in more detail in this chapter. The science opportunities for CELT will be explored in considerably more detail in the next phase of the project, with detailed simulations allowing important feedback to the telescope and instrument designs.

Anticipated major CELT science areas:

- Solar System explorations*****
- extrasolar planet searches and studies (including direct detection of hot Jupiters)*****
- star formations*****
- stellar seismology: high precision structure determination for the full range of stellar spectral types
- high precision astrometry for faint sources; detailed in-situ 3-dimensional kinematics throughout the Galaxy and Local Group
- chemical evolution and star formation histories of galaxies to 30Mpc*****
- resolving the mysteries of the Galactic center
- active galactic nuclei and black hole demography*****
- supernovae beyond z = 1: cosmological tools and probes of the star formation history
- the distribution of mass in the universe: intergalactic medium and weak lensing studies to large redshift*
- gamma ray bursts throughout the visible universe
- the era of galaxy evolution: high spatial, moderate spectral resolution studies of faint galaxies at z = 1 - 5*****
- the end of the Dark Ages: near-IR investigations of the initial star and galaxy formation events at z = 5 - 15

Much of the science outlined in the following sections assumes that technology development and implementation techniques for adaptive optics will proceed rapidly during the next decade, with the CELT project among the leaders in advancing the field. Although the full scientific power of the observatory will not be deployed until adaptive optics systems are working at the level detailed in Chapter 9 of this document, we emphasize that seeing-limited (i.e., non-AO) observational capabilities in both the optical and near-IR will be advanced significantly by the 30-m aperture and state-of-the-art seeing-limited instruments (Chapter 10) anticipated for CELT. As a result, about half of the science projects described in this chapter could proceed uninhibited by a slip in either schedule or scope of providing AO systems by first light. We cite as an example that the Keck 10-m telescopes operated without an AO system for the first seven years of normal operations, and most of its major scientific accomplishments to date have been based on seeing-limited observations. The advance in seeing-limited capability of CELT over Keck exceeds that of the advance of Keck over previous generation telescopes.

We believe that CELT will deliver AO systems performing to required specifications at first-light or soon thereafter; however, we emphasize that perceived and real technology risks in this area need not be seen as compromising the viability of the CELT observatory to significantly advance forefront science from the outset. Generally, the expectation is that adaptive optics capabilities will continue to improve during the lifetime of the CELT observatory and ultimately will exceed those assumed for the present science case.

2.2 Thirty-Meter Telescope Project Background

With increased light-gathering power and finer diffraction-limited images, optical/IR telescopes with larger mirrors will always benefit observational astronomy. Recent experiences with the Keck 10-m telescopes have shown how new facilities with larger apertures allow for “quantum leaps” in both the range and the quality of the resulting discoveries. The Keck light-gathering abilities allowed the discovery and study of populations of galaxies at z = 3 and beyond, made possible the discovery of the nature of gamma ray bursts, led to the discovery of the majority of the known extrasolar planets, was crucial for establishing the evidence of an accelerating universe, and revolutionized our understanding of the star formation history of the universe, to mention only a few of the dramatic Keck breakthroughs.

A pattern of breakthroughs can be discerned at other times throughout the 20th century, where each new generation of larger-primary-mirror telescopes has led to significant new astronomical discoveries. We cite two examples. In the 1920’s the 2.5-m telescope at Mt. Wilson allowed the first measurement of the expansion of the universe. Within five years of the Palomar 5-m first light (in the late 1950’s) our understanding of stellar populations in the Galaxy and other Local Group galaxies was advanced enormously, quasars were discovered, and the extragalactic distance scale was established to within 50% of the presently accepted numbers. In the past, the rationale for making advances in telescope aperture was almost exclusively driven by the larger collecting area; because delivered image size was set primarily by atmospheric turbulence, the smaller diffraction limit of larger primaries was generally not used to any scientific advantage. Increased angular resolution, as opposed to light-gathering power, is the primary reason that the Hubble Space Telescope (HST) has had such a profound impact on our understanding of the universe, despite its modest 2.5-m aperture. The HST spatial resolution of ~0.1 arcsec offered a ~5-fold improvement over previous ground-based facilities. With CELT, taking advantage of the recent and continuing revolution in adaptive optics, we will be able to make substantial improvements in both light-gathering capability and high spatial resolution simultaneously. In broad terms, the increase in capabilities from the Keck 10-m to the CELT 30-m will be similar to the angular resolution gain from ground-based facilities to HST in the mid-1990’s, coupled with an historically unprecedented gain in light-gathering power, a factor of nine increase from Keck to CELT (compared to the factor of four from the Palomar 5-m to the Keck 10-m telescopes).

While the Keck Observatory continues to produce exciting new results, and will continue to do so for years to come, a host of important problems in astrophysics are already clearly beyond Keck’s capabilities, whether because of inadequate spatial resolution, sensitivity, or both. Because the development of world-class astronomical facilities is a long lead-time activity, now is the time to think about the next step.

We envision CELT as an observatory with very broad capabilities operating over the wavelength range 0.3-30 μm, poised to address the most compelling science of its era. CELT will operate both with and without adaptive optics (AO). Unlike many past facilities, CELT is being designed with diffraction-limited performance as a driving force during a time in which full adaptive optics (AO) capabilities are being delivered on current 8-m-class telescopes.

Figure 2-1. A simulation of imaging at the diffraction-limited CELT resolution versus the Hubble Space Telescope.

2.3 Technical Background for Science Motivation

In the sections describing the scientific investigations to be undertaken with CELT we will refer to various capabilities, often in comparison to existing or planned facilities. We have collected the information adopted for signal-to-noise ratio (S/N) calculations in this section. Although the CELT site has not yet been chosen, we will use the Mauna Kea sky as our fiducial for the background material on sky brightness and transmission. The principal variable between the sites under consideration is the typical amount of water vapor above the site.

2.3.1 Image Quality

A very significant advance in astronomical instrumentation is the realization of adaptive optics (AO) for near-real-time correction of wavefront distortions as light passes through the Earth's atmosphere. As has been demonstrated with the Keck 10-m telescopes, it is possible to achieve diffraction-limited images for wavelengths longer than ~ 0.9 μm over fields 20-40 arcsec in diameter. This advance brings the arena of high spatial resolution imaging back to ground-based facilities, as it will likely be the case for the next century that the largest telescopes will be built on the ground. If adaptive optics can someday be extended to visual wavelengths, the space advantage for optical astronomy will all but disappear.

In the discussions that follow we will work in the context of two observing modes for the 30-m telescope. **Seeing-limited** observations will assume 0.5 arcsec FWHM images for point sources. This is typical in the visible for a good site and conservative for the near IR where image quality can be improved by as much as a factor of two compared to 500 nm. **Diffraction-limited** observations will assume the diffraction limit for a 30-m primary mirror. Each mode of observation is discussed in more detail below.

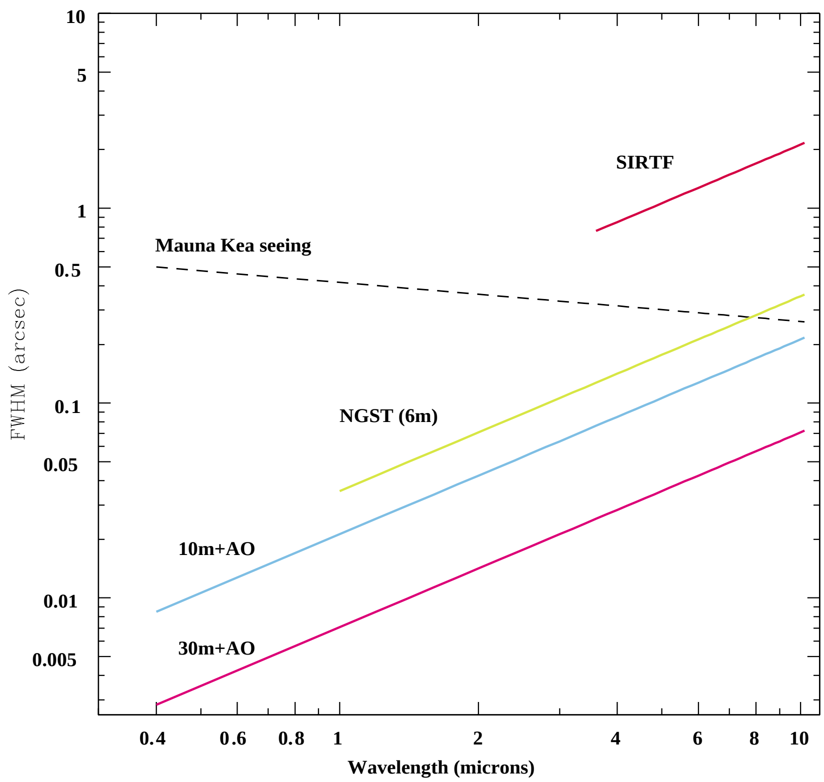

Figure 2-2. The diffraction limit as a function of wavelength for 10-m and 30-m telescopes, along with that of NGST and SIRTF. Seeing limited image size for Mauna Kea is shown as an example of image sizes at ground based telescopes. This curve applies equally to all large telescopes as long as the seeing size exceeds the diffraction limit of that telescope.

For reference in the following section, Figure 2-2 shows the FWHM of images for the Space Infrared Telescope Facility (SIRTF, a space-based 0.85-m infrared-optimized telescope), the currently-planned NGST (6 m, l < 0.6 µm), and diffraction-limited 10-m and 30-m telescopes. Also shown is typical ground-based seeing at Mauna Kea scaled by $l^{-0.2}$ assuming 0.5 arcsec images at 0.4 µm. Note that with currently-available AO systems it is not possible to correct the atmosphere for a 10-m (or 30-m) telescope to the diffraction limit with high Strehl for wavelengths shortward of 0.9 µm with large values of the Strehl ratio. It is our goal for CELT to extend useful correction (Strehl > 0.1) down to 0.5 microns (see Figure 3-1).

2.3.2 Atmospheric Transmission

The atmosphere is essentially opaque shortward of 0.3 μm and transparent up through the first significant water absorption band at 0.9 μm. In the near-IR, the commonly used bands (J, H, K) are set by the transmission of the atmosphere and are somewhat water vapor dependent. In the “thermal-IR,” between 2.5 and 25 μm, the available ground-based observational bands become increasingly more dependent on water vapor content of the atmosphere. Approximately half of the wavelengths between 0.9 and 25 μm are essentially inaccessible from the ground. The following three figures (2-3, 2-4, and 2-5) show the near-IR and mid-IR atmospheric transmission for different values of opacity, usually expressed in terms of the effective column of precipitable water above the telescope site. A very good site for the thermal IR has a median opacity of $\simeq$ 1 mm (e.g., Mauna Kea, Chajnantor). The numbers are extremely well correlated with altitude, with the highest sites (> 4000 m) being much drier.

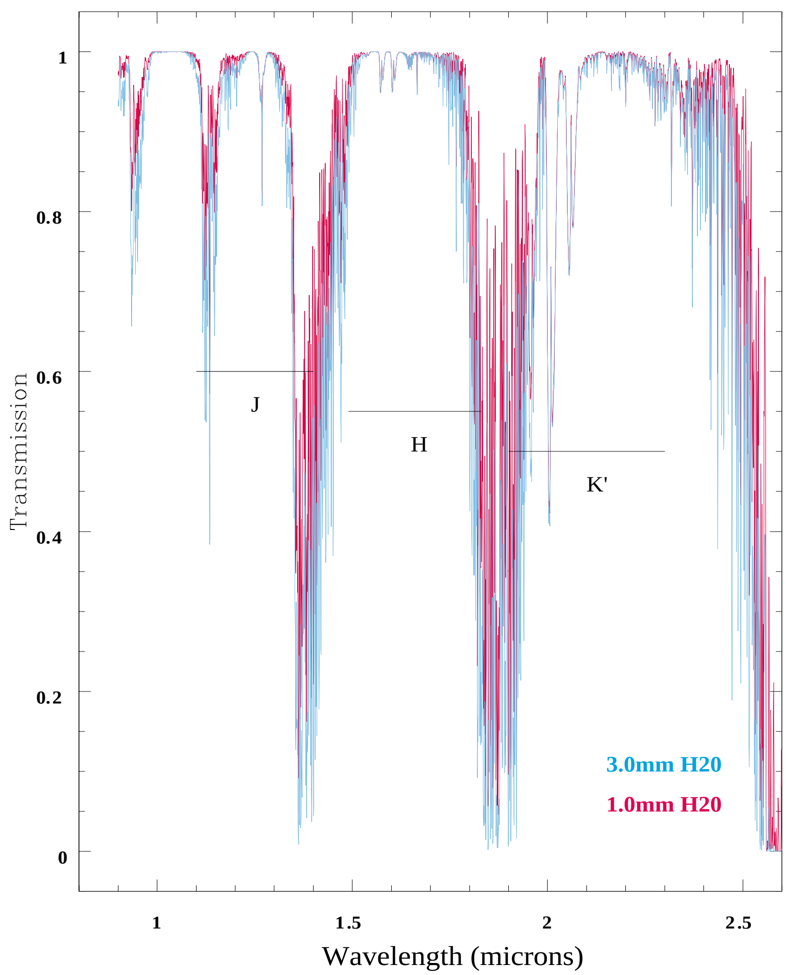

Figure 2-3. Atmospheric transmission in the near-IR for two water vapor levels.

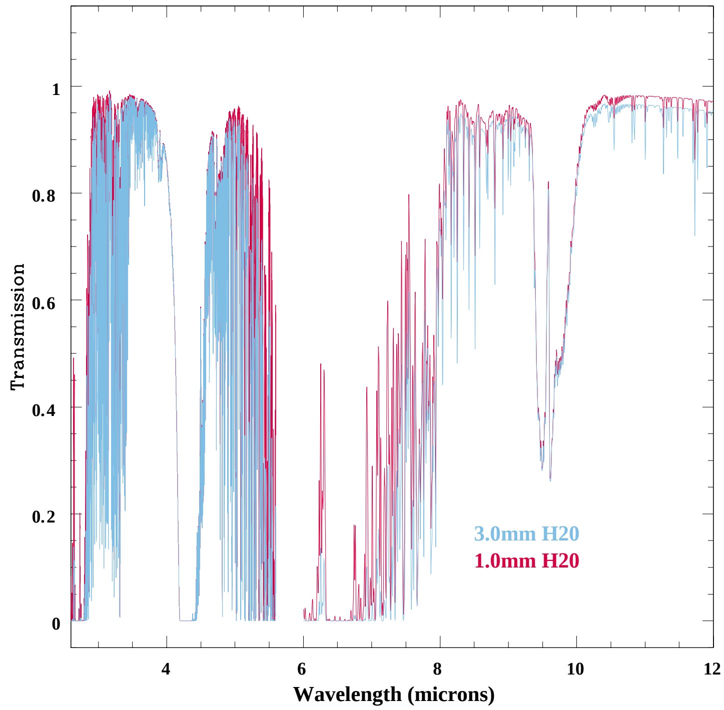

Figure 2-4. Atmospheric transmission in the thermal-IR for two water vapor levels.

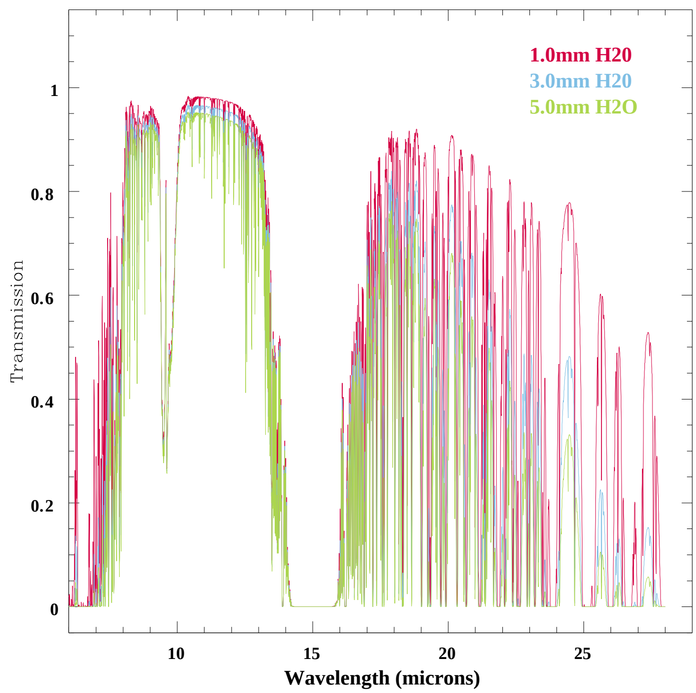

Figure 2-5. Atmospheric transmission in the 7-30 μm range for water vapor levels ranging from 1 mm to 5 mm; 5 mm is typical for sites at altitudes lower than 4000 m.

2.3.3 “Sky” Brightness

The table below gives the background sky brightness (from all sources not local to the telescope and enclosure) through commonly used broadband filters. These numbers are measured at the Canada France Hawaii Telescope on Mauna Kea and will be assumed for the rest of this chapter. Tabulated numbers are for new moon and the zenith. From ~ 0.7 μm through ~ 2 μm the night sky emission is dominated by OH molecular emission. At longer wavelengths water vapor and thermal continuum are the dominant source of photons. The telescope design becomes very important for background levels beyond 5 μm.

Table 2-1. Broadband sky brightness for Mauna Kea

Band	Central λ (μm)	Brightness (mag arcsec^{-2})	(AB mag arcsec^{-2})	(μJy arcsec^{-2})	Flux (photon cm^{-2}s^{-1}μm^{-1}arcsec^{-2})
U	0.36	21.6	22.5	3.3	1.74×10^{-2}
B	0.44	22.3	22.2	4.8	1.76×10^{-2}
V	0.55	21.1	21.1	13.2	3.62×10^{-2}
R	0.64	20.3	20.6	20.9	5.50×10^{-2}
I	0.79	19.2	19.7	47.9	1.02×10^{-1}
J	1.23	14.8	15.6	2089.3	2.49
H	1.66	13.4	14.7	4786.3	4.20
K	2.22	13.5	15.4	2511.9	1.74

For spectral observations we will use the emission models shown in the following figures, each based on measurements at Mauna Kea.

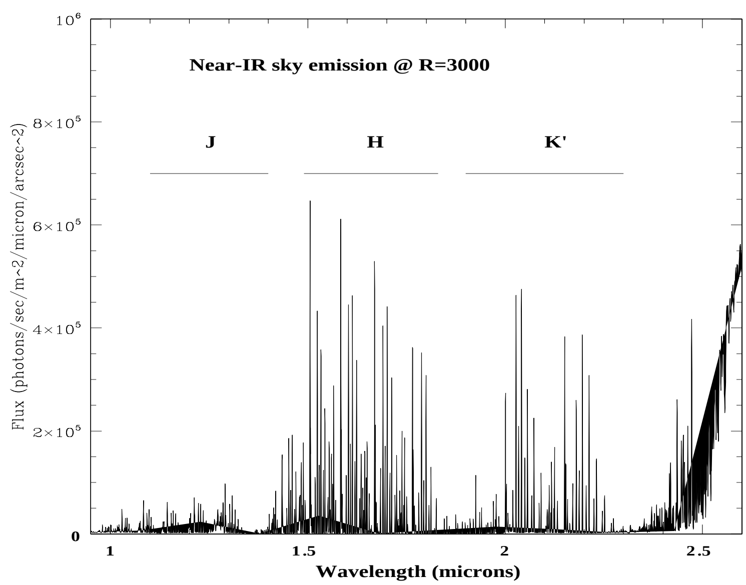

Figure 2-6. The emission from the atmosphere in the near-IR. Note that the level of the continuum emission is much lower than the average when all of the narrow OH emission features are included. Most spectroscopic observations will assume that the spectral resolution is high enough that only ~ 5% of the spectrum is contaminated by strong OH lines (R ≥ 4000). The broadband sky brightness in the J, H, and K bands are reduced by approximately a factor of 100 (5 magnitudes) between the bright OH lines.

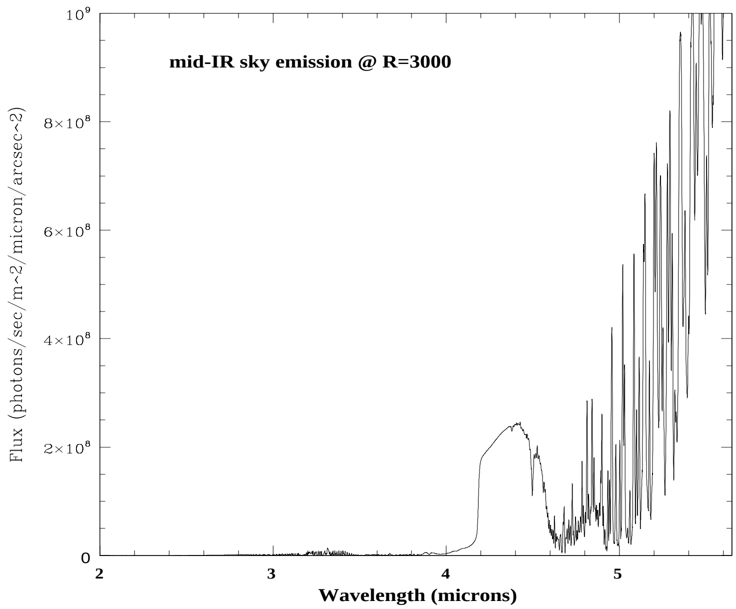

Figure 2-7. The emission from the atmosphere in the IR. The intensity axis is plotted linearly to emphasize the tremendous increase in atmospheric emission longward of 4 µm.

As we discuss below, achieving good spectroscopic sensitivity in the near-IR depends on having high enough spectral resolution that the effective sky background is that of the near-IR continuum, between the narrow OH features.

2.4 General Performance Capabilities of a 30-Meter Telescope

For the following discussion we will use this definition of signal-to-noise ratio (S/N).

$$S/N = S\,t / [\,S\,t + (sky \times At) + D\,A\,t + RN\,A\,]^{1/2} \qquad (2\text{-}1)$$

where "S" is the detected photon rate from the source, "Sky" is the detected photon rate per detector pixel from all foreground and background sources coincident on the sky with the source, "D" is the dark current rate per pixel of the detector; "RN" is the readout noise per pixel of the detector; "t" is the exposure time; and "A" is the number of pixels in the aperture in which the detection is measured. The expression above assumes that the estimate of the local sky does not contribute significantly to the variance (i.e., the background is estimated over a significantly larger area than the object of interest).

2.4.1 Thirty-Meter versus Ten-Meter Telescope

CELT will be dramatically faster and more capable than the best ground-based optical/IR telescopes. The comparison between a 30-m and 10-m with similar detectors and at the same site is very straightforward. Both S and Sky scale with telescope primary diameter D_M. For the case of AO correction to the diffraction limit, $A \sim D_M^{-2}$. In the common case where the sky background is the dominant noise source (faint sources and long exposure times), the limiting flux at fixed S/N and exposure time scales as D_M^{-1}, a factor of 3 comparing CELT to the Keck 10-m telescopes. The exposure time to reach a given S/N scales like D_M^{-2} for the seeing-limited case, so that CELT is nine times faster than Keck. For diffraction-limited observations of unresolved sources, the gain of CELT over a Keck telescope is a remarkable factor of 81. In the diffraction-limited case for resolved objects, the gain will fall somewhere between a factor of 9 and 81 depending on the size of the object.

2.4.2 CELT and the Next Generation Space Telescope (NGST)

NGST is a NASA mission that is in the development stages, intended for launch in the 2009-2010 time frame, with a total cost, including technology development, of about $2 billion. The current design concept is a 6-m aperture, lightweight deployable primary mirror, designed to be diffraction-limited at 2 µm, optimized in the 1-5 µm range, but zodiacal-background (as opposed to telescope thermal background) limited to 10 µm. The combination of the envisioned detectors and gold–coated optics will limit the range in the visible to longward of 0.6 µm. At the time of this writing, the planned NGST instruments are a 1-5-µm imager, a 1-5-µm multi-object spectrograph, and a mid-IR combination imager and low-resolution spectrograph that will likely work to wavelengths of 25-30 µm.

CELT will outperform NGST at all wavelengths < 2.5 µm, and at longer wavelengths when the higher angular resolution of CELT is needed or helpful. In general, CELT and NGST are complementary because each will excel at a different type of observation.

In the comparison with space-based telescopes, the large decrease in sky brightness for telescopes above the atmosphere is a significant factor. At optical wavelengths, the background sky at V is only slightly brighter on the ground, but starting around 0.9 µm where OH emission from the atmosphere becomes important, the ground-based sky becomes orders of magnitude brighter (reaching a factor of 10^6 by 3.5 µm). Final design of the NGST telescope will set the background levels achieved longward of 2.5 µm (see Figure 2-8).

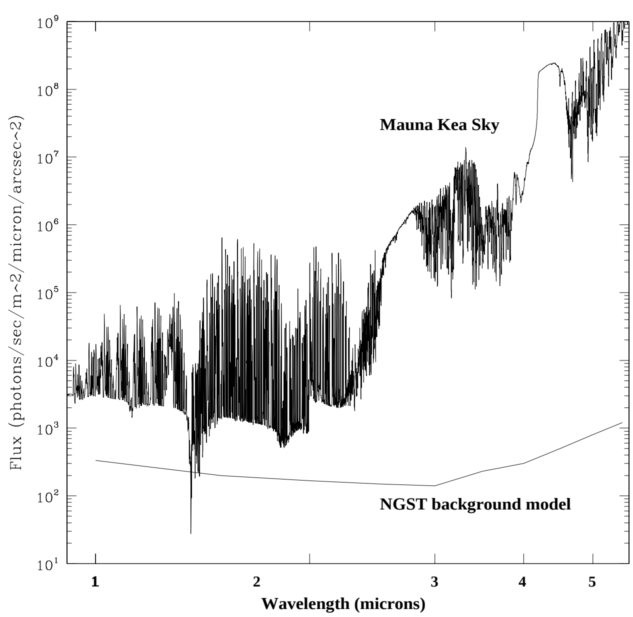

Figure 2-8. The dark sky comparison between Mauna Kea and a model for the NGST. There is a component of the spacecraft emission in this model longward of 3 µm.

Most of the relatively bright background in the 1-2.5 µm ("near-IR") windows for observations from the ground is concentrated into very bright emission from OH molecules in the upper atmosphere, with very narrow intrinsic line widths; as a result, the effective background at these wavelengths can be reduced to within a factor of ~10 of that achieved in space by observing at high spectral resolution. Instruments using "integral field," or 3-dimensional spectroscopic techniques (2-dimensional imaging with high-resolution spectroscopic information recorded simultaneously), effectively suppress the OH emission by censoring wavelength channels contaminated by atmospheric emission lines. *This same high spectral resolution is the main scientific requirement for unraveling the physical details of faint astrophysical sources, and it will require a very large collecting area (aperture) and very large instruments that are much better suited to terrestrial environments.*

Beyond 2.5 µm, NGST will be the telescope of choice for both imaging and low-to-moderate dispersion spectroscopy; the exception is when the ~5 times higher spatial resolution achieved with CELT would more than outweigh the significant loss in sensitivity inherent in terrestrial sites. As described below, there are significant areas of astronomy where thermal-IR observations with CELT will be revolutionary even in the era of NGST.

Figure 2-9 is adapted from Gillette and Mountain (1998) and shows the relative S/N for NGST versus CELT for three different spectral resolutions in the near- and mid-IR bands accessible from the ground. Red bars are for spectral resolution R =10,000, green bars for R =1000 and blue bars for R = 5 (broadband imaging). (Note: At present, NGST will not have spectroscopic capability with R > 1000. This is largely because of the gains to be had using large-aperture ground-based telescopes.) The combination of low background in space and relatively high dark current for IR detectors means that at the higher resolution, NGST observations would be detector-noise-limited. For this plot, NGST exposures of 4 x 1000 seconds and S/N of 10 were assumed. The detector characteristics for CELT and NGST assumed are: dark current = 0.01 e^-/s, read noise = 4 e^- for wavelengths shortward of 5.5 µm; and dark current = 10 e^-/s, read noise = 30 e^- for observations longward of 5.5 µm.

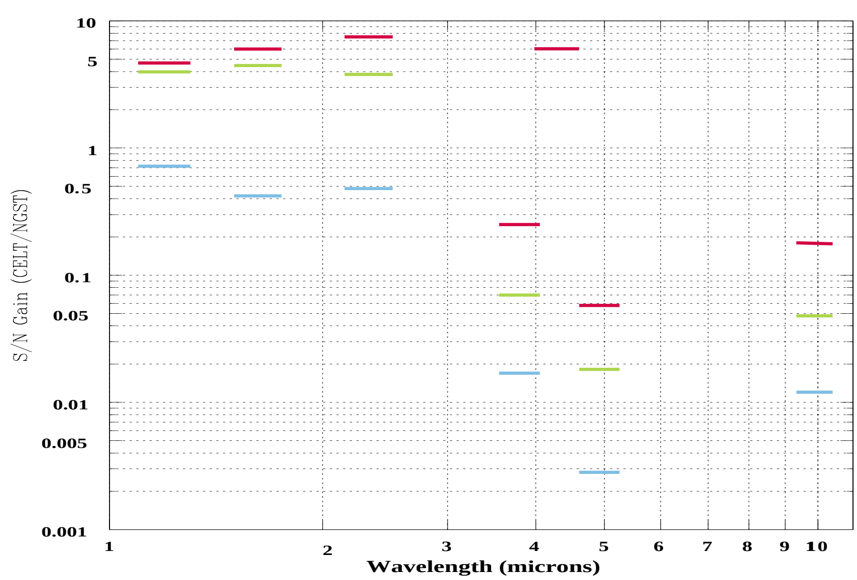

Figure 2-9. S/N gain for CELT versus a 6.5-m NGST for three spectral resolutions. Red bars are for R=10,000, green for R=1000, and blue for R=5.

At longer wavelengths, Figure 2-10 shows the expected limiting fluxes for R = 10 observations for CELT, Keck, SIRTF, and different configurations for NGST. Also shown is the background at two angles with respect to the ecliptic for the zodiacal light background level.

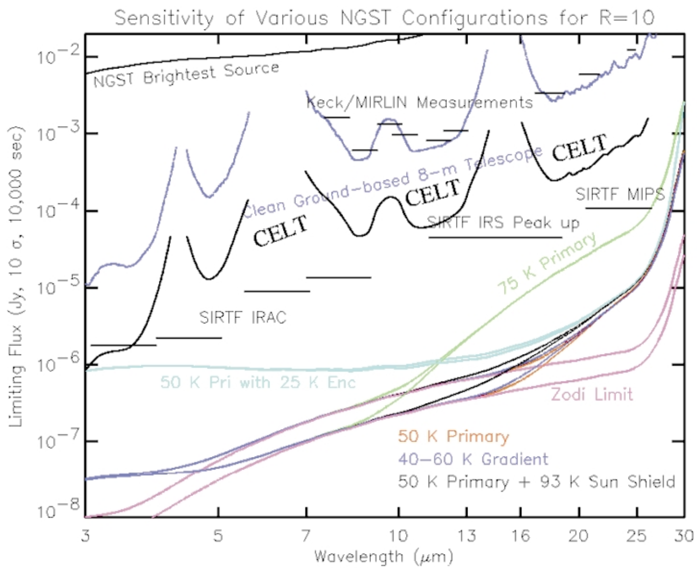

Figure 2-10. CELT, Keck, NGST and SIRTF at long wavelengths. Note that CELT will have close to the mid-IR sensitivity of SIRTF (but with 35 times higher spatial resolution) and will approach that of NGST at 25 µm if the specifications on telescope temperature are relaxed to 75K. These calculations were done assuming an 8-m NGST (current de-scoped telescope is 6 m) and a CELT emissivity of 5% (approximately the same as the Keck telescope).

Perhaps the greatest advantage of a ground-based facility over a space mission like NGST is the opportunity to carry out major programs over extended periods of time, and to continue to develop state-of-the-art instrumentation over a much longer observatory lifetime. This would allow a more rapid reaction to new developments in science over time, and would offer the versatility of applications both foreseen and unforeseen. Ground-based telescopes are much less expensive to build and operate and can be readily upgraded with better instrumentation as technology advances allow. One benefit of this situation is that ground-based facilities can be more flexible, and with a proper suite of instruments be far more versatile than an orbiting telescope. To a very large extent, NGST is being developed to excel in just the areas that will be difficult from the ground: extremely sensitive IR imaging and low-resolution identification-quality spectroscopy.

In short, the capabilities of NGST and a large (~30 m) ground-based telescope that is diffraction-limited would be almost completely complementary. This is discussed in more detail below on a scientific case basis.

2.4.3 CELT and ALMA

The Atacama Large Millimeter Array (ALMA) is a planned international facility (current partners are the U.S., Europe, and Japan in roughly equal proportion) that will consist of 64 12-m antennae placed on a high plateau (5000 m) in the Chilean Andes. On the current schedule, ALMA will be operational by the end of this decade, and so would be a contemporary with CELT. ALMA will operate in atmospheric windows from 350 μm to 8 mm, optimized for wavelengths of ~1 mm. ALMA will operate in a number of different array configurations, ranging from a compact, nearly filled aperture array with baseline of 150 m, to a high-resolution configuration with maximum baseline of 10 km. In the compact configuration, ALMA will have point source sensitivity (estimated) for continuum observations of ~0.1 mJy (10 sigma, 1 hour) at 1 mm with a spatial resolution of ~0.5 arcsec; in the high resolution configuration ALMA will have a spatial resolution of 0.030 arcsec at 1 mm. As with NGST, CELT observations will complement those of ALMA. ALMA will excel at measuring thermal emission from dust, while CELT will observe the less obscured stars in the same local star-forming regions or high redshift galaxies.

The science case for ALMA includes many of the same fundamental questions we address below for CELT. For example, we argue that CELT will allow detailed physical investigations of galaxies at high redshift, using both the light-gathering power and the very high spatial resolution (roughly five times better at 1 μm than for ALMA at 1 mm). ALMA will be most powerful for examining the re-radiated emission from dust in high redshift galaxies: At 1 mm and z = 3, ALMA will be sensitive to thermal dust emission for galaxies exceeding $10^{11}L_{Sun}$ (star formation rates of $20M_{Sun}$ per year) , which would in the present-day universe be classified as luminous infrared galaxies (LIRGs); more luminous objects will probably be required for rest-frame far-IR spectroscopy. CELT, on the other hand, will have *spectroscopic* sensitivity in the UV to near-IR for objects down to the 10 nJy level (and down to rest-UV luminosities of perhaps 10^8L_{Sun}, or unobscured star formation rates of $\sim 0.2M_{Sun}$ per year) at the same redshifts. It is now well known from observations in the sub-mm from the ground that there is a significant number of very luminous ($L_{bol} > 10^{12}L_{Sun}$), heavily obscured ($L_{FIR}/L_{UV} \sim 500$) sources at high redshift, but that the objects which comprise most of the sub-mm background are objects with about 10-times smaller luminosities and 10-times smaller extinction. These more common objects, which will be within the simultaneous reach of both CELT and ALMA, are those that produce most of the stars and metals in the high redshift universe. ALMA will allow the robust measurement of their bolometric energy production and molecular and atomic chemistry for the brightest sources, while CELT will more easily provide measures of redshifts, kinematics, and stellar populations.

ALMA and CELT will also be highly complementary for studies of the details of star formation in the nearby universe. With CELT operating in the 1-30 μm range at resolutions from 0.006 arcsec to 0.180 arcsec and ALMA in the 350 μm to 8 mm range with spatial resolution of 0.010 arcsec to 0.230 arcsec, these great observatories will resolve down to AU length scales at distances of 100-150 pc, providing access to the detailed chemistry and kinematics in the nearest star-forming regions in the galaxy. These measurements will be used together to understand the formation of stars and the protoplanetary disks that give rise to planets.

2.4.4 CELT and Other Future Facilities

We have learned from the Keck Observatory that an extremely important role is played by large ground-based optical/IR telescopes in following up sources first identified at other wavelengths, both on the ground and in space. For example, Keck has so far played a vital role in the identification of faint X-ray sources with Chandra, and gamma-ray bursts with Compton Observatory; worked with HST in identifying the high redshift supernovae, allowing measurement of the acceleration of the universe; spectroscopically identified rare low-mass stellar objects from the 2-MASS all-sky survey; identified most of the 850 μm sources for which redshifts are currently known; and obtained high-quality spectra of the highest redshift QSOs from the Sloan Digital Sky Survey, spectra which is beginning to elucidate the epoch when the universe became fully-ionized. While much of the credit for these discoveries often goes to the other facilities, the science would be much less rich, and even not possible, without the Keck telescopes. We anticipate that CELT will play a similar role alongside future facilities and surveys both on the ground and in space. A large fraction of astronomy in the future will require spectroscopic observations of sources that are extremely faint in the optical and IR, and the sensitivity of large telescopes on the ground at these wavelengths will not be easy to surpass.

2.5 CELT Science Opportunities

There is virtually no astrophysical problem for which CELT will not represent a huge gain over the Keck telescopes, due to the order-of-magnitude gain in both collecting area and diffraction-limited PSF-size. Below we outline scientific programs that would particularly benefit from CELT; past experience shows that the science we envision now may not be among the most exciting projects for which CELT will be used by the time it is operational. Nevertheless, they illustrate of the kinds of gains that will be enabled using the next-generation state-of-the art ground-based optical/IR telescopes, and they point out the general capabilities desired for the telescope and instruments to guarantee a large scientific return in the future. Toward this end, we call out particular telescope and instrument goals/ requirements that would be necessary to carry out each of the proposed projects.

The science projects described are not meant to be exhaustive lists of all the areas where CELT will revolutionize observational astronomy. Rather, our intent is to reflect the great breadth of science, ranging from Solar System studies to investigation of the highest redshift universe, that CELT will be able to address.

2.5.1 Solar System Science with CELT

High resolution imaging

In many cases, global infrared images of planets and satellites of the Solar System observed with CELT would be *higher resolution* than those obtained by spacecraft exploring the Solar System. In addition, ground-based telescopes offer the possibility of significantly higher spectral resolution than has been obtainable on board spacecraft. The combination of these two capabilities will allow a 30-m telescope anchored to the Earth to make significant contributions to the exploration of the Solar System. A further advantage of CELT over explorer-type missions is the ability (thanks to the permanent nature of the facility and a routinely operating adaptive optics system) to monitor changes, e.g., weather and volcanic activity, on Solar System objects.

As an example, we consider the case of Jupiter's satellite Europa. Europa's surface is covered with water ice, but evidence suggests that underneath this ice layer a global liquid water ocean may exist. The water from this ocean may sporadically reach the surface of Europa in the many cracks penetrating the icy surface of the satellite. One piece of supporting evidence for this ocean is that low-resolution spectroscopy from the Galileo spacecraft has suggested that the dark regions around the cracks are composed of hydrated salts evaporated from the seawater below. If this were true, the composition of the salts would hold important answers to questions of composition of the proto-solar nebula, the degree of aqueous processing of the satellites, and the potential for supporting life or pre-organic chemistry. Unfortunately, at the spectral resolution of Galileo (R ~ 200), the identification of the dark materials on Europa is not certain. A resolution approximately 10 times higher, however, would allow the many different salt species or other possible components to be readily discerned. While such spectral resolutions are routinely available from the ground today, at the low *spatial* resolution of typical ground-based observations the spectra of the large icy regions hide the spectra of the unresolved dark areas. At CELT resolution, however, the dark regions on Europa are resolved (Figure 2-11).

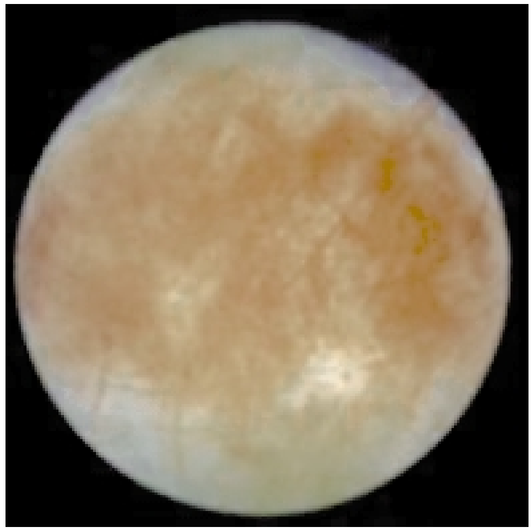

Figure 2-11. A visible-light Galileo image of Europa, convolved to the resolution of CELT. Linear cracks, expected to be the location of evaporated oceanic salts, are clearly resolved, as are craters and large icy regions. High-resolution spectroscopy of these features will allow definitive compositional understanding that is currently not possible.

High spatial and spectral resolution imaging of the satellite will allow definitive compositional identification that will help to solve many of the questions of this satellite and its possible oceanic interior. Similar problems will be solvable on the other Galilean satellites and on many other bodies of the Solar System.

Studying the edge of the Solar System

Most of the original material in the disk of gas, dust, and ice that formed the sun and planets of our Solar System has been heated, stirred, and compressed beyond recognition, leaving little information about the initial conditions that led to the current Solar System. Recently, however, planetary astronomers have discovered a vast swarm of small icy bodies -- named the Kuiper belt -- orbiting at the edge of the Solar System. While closer to the sun everything was heated and swept into planets, beyond Neptune the density of material was so low that no planets formed. These Kuiper belt objects (KBOs) have been preserved in deep freeze since the time of the formation of the Solar System. Study of the composition of these objects provides direct access to the make-up of the material out of which the planets formed.

The composition of icy bodies such as these is best determined through moderate-resolution ($R \sim 1000$) spectroscopy in the near-infrared (1-2.5 μm) where most important ices have strong absorption features. Because of their vast distances and small sizes, these objects are extremely faint (typically $V \sim 24$), so such infrared spectroscopy has not been possible. Using the Keck telescope, a few KBOs have been observed at lower resolution sufficient to detect ices with particularly strong and wide absorptions similar to water, but because of the small numbers of objects studied no concrete conclusions have been possible. In lieu of spectroscopy, astronomers have been studying the broadband colors of

KBOs from the blue to the infrared. While colors cannot provide compositional information, they can at least indicate which objects might be compositionally similar and which different. From studies of dozens of objects, it is apparent that KBOs come in a wide range of compositions with colors varying from essentially neutral to the reddest objects ever observed in the Solar System. It is clear that once spectroscopy is possible, astronomers will be rewarded with a rich assortment of spectral and compositional types holding many clues to the earliest history of the Solar System.

With the advances of laser guide star AO on the Keck telescope, the brightest KBOs will be just within reach of infrared spectroscopy. While these are likely to hold many compositional surprises, the color information suggests that these largest objects are the *least* compositionally different, and to understand the true diversity of compositions in the outer Solar System we will have to be able to reach to the much more abundant fainter objects. CELT will allow us to make this jump. With CELT we expect that hundreds (if not thousands, by then) of moderately faint KBOs will be well within the range of moderate-resolution spectroscopy. Because of the relative youth of this field, it is difficult to speculate on the discoveries that will be enabled by these advances. However, it is clear that this type of basic exploration of the Solar System will yield important insights into the formation of our and other planetary systems for many years to come.

Technical/Instrumental requirements

Most Solar System observations do not require particularly specialized instrumentation. Imaging of Solar System objects will be enabled with any of the planned AO imaging capabilities. Most important for efficient spectroscopy is the ability to perform small field (~ 2 arsec) integral field spectroscopy at moderate resolution (R ~ 1000) with large wavelength coverage to quickly cover the entire available band (cross dispersion is ideal).

The telescope needs to efficiently guide and track at non-sidereal rates as high as those expected for typical bright comets. Solar System observations are often time-specific, focusing on a certain face of a planet or alignment of satellites, so the telescope needs to maintain maximum flexibility in pointing and scheduling. Planets and satellites are often bright; care needs to be taken to make sure that no instrument is designed in such a way as to preclude observation of such bright objects.

2.5.2 Terrestrial Planet Searches and Studies with CELT

We describe potential observational programs with CELT to study terrestrial planetary systems outside of our Solar System. The large aperture of CELT will enable the order-of-magnitude leap required to advance from detecting and studying Jovian planets to similar investigations of terrestrial planets. Once extrasolar terrestrial planets are identified, we will be able to investigate spectroscopically with CELT whether life may exist on them.

Background

The first planets outside the Solar System were discovered around the pulsar PSR 1257+12 (Wolszczan and Frail 1992). The relatively short periods of 70 to 100 days for these planets implied that they were not long-lived survivors of the pre-supernova because they would have been engulfed when that star was a red supergiant. Instead, these pulsar-orbiting planets were viewed as a remarkable and curious consequence of a supernova explosion, but not in any obvious sense relevant to providing clues to the formation and evolution of our own Solar System.

The discovery in 1995 (Mayor and Queloz 1995) of a planet around the solar-type star 51 Peg, and the many other planetary discoveries since then, have dramatically improved our ability to learn about our own history. Currently, about 50 stars are known to possess roughly Jupiter-mass planets; at least 6% of approximately solar-mass main sequence stars have planetary companions (Marcy, et al., 2000). As we study these objects we are now in the position to learn more about the evolution of our own Solar System and even to address the question of whether life has formed and evolved elsewhere in the universe.

The bulk of our knowledge of planets comes from observing the reflex motion of the star that they orbit. We therefore learn about their orbital periods and eccentricities as well, M/sin(i), where M is the mass of the planet whose orbital plane is tipped at angle i relative to the plane of the sky. To date, the lowest known planetary masses are perhaps as low as 25% that of Jupiter (Marcy, Butler and Vogt 2000). The orbital periods of the planets are less than about 3 years.

In addition to observing their subtle gravitational effects on the star they orbit, there have been efforts to directly or indirectly detect light from the planets. The most striking result to date is the occultation of HD 209548 by its companion in a 3.5 day orbit (Henry, et al., 2000; Charbonneau, et al., 2000). The amplitude of the eclipse allows for a direct determination the planet's radius, which equals 1.5 ± 0.1 times the radius of Jupiter (Jha, et al., 2000).

If a planet is near enough to its host star, it can reflect enough light that its spectral lines might be detectable. By searching for such reflected light, Charbonneau, et al., (1999) have placed an upper limit of 0.3 to the albedo near 4800 Å of the planetary companion to τ Boo. This value of the albedo is lower than that found for the giant planets in the Solar System which are 0.46, 0.39, 0.60 and 0.58 for Jupiter, Saturn, Uranus and Neptune, respectively (Karkoschka 1994).

One of the strongest motivations for studying extrasolar planets is to learn if life exists elsewhere in the universe. While there is some possibility that Jovian planets, and especially their satellites, could harbor life (Sagan and Salepter 1976), it seems more promising to search for life on Earth-like planets.

In the Solar System, there are two classes of planets: the Jovian gas giants and the Earth-like (terrestrial) planets. The Jovian planets are 320 (Jupiter), 95 (Saturn), 15 (Uranus) and 17 (Neptune) times more massive than the Earth. Therefore, to study Earth-like systems, we should hope to study planets with masses not more than 10 times that of the Earth. This advance requires roughly an order-of-magnitude increase in sensitivity over current technology: this is achieved with the ratio of the collecting area of a 30-m CELT compared to a 10-m Keck.

During the past five years, we have succeeded in the ancient dream of detecting planets around other stars. We are beginning the physical study of these objects. Below, we list how CELT can play a vital role by expanding our studies to terrestrial as well as Jovian planets. First, we will describe how CELT can be used to detect new planets. Second, we will discuss how CELT can be used to study the planets that have been detected.

The Search for Terrestrial Planets

One of the main avenues of planetary research will be to identify more of these systems. With the ability to make catalogs, it will be possible to constrain models for the formation and evolution of these systems. Many questions arise:

- What is the mass distribution of planets? At the moment, it looks like the number of planets increases approximately as $dN/dM \sim M^{-1}$ (Marcy and Butler 2000). This implies that there are many low mass planets yet to be discovered.

- There is a hint that planets are mainly found around stars with metallicities greater than or equal to that of the Sun (Gonzalez, Wallerstein and Saar 1999). Is this an important clue for planet formation?

- Why do all the planets with a semi-major axis of their orbit larger than 0.2 AU have distinctly non-zero orbital eccentricities (Marcy and Butler 2000)?

- What is the chemical composition of these planets? Are the massive planets similar to Jupiter and Saturn?

- Three companions have been identified around HD 9826 (Marcy, Butler and Fischer 1999); are multiple planets common?

To answer these questions one must increase the sample of known planets.

Currently, the most successful technique to find extrasolar planets has been that of very high-precision radial velocity measurements; a typical rms scatter of 3 m/s has been achieved at Keck (Vogt, et al., 2000) and 7 m/s at European Southern Observatory (Santos, et al., 2000). To date, the surveys at Keck have focused on main sequence stars from spectral type F7 to M5 that have estimated masses of 1.2 M_{Sun} to 0.2 M_{Sun}, respectively (Drilling and Landolt 1999). The lowest mass star with a known planet is Gliese 876, which has a stellar mass of 0.32 ± 0.3 M_{Sun} while its companion has a mass of 2.1 M_{Jup} / sin(i) (Marcy, et al., 1998).

While current telescopes are very successful at finding planets around relatively bright stars, CELT will be able to search for planets around fainter stars. We expect CELT will have a high-resolution optical spectrograph similar to the HIRES echelle spectrograph at Keck. We therefore imagine that with an aperture of 30 m CELT will be able to study objects that are about 2.5 mag fainter than the current limit for Keck observations. Since Keck is currently observing stars as faint as m_V = 11 mag, this implies that CELT will be able to study stars as faint as about m_V = 13.5 mag. The advantage of extending the search to fainter stars is that it is possible to search for planets around lower mass stars. As a result, since the minimum mass to detect a planet scales directly to the mass of the orbited star, if we can monitor lower-mass stars, we can hope to find lower-mass planets.

Because the number distribution of planets seems to increase toward the lower masses, the current data suggest that there are large numbers of terrestrial planets in the Milky Way. With CELT, we should be able to identify terrestrial planets around nearby M dwarfs. Since planets with masses as low as 0.25 M_{Jup} have been detected around stars of 1 M_{Sun}, by extending the survey to stars of 0.15 M_{Sun}, it may be possible to detect planets with masses as low as 0.04 M_{Jup}, which is 13 M_{Earth}. With a large sample of surveyed stars, it should be possible with current technology to detect planets with masses perhaps a few times that of the Earth, if CELT is built (see Figure 2-12).

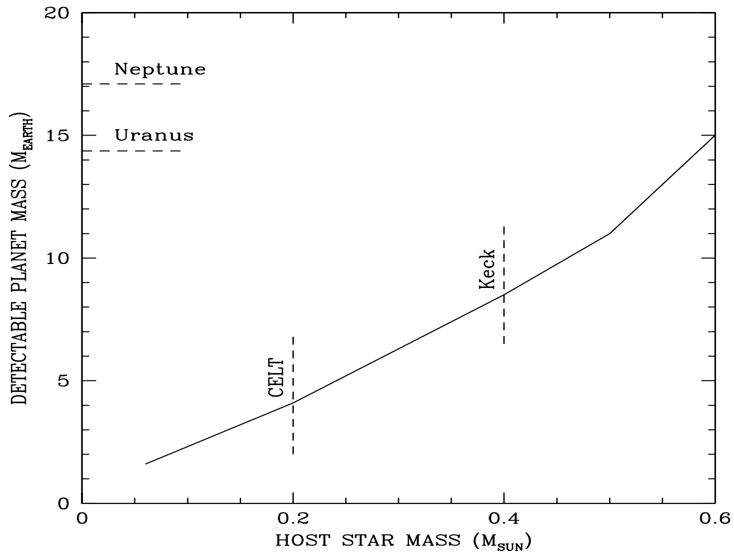

Figure 2-12. A plot of the minimum-mass planet that can be detected around a main-sequence host star, via radial velocity measurements, with the assumptions that the planet is a black body at 300 K, the orbital plane is viewed edge-on, and the star moves in a circular orbit with a speed of at least 3 m/s. (We choose T = 300 K so that the planet lies in the habitable zone and thus may possess life.) The dashed line for Keck is given by the constraint that the host star must be brighter than m_V = 11.0 mag. In the solar neighborhood, only stars earlier than M3 or about 0.4 M_{Sun} are found which satisfy this criterion. The dashed line for CELT assumes the same sensitivity, except now stars as faint as m_V = 13.5 mag can be studied. The larger telescope will enable searches for planets around stars as late as M5 or about 0.2 M_{Sun}. The Keck telescope appears to be restricted to searching for planets in the habitable zone that are ≥ 9 M_{Earth}, somewhat less than the mass of Uranus (14 M_{Earth}). With CELT, it may be possible to detect terrestrial planets of 3 M_{Earth} that lie in the habitable zone.

Assuming a random distribution of stars within the nearest 25 pc around the Sun, the number of sources that can be detected to a limiting flux, F, varies as $F^{-1.5}$. Because CELT can be used to study stars that are ~ 10 times fainter than is possible with Keck, then the sample of very low mass stars that can be studied with CELT is about 30 times larger than the sample that can be studied with Keck. For example, the catalog of nearby stars is maintained on the NSTARS web site (http://web05.arc.nasa.gov/nstars/). Among the 100 stars within 7.2 pc of the Sun, for stars brighter than m_V = 11.0 mag, there are two stars (Gliese 699 and Gliese 729) with estimated masses less than 0.2 M_{Sun}. However, for $m_V < 13.5$ mag, there are 30 stars with such low estimated masses.

Spectroscopic Study of Terrestrial Planets

If we are successful in detecting terrestrial-mass planets around nearby M dwarfs, then it may be possible to investigate spectroscopically the atmospheres of these planets, although the light from the central star will generally exceed that of the planet by a substantial amount.

As a representative example, consider a main-sequence star of mass 0.15 M_{Sun} with a luminosity, L_*, of 3 x 10^{-3} M_{Sun} yr^{-1}, an effective temperature, T_*, of 3200 K and a radius, R_*, of 1.3 x 10^{10} cm (Burrows, et al., 1993). Assume a planet of mass 3 M_{Earth} that lies at a distance, D, of 1.0 x 10^{11} cm from the star. Assume that the radius of this planet, R_{Planet} is $3^{1/3}$ times greater than that of the Earth, or 9.2 x 10^8 cm. If the planet is in a circular orbit at the most favorable inclination of 90^o, it would produce a total amplitude of radial velocity variation of the M dwarf of 17 m s^{-1}, which is easily measurable with current techniques.

If p denotes the geometric albedo of the planet, then the ratio ε of the observed flux from the planet to that of the star is:

$$\varepsilon = p\,(R_{Planet}/D)^2 \qquad (2\text{-}2)$$

The value of p depends on the amplitude and angular dependence of the various sources of scattering in the planetary atmosphere, integrated over the surface of the sphere (Charbonneau, et al., 1999). For a Lambert-law sphere, $p = 2/3$. Therefore, in this example, $\varepsilon = 5 \times 10^{-3}$. Charbonneau, et al., (1999) already have been able to measure a contrast between π Boo and its companion at this level ($\varepsilon = 5 \times 10^{-3}$) with Keck; therefore, a similar spectroscopic investigation of terrestrial planets with CELT is realistic.

There are other possible methods for performing spectroscopic studies of terrestrial planets. If the planet happens to eclipse the central star, as occurs with HD 209548 and its companion, then absorption lines produced in the atmosphere of the planet may be studied during the eclipse. Also, the duration and amplitude of the eclipse will allow a direct determination of the radius and albedo of the planet.

Spectroscopy in the mid-IR should be an important tool to study the planet's atmosphere. If the planet is at a distance of 10^{11} cm from the star, which is only a factor of 2.5 greater than the distance between the Earth and the Moon, it is likely that the planet's rotational period will be tidally locked to its orbital period. This means that the planet will always present the same face to the star it orbits. Consequently, although there will be a range of temperatures on the surface, the mean temperature on the illuminated side of the planet, T_p, if the albedo, w, is 0.3 will be given by the expression:

$$T_P^4 = (1 - w)\, L_* / (4\, p\, s_{SB}\, D^2) \qquad (2\text{-}3)$$

where s_{SB} is the Stephan-Boltzmann constant. With the parameters given above, then $T_p = 1000$ K.

Therefore, if we assume that both the planet and the star radiate like black bodies, the ratio of the thermal flux from the planet to that from the star is given by the expression:

$$F_\nu(\text{planet}) / F_\nu(*) = (R_p / R_*)^2\, (B_\nu\,[T_p] / B_\nu[T_*] \qquad (2\text{-}4)$$

At 10 μm, $F_\nu(\text{planet}) / F_\nu(*) = 9 \times 10^{-4}$. With an S/N of about 1000, it should be possible to measure the spectrum of the planet since in the mid-IR we expect that the spectrum of the planet and that of the central star are very different from each other. Furthermore, the planet's spectral lines will exhibit strong, periodic, predictable Doppler shifts that will provide an additional signature of light from the planet.

While we do not imagine life similar to that on the Earth to exist at 1000 K, the dark side of the planet will be much cooler. As a result, there may be a habitable zone on the surface of the planet.

One of the spectroscopic signatures of life on a planet might be the presence of O_2. This molecule is very difficult to measure from the ground. However, its daughter molecules, OH and O_3, may also be indirect signatures of the presence of biological processes in the atmosphere of an extrasolar terrestrial planet. We should be able to detect OH in the near-IR and O_3 in the mid-IR in the spectrum of such a planet. That is, although these two molecules are present in the Earth's atmosphere, they would exhibit a predictable velocity shift of 140 km s^{-1} with a period of ~ 0.5 days in the spectrum of the extrasolar planet. This predictable shift will enable us to separate the telluric lines from those intrinsic to the planet, and we will be able to measure the amount of OH and O_3 in the planet's atmosphere. These molecules may signal that life exists on the planet. With CELT, we will be able to begin a focused scientific search for signs of life elsewhere in our Galaxy.

Direct Imaging of Extrasolar Planets

A powerful complement to the indirect planet-detection techniques (radial-velocity measurements and astrometric measurements) and spectroscopic detection discussed above will be *direct* imaging of extrasolar planets themselves by resolving them from the parent star. Such detections would then allow photometry or spectroscopy of detected companions, allowing measurements of their composition and perhaps temperature, and allowing (for example) the rocky giant planets to be distinguished from small gaseous planets. It will also be an important step towards the direct imaging of true Earth analogs, as proposed by NASA's Terrestrial Planet Finder program.

Direct detection of extrasolar planets is extremely difficult. Jupiter is approximately a billion times fainter than the sun. Seen through the Earth's atmosphere, stars are surrounded by a diffuse halo of scattered light. The key to direct detection is to enhance the contrast of the planet relative to this halo. There are two regimes in which this will be possible with CELT: searches for young extrasolar planets through near-IR emission with a normal AO system, and searches for solar systems like our own using high-contrast "extreme" adaptive optics.

Direct Detection of Young Extrasolar Planets

The first regime for CELT direct planet detection is the search for *young* extrasolar planets; at an age of 10 million years, a Jupiter-mass planet would still have an effective temperature of 600-800 K, and be only a factor of 10^3 dimmer than a sun-like star in the near-infrared. Current 8-10-m telescopes with AO systems could detect such objects at separations of ~0.5-1.0 arsecs. Since the nearest populations of young stars (e.g, the TW Hydrae association) are ~ 50 pc from the Earth, this corresponds to a scale of 25 AU; it is currently unknown whether giant planets are common on such wide scales.

In this regime, the adaptive optics system does little to suppress the halo of scattered light, and sensitivity comes primarily from concentrating the light from the planet into a diffraction-limited spike. Based on current Keck AO performance and predictions of CELT AO performance we could therefore expect to detect young planets at separations of ~0.2-0.3 arcsec, corresponding to a scale of 10–15 AU. This opens up the possibility of seeing solar systems like our own in the process of formation, providing a direct test of the conventional planet-formation paradigm.

Detection of Extrasolar Planets in Reflected Starlight

The second regime for planet detection is a search for reflected starlight from Jupiter-like planets orbiting nearby stars. As mentioned above, conventional AO systems with sub-aperture size d = 50 cm have little effect on the scattered light halo. By the time CELT is a reality it will be possible to construct so-called "extreme" adaptive optics (EAO) systems with d = 5-1 cm, using new technologies such as MEMS deformable mirrors. Section 9.5.1 discusses the design and performance of such systems in more detail. Briefly, such systems massively suppress the scattered light halo to an intensity 10^6-10^7 of the central star, and with long (1-4 hr) integration times, could overcome noise from residual halo fluctuations and see Jupiter-like planets at 1-10 AU separations.

Deployed on an 8-10-m telescope, such a system would require stars brighter than m_R~ 3.5, limiting it to a handful of nearby stars. On CELT, such a system would operate to m_R~ 5-6, opening up ten times as many target stars and allowing for a large-scale survey, e.g., of all sun-like stars within 10 pc. As indirect techniques become sensitive to planets in wider orbits, this will also produce several cases in which planets detected by astrometric motions or radial-velocity variations are within reach of direct CELT AO imaging, an extremely powerful combination. It is even possible that around the nearest sun-like stars CELT could achieve contrast levels of ~ 4 x 10^{-10} at separations of 1-2 AU, sufficient to detect an Earth-like planet, thus paving the way for space-based spectroscopic follow-up.

Technical and Instrumental Requirements

The indirect planet searches described above require a high-resolution (R ~ 40,000) optical spectrograph, similar to the HIRES instruments on Keck. Spectral multiplexing is not important for this particular application.

The spectroscopic detection of planets requires diffraction-limited intermediate-to-high-resolution spectroscopy in both the near-IR (1-2.5 μm) and in the thermal-IR (5-12 μm).

Direct imaging of young extrasolar planets requires only the basic CELT AO system as discussed in Chapter 9, operated in either laser guide star or natural guide star mode, combined with an infrared camera similar to Keck's NIRC2, with a Lyot mask or other coronagraph. (Segment aberrations, if severe, may require a more sophisticated coronagraph.)

Detection of mature extrasolar planets orbiting nearby stars requires a full-fledged EAO system with 10^3 to 10^6 actuators; this daunting but exciting prospect is discussed in detail in Section 9.5.1.

The two latter projects place requirements on the telescope and site choice. The largest known populations of nearby young stars, such as the TW Hydrae association and Tucanae association, are located in the southern hemisphere from ~25 to ~70 degrees DEC. Although some young associations are being discovered further north, it appears that (for currently unknown reasons) the bulk of the nearby young stellar groups are in the south.

For the EAO mode, by contrast, the primary site consideration is seeing; EAO performance drops sharply with increasing r_0. An EAO system should be located at a site that experiences a significant number of nights with $r_0 > 50$cm in the I-band.

2.5.3 CELT and Star Formation

The development of the theory of stellar structure and evolution is one of the great achievements of twentieth century science. Yet this elegant theory that explains the life cycle of stars is incomplete in one critical aspect: It does not predict nor account for the formation of stars. Star formation plays a key role, at small scales, in the origin of our own Solar System; and at much larger scales, in the appearance, structure, and evolution of galaxies. However, it is the least understood aspect of these fundamental processes. Nonetheless, over the last quarter-century impressive advances in our understanding of star formation have resulted from the continued development of new technological observation capabilities from both the ground and space. During this period we have learned:

1. Stars form continually in our galaxy within the dense cores of giant molecular clouds.

2. The process of star formation is almost always accompanied by the formation of a circumstellar disk. By analogy with the Solar System this suggests that conditions suitable for planet formation may be a natural by-product of the star formation process and that planetary systems may be common in the galaxy. The recent detection of extrasolar planetary systems around a few nearby stars has provided support for that notion.

3. Star formation is a complex and dynamic process dominated by gravitational collapse, but is always accompanied by (and may even require) the energetic ejection of spectacular bipolar jets and outflows.

4. Stars tend to form in pairs, groups and clusters, but rarely in isolation.

Existing theories cannot simultaneously account for all these facts. Moreover, a number of additional mysteries still need to be solved before a credible theory of star formation can be constructed. Perhaps two of the most critical of these issues are: 1) identifying the physical factors that determine stellar mass, and 2) determining the origin of the initial mass function (IMF). Until these issues are resolved our knowledge of the entire life cycle of stars will be incomplete and our understanding of galaxies will remain on a shaky foundation. The physical process of star formation spans an enormous range in both spatial scale (~ 8 orders of magnitude) and density (~ 20 orders of magnitude), and although much has been learned in the last two decades, direct observations of various key stages has proved to be a formidable challenge. In particular, we have little knowledge of the critical processes that occur on relatively small physical scales (< 200 AU), such as the development of energetic bipolar jets, the growth and evolution of a protostar through accretion and infall of circumstellar matter, and the evolution of a circumstellar disk to form a system of planets.

CELT, working in concert with the NGST and ALMA, will have a profound impact in the upcoming decades on our understanding of the origins of both stars and planetary systems. Working at differing wavelengths and probing a range of angular scales (from 1-200 AU), these new facilities will provide a more detailed and comprehensive picture of the earliest stages of star and planet formation than has been previously possible. In particular, the angular resolution and sensitivity afforded by a diffraction-limited 30-m telescope such as CELT provides a unique opportunity to obtain spatially resolved observations of regions as small as 1 AU (at 1 μm) in the nearest protostellar clouds.

Observations with such a large telescope will yield information on:

- **The origin and nature of bipolar jets.** High angular and spectral resolution observations should be able to determine how close to the central protostar the jets are collimated and whether jets form as disk winds or are driven from close to the surface of the protostar itself. Detailed knowledge of the driving mechanism of such jets may be needed to assess whether such ejections regulate the mass of the star and the form of the IMF in the star formation process.

- **The structure and nature of protostar.** High-resolution spectroscopy at near-infrared wavelengths would probe the velocity/density structure of protostellar environments on scales from a few AU down to the stellar surface (even in seeing-limited mode). Protostars gain mass through infall and disk accretion; disk accretion is believed to dominate in the inner regions. However, the nature of the accretion mechanism is unclear. Does material accrete directly from the disk onto the stellar surface or instead along dipole field lines from a truncated disk? Is the accretion steady or episodic?

Is the accretion path the same in protostars as in pre-main sequence stars? Detailed observations by CELT of the inner regions of the protostellar disk and envelope are essential to answering these questions. In addition, the added sensitivity provided by the increased light-gathering power of CELT will enable measurement of the photospheric absorption lines from protostellar atmospheres that are too heavily veiled to be easily detected with smaller telescopes, even with high spectral resolution. This will enable direct measurement of such physical properties as the effective temperatures, surface gravities, rotation rates, and even accretion energy of protostars, and will critically constrain protostellar theory.

Figure 2-13. The dynamics of both binary stars and disks can be used to measure the masses of young stars, and thereby calibrate the pre-main sequence evolutionary models that currently produce widely discrepant results towards lower masses. The figure shows a simulation (provided by M. Brown) of H2 emission (at 17 μm) from a disk with a 0.5 M_{Sun} star (left) compared to the view of an 0.8 M_{Sun} star (right). In all cases the star is located at 50 pc. In the image, wavelength runs left to right, distance up and down. The full extent of the visible disk is 100 AU in radius with 12 AU per pixel. The velocity scale has 1.5 km/s per pixel. CELT (bottom) compared to Keck (top) observations clearly show how the factor of 3 resolution increase is key. By observing regions closer to the central star we will observe regions of higher velocities, and thus will more easily and more accurately measure rotation speeds.

- **Protostellar companions and masses.** High angular resolution imaging and spectroscopy will permit the measurement of the frequency, separations, and orbital motions of binary companions to protostars and more evolved young stellar objects (such as T Tauri stars) on scales of 1-5 AU in the nearest star forming regions. This would yield the first direct determinations of protostellar masses, knowledge of which is fundamental to the development of a complete theory of protostellar formation and evolution (see Figure 2-13). Moreover, determination of the frequency of protostellar companions is vital to understanding the process of star formation and the survivability of protoplanetary disks.

- **Disk structure and chemistry.** CELT will provide both the spatial and spectral resolution needed to investigate the physical and chemical structure of disks. For instance, the majority of the mid-infrared emission from a protoplanetary disk is confined to the inner circumstellar regions (r < 20 AU). The improvement in angular resolution with CELT will allow the first spatially-resolved mapping of the dust structure and chemistry of young disks in the region where planetary systems are thought to form (see Figure 2-14). For both these disks and the older debris disks (for which the first spatially resolved images have recently been obtained, Figure 2-15), maps of the thermal emission at mid-infrared wavelengths, or scattered light at near-infrared wavelengths, have the potential to reveal gaps and spiral arms in the surface density caused by gravitational interaction with embedded protoplanets. For instance, Jupiter would have first cleared the primitive solar nebula to form a gap of ~1 AU at an orbital radius of 5 AU. This would be detected at the distance to the nearest star formation regions (d = 150 pc).

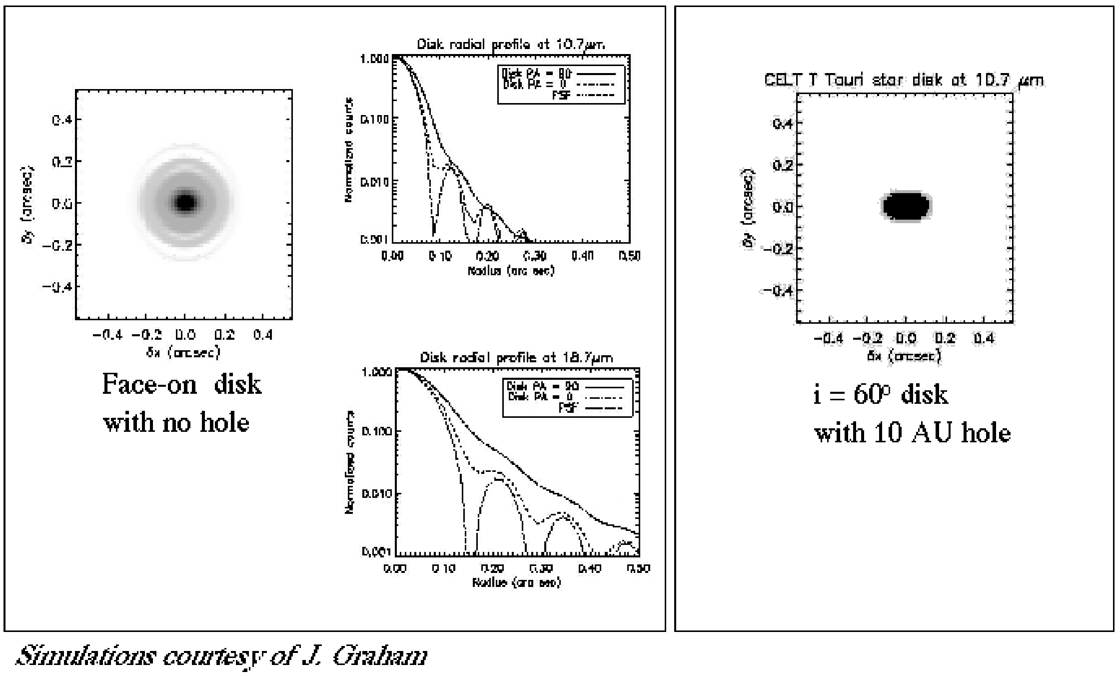

Figure 2-14. Simulations of mid-infrared observations of a disk surrounding a young low mass (T Tauri) star. The disk extent is clearly resolved and detailed structure such as a 10 AU gap can also be detected.

Technical and instrumental requirements

The instrumental requirements for star formation studies with CELT fall into two categories: high-order AO-based imaging and spectroscopic observations in the 1-5 μm range, and diffraction-limited imaging and spectroscopy in the thermal-IR (5-30 μm). In the near-IR a relatively narrow field, high Strehl AO imaging system, and the ability to do spatially-resolved spectroscopy (e.g., using an IFU) would be ideal. It is not foreseen that a patrolling multi-headed IFU system, or a particularly wide AO-corrected field, would be essential for most star formation science.

The requirement for the thermal-IR observations has the potential for acting as a much stronger driver for aspects of the telescope and low-order AO system design, as well as for the choice of the CELT site. With the exception of the 10 μm atmospheric window, which is quite transparent (see Section 2.3.2 above), the thermal-IR transmission depends critically on the water vapor content in the atmosphere. The best terrestrial sites average 1 mm of precipitable water vapor or less (e.g., Mauna Kea and sites in the high Andes in Chile); other sites that have been developed recently (e.g., Cerro Paranal in Chile) have much worse statistics. The water vapor content is strongly correlated with the altitude of the

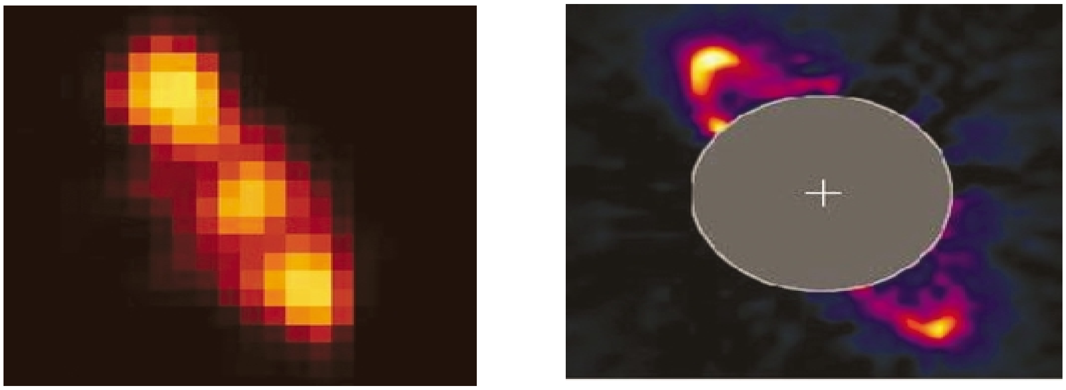

Figure 2-15. Direct images of the debris disk around the main sequence A star HR 4796, which show both the advantage of high spatial resolution and the interplay between ground- and space-based facilities. On the left is a mid-infrared (24.5 μm) image from the Keck Telescope of the thermal emission from the disk. On the right is a near-infrared (1.1 μm) image taken with NICMOS aboard Hubble Space Telescope, which detects the disk in light scattered from the central star. With CELT, much higher resolution images could be obtained of these disks around A stars, and of disks around lower mass and younger stars that are currently unobtainable.

observatory. As discussed above in Section 2.4.2**,** the thermal IR observations with CELT cannot compete in raw sensitivity with NGST, but all of the science discussed above is driven by the five times higher spatial resolution afforded by CELT, and by the ability to obtain very high spectral resolution mid-IR spectroscopy.

Two different mid-IR instruments are suggested: a 5-30 μm imager, and a 5-30 μm spectrograph capable of R ~ 100,000. As discussed in Section 9.5, there are several concepts being explored for a mid-IR optimized AO system and focal position. The emissivity of the telescope combined with the AO system may be prohibitive if the same AO system is used in the thermal-IR as in the near-IR.

2.5.4 Nearby Galaxies: Chemical Evolution and Star Formation Histories

Introduction

The vast majority of galaxies are studied in the merged light of millions or billions of stars and other glowing gases. In our own Galaxy, on the other hand, we can study individual stars and have been able to construct a remarkably clear picture of the star formation history, the gradual buildup of elements higher in atomic number than helium, and the kinematic and dynamical processes that shape the Galaxy. There are still a number of unresolved issues in our understanding of the history of the Galaxy. One such issue is the relative contribution of a global initial collapse of gas and dust versus the incorporation of dwarf galaxies or galaxy fragments through tidal interactions (as predicted by hierarchical structure formation). Because stars with initial mass slightly lower than the Sun have lifetimes comparable to or greater than the age of the Galaxy, we have many examples of stars that formed in the initial collapse of the Galaxy as well as stars formed throughout the history of the Galaxy. This is what is known as the "fossil record" for Galactic history.

It is already known that the complement of dwarf galaxies around the Galaxy had their first burst of star formation synchronized remarkably well with that of the Galaxy. However, the subsequent star-formation histories and chemical enrichment histories are different in almost every case for the companion galaxies of the Milky Way. With HST and the Keck 10-m telescopes the first steps have been made toward detailed study of the fossil record of old stars in M31 and some of its companions. One very exciting capability of a 30-m telescope is the extension of detailed fossil record studies to other members of the Local Group and beyond.

Photometry

The color-magnitude diagram studies of star clusters and dwarf galaxy companions of the Galaxy have been used with great success to estimate distances, overall metallicity, and ages. Specific useful observations are:

- apparent level of the horizontal branch (HB) as a standard candle for distance measurements,
- slope and color of the red-giant branch (RGB) along with its intrinsic color width for estimating [Fe/H] and metallicity distributions,
- the apparent magnitude of the main-sequence turnoff (MSTO) for direct estimates of the age(s) of a stellar population, and
- the apparent brightness of the tip of the RGB for estimating distances.

The typical surface density of giants at the center of a dwarf spheroidal galaxy at the distance of Virgo is around 1000 per square arcsec. For seeing-limited observations this density makes observations of individual stars impossible. However, at the diffraction limit of a 30-m telescope this is less than 0.05 stars/resolution element at R. The local universe out to Virgo contains hundreds of dwarf galaxies, and many massive spiral and elliptical galaxies. The sample of objects for which we would have accurate estimates of star formation histories and chemical enrichment histories would go from the handful in the Galaxy's complement of dwarfs to hundreds, spanning a huge range in environment. Important issues that could be addressed are: the importance of local galaxy density in determining star formation history; the dispersion in the chemical evolution histories for galaxies of similar mass; and the very puzzling situation that galaxies apparently similar in total mass and environment can have very different histories of using and losing their initial gas content.

Moderate- and high-resolution spectroscopy

The chemical evolution history of a galaxy, or component of a galaxy is written in the details of the distribution of elements seen in the atmospheres of stars. Particularly with Keck high-resolution spectroscopy we are beginning to piece together the details of the chemical evolution of the Galactic halo going all the way back to the first epoch of star formation. The principal inputs are relative distributions of elements with different nucleosynthetic origins. With high-resolution spectroscopy limited to relatively bright stars with 10-m telescopes, the nearby galaxies are so far unexplored.

It is in the realm of $R > 5000$ spectroscopy that CELT will excel. There are a large number of open questions in Galactic stellar astronomy that have proven too difficult for the current 8-10-m telescopes. Extending abundance and kinematic studies for individual stars to other Local Group galaxies and beyond will be a very important strength of CELT. $R \sim 5000$ spectroscopy allows absorption-line velocities to be determined with a precision of 1 km/sec, and abundances of certain elements to be measured based on equivalent-width measures for individual transitions. For the I through H bands, this resolution is sufficiently high to resolve the OH emission of the sky and allow work in uncontaminated regions of the spectrum (see Figure 2-6).

Higher spectral resolutions (typically 25,000 < R < 60,000) are required for detailed chemical abundance studies that include elements throughout the periodic table and represent all of the nucleosynthesis paths in stars and supernovae explosions.

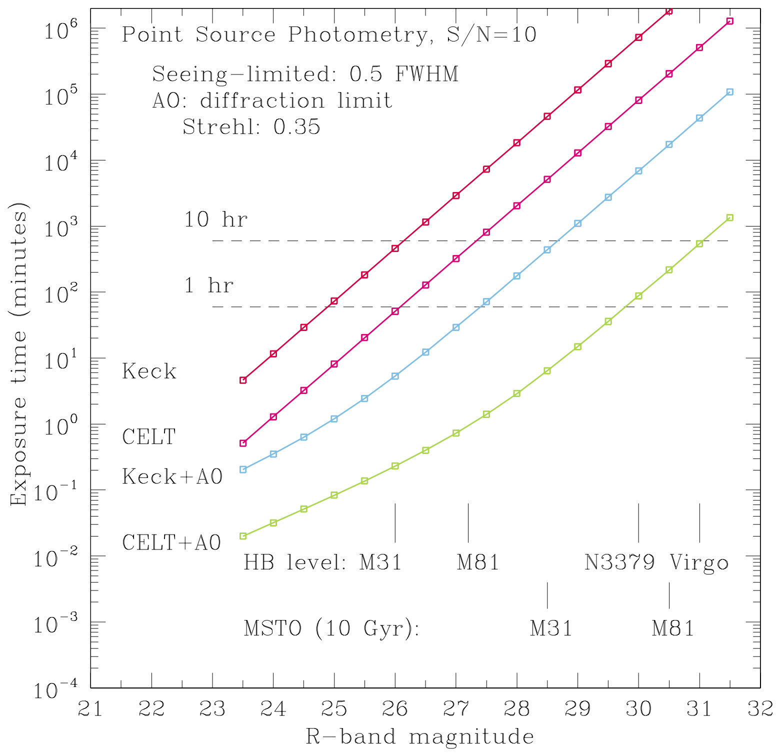

Figure 2-16. The integration time required for R-band imaging as a function of magnitude to reach S/N=10 for a 10-m telescope and 30-m telescope operating in seeing-limited and diffraction-limited modes. For AO correction at this wavelength a Strehl of 0.35 is assumed. Also shown is the level of the HB and an old population main sequence, as they would appear at the distance of M31, the M81 Group (4 Mpc), NGC 3379 in the Leo Group (10 Mpc) and at the Virgo Cluster (16 Mpc). For AO observations with CELT, RGB stars are relatively easily observed throughout the local universe to the distance of the Virgo cluster. The horizontal branch is accessible with some effort with CELT and AO in this same volume. Direct measurements of an old population's MSTO will be possible throughout the Local Group and at the distance of the nearest neighbor groups around M81, NGC 5128 and Cen A.

State-of-the-art observations of these kinds with 8-10 m facilities are limited to the nearest members of the Local Group (out to M31) for R ~ 5000 studies (kinematics and rough chemical abundances) of bright giants. Detailed abundance studies at higher spectral resolution are limited to V < 16 – giants in the halo and dwarf stars in the solar neighborhood only.

There are tremendous possibilities in these areas with CELT both in extending work in the Galaxy and moving out into the Local Group and for some projects into the nearby M81 (north) or Cen A (south) groups.

Specific areas that will have to await a 30-m telescope for further progress are:

- in situ detailed abundances for Galactic main-sequence globular cluster stars;
- the properties and number density of halo white dwarfs (currently thought to be a significant contributor to the Galactic dark matter halo based on the MACHO project);
- detailed abundance studies for giant stars in the outer Galactic halo, M31, the M31 dwarf companions, and M33;
- detailed abundance studies of early-type stars in low-metallicity environments (dwarf galaxies).

Technical and instrumental considerations

Direct imaging color-magnitude diagram studies require reasonably high Strehl observations (> 0.3) to 800 nm over modest fields (10-30 arcsec diameter). Traditional stellar abundance studies have been carried out shortward of 600 nm where there is an abundance of atomic absorption lines. Rarely are spectroscopy studies in this regime background-limited, and AO-fed spectroscopy does not result in significant gains. Much of the chemical abundance work described above would be carried out in the seeing-limited mode.

2.5.5 Probing Galactic Nuclei with CELT

Super-massive black holes are believed to provide the central engines that power the abnormally luminous galaxies called quasars (with luminosity exceeding 10 times that of a normal bright galaxy), and the somewhat less luminous, but still anomalously bright, galaxies called “active galactic nuclei” or AGNs. This insight was achieved more than two decades ago.

We are now learning that super-massive black holes are common at the centers of nearby galaxies, with masses ranging from 10^6 to 10^9 M_{Sun}. After years of work combining HST imaging with HST and ground-based spectroscopy, an incomplete census of ~35 super-massive black holes among the nearest galaxies has been assembled. The progress of this work was fueled by the recent installation of STIS on the HST, which offered long-slit spectroscopy with a narrow slit, thus enabling astronomers to take full advantage of the superb spatial resolution of HST in the spectroscopic mode.

As shown by Ferrarese and Merritt (2000), and also by Gebhardt, et al., (2000), there is a close relationship between the deduced mass of the black hole and the velocity dispersion of the host galaxy’s bulge. A summary of the current state is shown in Figure 2-17, and a prediction of M_{BH} is given, with surprisingly small scatter, by

$$M_{BH} = 1.2 \times 10^8 M_{Sun} (\sigma/200 \text{ km s}^{-1})^{-} \qquad (2\text{-}5)$$

where σ is the bulge velocity dispersion. This implies that the presence and ultimate size of the central black hole must be closely related to how the galaxy itself formed. A correlation with somewhat larger scatter between the black hole mass and the bulge luminosity of the galaxy,

$$M_{BH} = 0.9 \times 10^8 M_{Sun} [L_B \text{ (bulge)} / 10^{10} L_{BSun}] \qquad (2\text{-}6)$$

has been known for the past few years (Kormendy 2000). These relationships apply to galactic bulges, but *not* to galactic disks.

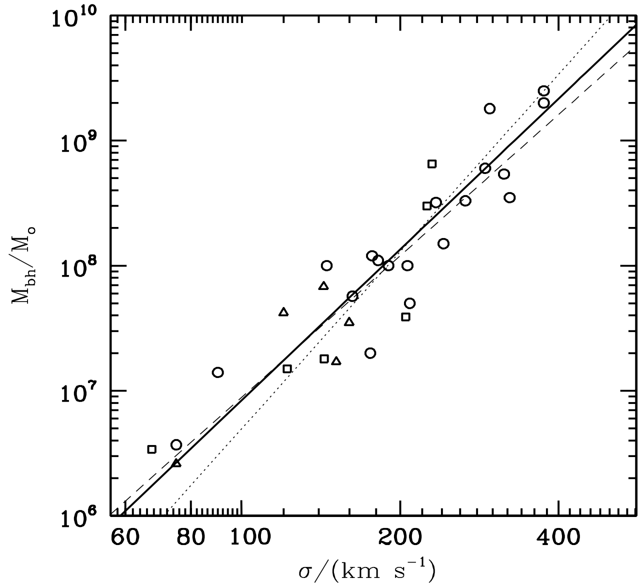

Figure 2-17. The empirical relationship between inferred black hole mass and galaxy central velocity dispersion (Gebhardt, et al., 2000).

This new insight suggests that most galaxies contain super-massive central black holes, but at the present time these are relatively inert and not being "fed" enough gas to produce high-luminosity central sources. This paradigm offers new possibilities for constraining the process of galaxy collapse and formation, and understanding the dynamics of the central regions of galaxies. Theoretical efforts are already underway to understand the relationship between central black holes and star formation rates, gas dynamics and other forms of feedback (Ciotti and Ostriker 1997, 2000; Blandford 1999; Silk and Rees 1998). We also want to understand the complex issues associated with transferring angular momentum outwards so that the central engine can be "fed" by infalling material from a massive accretion disk.

We believe that understanding the phenomena associated with super-massive black holes in the nearby universe, and exploring this phenomena in more distant galaxies are significant tasks for which CELT science will bring major advances. Kinematic estimates of the masses of central black holes in AGNs rely on either measurements of the rotation curves of gas circulating around the black hole or measurements of the velocity dispersion of the stars in its close vicinity. In either case, the high spatial resolution of CELT will be critical to such studies.

AGN Accretion Disk Sizes and Spatial Resolution Issues

In the case of QSOs and Seyfert nuclei, the central black hole is fueled by an accretion disk that is responsible for thermal radiation at a temperature of around 20,000 K, and produces the "big blue bump" at around 2500 Å on top of the power law continuum due to synchrotron radiation. The size of the optical disk is about 10^{14} cm for a typical Seyfert galaxy and 10^{16} cm for a QSO. The broad emission lines characteristic of QSOs and Seyfert galaxies are produced in a region about ten times bigger than the optical disk, although the relationship between the two phenomena is not understood.

These structures immediately surrounding the central engine and responsible for its radiation cannot be resolved by even a 30-m telescope.

Black hole masses, on the other hand, can be determined using a number of techniques. The first is the dynamical perturbation introduced by the central super-massive object. The presence of a central black hole is deduced from a rise in the velocity dispersion of the stars as the central point mass begins to dominate the gravitational potential. For a black hole of mass M_{BH} in a galaxy with a stellar velocity dispersion of $\sigma_V = 300$, this happens at a radius r_D such that $GM_{BH} / r_D \sim \sigma_V^2$ or $r_D \sim 6$ pc for $M_{BH} = 3 \times 10^9 M_{Sun}$. The perturbation to the central velocity dispersion can be measured out to radii $r \sim 10\, r_D$ (depending on the surface brightness of the stellar bulge), or perhaps ~ 60 pc (about 0.6 arcsec at the distance of the Virgo cluster). This scale is so small that for higher redshifts or smaller black hole/ galaxy masses, and given the preponderance of nuclear star formation at earlier cosmic epochs, most of the measurements are likely to be based on gas dynamics of the nuclear disks rather than on traditional measures of stellar velocity dispersion.

HST observations have shown that many local AGNs have a relatively large rotating disk of emitting gas which is responsible for spatially unresolved sharp emission lines observed in ground-based spectra. As an example, the emission line disk seen in M87 by HST is about 150 pc in diameter and is believed to feed a black hole with mass $3 \times 10^9 M_{Sun}$. (The black hole mass deduced from the rotation of the accretion disk gas agrees with that obtained from observations of the velocity dispersion of the stars in the vicinity of the center of M 87.) A recent study by Sarzi, et al., (2000) of 24 nearby AGNs using HST/STIS revealed evidence for emitting gas in the majority of the objects. In a substantial minority the velocity field was sufficiently symmetric to be attributed to rotation and the mass of the central black hole could be estimated. These emitting disks range in size from a few pc to as large as ~ 150 pc for the most massive black holes.

The spatial resolution of CELT, if diffraction-limited, will be $\theta = \lambda / 30\text{ m} = 3.3 \times 10^{-8} (\lambda / 1\ \mu\text{m})$ radians, which corresponds to 0.007 (λ/ 1 μm) arsecs. At a wavelength of ~ 1 μm, this corresponds to a spatial resolution of 0.5 pc at the distance of the Virgo cluster, and 35 pc at $z = 0.5$ (at which point the Hα line is redshifted into the 1 μm window). Thus, it may result that black hole demographics can be extended, especially for the most massive cases, to cosmological redshifts. Because the physical scale corresponding to a fixed angular resolution changes only very slowly beyond $z \sim 0.5$ (see Section 2.4.6: even at $z \sim 3$, the CELT resolution element at 1 μm corresponds to ~ 60pc), *the CELT diffraction-limited angular resolution may well be high enough to resolve nuclear disks around super-massive black holes to the highest redshifts.*

The range of sizes and rotation speeds of these outer gaseous disks is not known; it is also not known if they exist around the central engines of QSOs. A search for such structures in both active and quiescent galactic nuclei would be a prime subject for CELT. In any case, the high spatial resolution of CELT will allow unprecedented ability to discern non-stellar nuclear activity in galaxies at all redshifts for which they can be detected (perhaps $z \sim 5$).

Technical and instrumental considerations

An integral-field spectrograph operating under diffraction-limited conditions would be ideal for this application. There is no need for multiple movable probes, but rather for coverage by a single IFU over an area as large as possible, and certainly not less than 2 x 2 arcsec. The velocity resolution required, given the intrinsic stellar velocity dispersion of galactic bulges and the rotation speeds of the disks, is ~ 30 km s^{-1}, for a spectral resolution of R = 10,000.

Direct imaging, both through narrow- and broadband filters, at the full diffraction-limited spatial resolution over a field at least 10 x 10 $arcsec^2$ will also be required in order to help disentangle stellar and nebular components in the galaxy centers.

Future developments in extreme AO (i.e., extending AO capabilities into the optical) have the potential to increase the resolution by a factor of 3-4 over that in the near-IR and could conceivably improve sensitivity to nuclear activity as well, allowing access to nuclear black hole studies for even intermediate mass black holes during the "epoch of galaxy formation" at z ~ 1-4. This capability would provide access to black hole statistics during the very time that the stellar bulges are being formed, allowing a direct assessment of the origins of the correlations seen locally.

2.5.6 Diffraction-Limited Studies of the History of Galaxies: The z = 1-5 Universe

It is anticipated that a major activity of the next decade for the current 8-10-m telescopes will be surveys and global statistics of galaxies and QSOs as a function of look-back time, and that substantial progress will have been made by 2010. Placing these objects into a cosmological context, and understanding both obvious and subtle forms of evolution as a function of time, will require delving into the detailed astrophysics of individual galaxies. This would involve measuring small-spatial-scale internal kinematics, chemical abundances, abundance gradients, gas-phase physical conditions, stellar content, sub-kpc morphology, etc., all as a function of large-scale environment and of cosmic time.

There is little question that NGST will in most cases be the preferred facility for observing galaxies at $z >> 5$, where the most important diagnostic features in the spectra of galaxies move into the thermal IR; and for opening up the currently unexplored "dark ages" prior to reionization. Beyond 2.5 μm, the improved spatial resolution from a 30-m ground-based telescope will be nullified by the prohibitive background for faint object science (see Section 2.4). However, for tracing the evolution of galaxy populations over the period of cosmic history most important in forming the stars and metals present in the universe today, more modest redshifts -- but significantly greater spectroscopic capability -- are required. As discussed in Section 2.4, at high spectral resolution ($R \geq 5000$), the terrestrial background in the 0.8-2.5 μm range can be reduced to within a factor of ~10 of that in space, as the bulk of the background comes from very narrow OH airglow lines and not from thermal emission. Coincidentally, this is also the regime in resolution where spectroscopy opens up new possibilities for studies of distant galaxies. These include measuring the relationship between luminosity and mass and measuring the chemical properties of galaxies. These will be made using nebular line diagnostics, the rich interstellar absorption line spectrum in the rest-frame UV, and through the integrated stellar light. These observations will be necessary for understanding galaxy formation and evolution and how they are related to the development of large-scale structure of the universe.

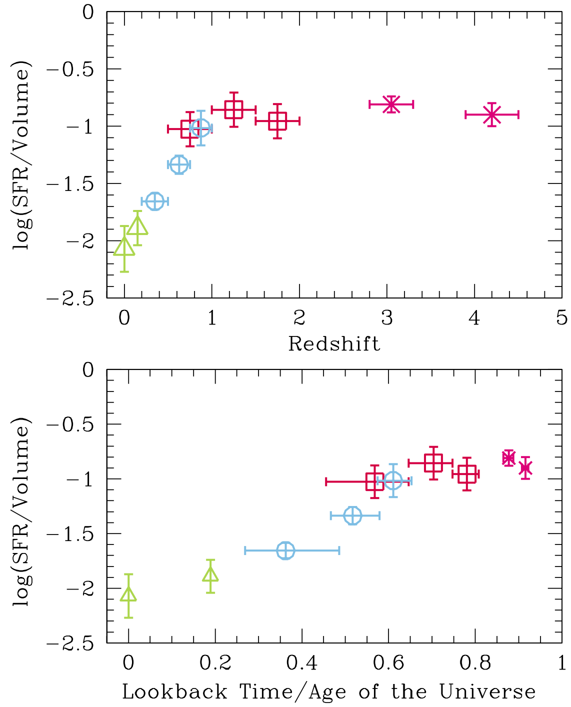

Figure 2-18. Two views of the star formation history of the universe, based on current data. Note in the bottom panel that there is essentially no cosmic time prior to z ~ 5. NGST will explore the very high redshift universe; large surveys for galaxies in the redshift range 1 < z < 5 will be carried out using 4-8-m class survey telescopes and 8-10-m telescopes for follow-up spectroscopy over the next decade. A 30-m, diffraction-limited telescope will provide detailed access to the chemical and dynamical history of the z = 1-5 universe through spectroscopic and imaging capabilities that will be unparalleled.

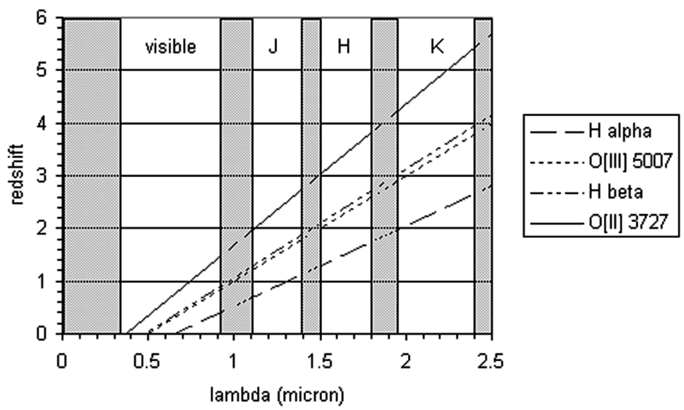

Figure 2-19. Plot showing the accessibility of important diagnostic spectral features as a function of wavelength and of redshift. The nebular emission lines of [OII], [OIII], Hb, and Ha are expected to be important for measuring both chemical abundances and kinematics of galaxies during the z = 1-5 cosmic epoch, and have the advantage of increasing the detectability of galaxies by a factor as large as 5 magnitudes. The brightest objects at these redshifts will be amenable to spatially resolved continuum spectroscopy, capable of yielding information on (e.g.) stellar abundance, age gradients, and stellar velocity dispersions.

Ideally, one needs spectral resolution of R ≥ 5000 in order to resolve the rotation curve or velocity dispersion of a (potentially) low-mass galaxy. The typical half-light radius of galaxies in this range of redshift is ~ 0.2-0.3 arcsec. We do not know at present if these galaxies are rotationally supported, as resolved spectroscopy is currently difficult or impossible. Adaptive optics on 8-m class telescopes will allow (with a great deal of effort) diffraction-limited images of these distant galaxies that will be significantly better than those achieved so far using the HST; however, they will generally lack the sensitivity to exploit the spatial resolution with spectroscopy. The physical measurements allowed by high-dispersion spectroscopy are key for relating one observed epoch to another, and for connecting theory to observation. Detailed spectroscopy at high spatial resolution will be capable of revealing the physical processes behind the observed morphologies.

With a 30-m diffraction-limited telescope we will be able to achieve the same kind of spatial resolution on a galaxy at z = 1-5 as can presently be achieved at the distance of the Virgo cluster with typical seeing-limited resolution (~ 50 pc per resolution element). This would place as many as ~ 50 resolution elements across a typical compact galaxy at high redshift. These galaxies currently appear as small "fuzzballs" even at HST spatial resolution of ~ 0.1 arcsec. We expect that at much higher spatial resolution they will break up into very small, luminous "knots," making it possible to measure chemical abundances for individual star clusters/giant HII regions, trace the kinematics of large-scale outflows across the face of the galaxies (using the interstellar absorption lines against the UV continuum produced by massive stars), and see whether the overall kinematics of the galaxies are chaotic or follow an underlying ordered motion. It should, therefore, be possible not only to measure the masses of the (generally) compact galaxies observed at high redshift, but also to delve into the detailed baryon physics that controls the appearance and evolution of the galaxies.

The 0.6-2.5 μm range will contain information on the far-UV to the optical/near-IR for galaxies in the redshift range $1 \leq z \leq 5$. This range-of-rest wavelength contains information about the most massive stars, the physics of the interstellar medium, the chemical abundances in HII regions, and the stellar features most commonly used to measure velocity dispersions and age-sensitive line indices for nearby galaxies. The 30-m diffraction-limited telescope will essentially allow *diagnostic* study of galaxies during the epoch of galaxy formation that is equivalent to the current state-of-the-art study of nearby galaxies.

There are several outstanding questions that might be answered. When did galactic bulges form? Are distant galaxies rotationally supported? What controls the decline in the global star formation rate that begins at $z \sim 1$? What is the mass function (as opposed to the luminosity function) of distant galaxies? How much metal mass is ejected from galaxies during their robust star-forming phase, polluting the IGM? Are chaotic morphologies really indicative of mergers, or are they a natural consequence of rapid star formation? What has been the influence of the large-scale environment on the detailed evolution of galaxies? What controls the epoch when recognizable spiral disks appear? Answers to all of these questions require a combination of spectral and spatial resolution (and the necessary sensitivity when operating in this mode) that is beyond the capabilities of either 8-10-m telescopes *or* NGST.

Practical Issues and Limitations

How will CELT with AO complement and compete with NGST and ALMA, the forefront new facilities that will become operational on roughly the same timescale?

The issues of sensitivity for CELT and NGST are reasonably clear, and are summarized in Section 2.2 of this document. CELT is inferior in sensitivity relative to NGST longward of 2.5 μm, but achieves superiority for any spectroscopic applications shortward of 2.5 μm. ALMA will be superior to CELT for studying the molecular gas content of high redshift galaxies, and for studying the thermal dust continuum in the observed-frame sub-mm. Here we consider the efficacy of AO-fed observations in the 1-2.5 μm range with CELT.

Galaxies are *not* point sources, and the strength of any general statement one can make is based on the statistics of the sample rather than on any spectacular single observation. Just to set the stage, following is a summary of the spatial resolution of CELT and NGST and the projected physical scales at a variety of redshifts. The assumed cosmology is $\Omega_m = 0.3$, $\Omega_\lambda = 0.7$, h = 1.

Table 2-2. Resolution versus Redshift at 2 μm

Redshift (Z)	**Scale** (kpc/arcsec)	**NGST** (diff limit)	**CELT** (diff limit)
0.5	4.3	350pc	70pc
1.0	5.5	450pc	90pc
2.0	5.9	475pc	95pc
3.0	5.4	450pc	90pc
4.0	4.9	400pc	80pc

We already know that the bulk of galaxies in the universe at $z > 1$ have very small physical sizes, with half-light radii on the order of 1-2 kpc. This means that the 0.06 arsec resolution of NGST at 2 μm will barely resolve such objects. With CELT resolution we can place 10-20 resolution elements across a typical compact high redshift galaxy. We do not know what these objects will look like at such high spatial resolution, and the gains with AO will depend strongly on this unknown. We have hints, however, from starburst galaxies in the relatively local universe, that the compact galaxies will become resolved into a number of "super star clusters." The spatial resolution of CELT/AO approaches the physical size of individual HII regions in the local universe.

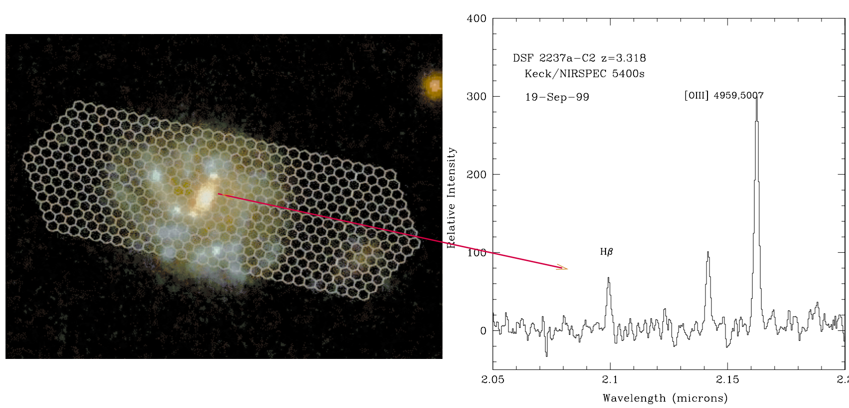

Figure 2-20. The proposed most-efficient mode of observing faint galaxies with CELT will involve integral field spectroscopy, where multiple IFU "units" can be deployed on interesting objects within the AO-corrected field of view. 3-D spectral maps are produced, where each spatial sample within an IFU unit is recorded as a separate spectrum on the detector, as shown schematically in the right hand panel. The quality of the spectrum on the right is roughly that expected for an average 0.05 x 0.05 arcsec:spatial sample on a galaxy at z ~ 3 (although the spectral resolution we are proposing is ~ 3 times higher).

This is interesting from a morphological perspective for galaxies in the redshift range z = 0.5-5 or so; however, the biggest gains of CELT will likely come from (multiplexed) integral field spectroscopy behind AO (see Figure 2-20). The advantages of a ground-based telescope with a large aperture are very clear for spectroscopy, particularly at spectral resolution R ≥ 5000, for several reasons. We have already discussed how high resolution effectively lowers the background by ~ 2 orders of magnitude by resolving out the OH emission. In addition, NGST will most likely not have spectroscopic capability of R >1000. This corresponds to a maximum resolution of ~ 300 km s^{-1}, and while adequate for measuring redshifts of extremely faint galaxies, it is not suitable for detailed kinematics of halos having circular velocities typically in the range 30-200 km s^{-1}. The capability of achieving ~ 80 pc spatial resolution on galaxies in the z = 0.5-5 universe could very well revolutionize the study of very distant galaxies if the resolution is feeding a moderate to high dispersion spectrograph, allowing for spatial dissection into individual knots with accurate velocities and chemistry accessible for each one.

In general, low-resolution (i.e., identification-quality) near-IR spectroscopy of faint objects that are not point sources will be better done with NGST. The CELT/AO limits for faint galaxy spectroscopy will depend very sensitively on what the galaxies look like at 80pc (0.16 arcsec) resolution at 2.2 μm. In the worst case that galaxies are smooth on scales smaller than ~ 0.2 arcsec (the limit of current near-IR images from either ground or NICMOS), then experience with Keck suggests that spectroscopy of objects with K ~ 22.5 should be possible for emission line studies using CELT. Continuum studies might be extended to K~ 20.5 if the observations are background-limited. In the case that our putative galaxy is resolved into many pieces spread over 0.2-0.3 arcsec, it is conceivable that one could reach magnitudes as faint as K ~ 24-25 for successful emission line spectroscopy. This type of observation would be best done with an integral-field-like configuration, where one could focus only on the regions that exceed a certain S/N (unknown a priori). While these limits are still 5-6 magnitudes brighter than the faintest galaxies that deep NGST images will uncover, *they extend to several magnitudes fainter than L* for all redshifts* z = 1–5.

Even at K ~ 22.5 the surface density of galaxies is ~ 50 $arcmin^2$, so that a 1 armin field AO system would include as many as 50 potential spectroscopic targets, and perhaps many more than that. (If one is targeting a particular redshift or range of redshifts then the number will go down significantly, e.g., the number of z = 2-2.5 galaxies in that same collection of 50 would be on the order of 5.) Given the likely limits for spectroscopy with CELT/AO in the near-IR, most of the targets could be easily selected with Keck images, as long as the selection can be done in the optical or near-IR (i.e., no need for NGST). Most of the objects imaged by NGST would be out of the reach of CELT for spectroscopy. We conclude that the CELT AO field size should be driven by science considerations *other than* complementarity with NGST, and even 1 arcmin fields would be scientifically interesting for AO-fed integral field spectrographs. Obviously, larger fields would mean more science per unit integration time.

Note that measuring redshifts for most objects in this same redshift range that have strong spectroscopic features falling in the 1-2.5 μm range can be trivially accomplished using seeing-limited observations in the optical (using CELT, e.g.). The primary purpose of the AO-fed near-IR observations would generally be physical measurements of, e.g., chemistry and kinematics, rather than simply measuring redshifts. In Section 2.5.7 we discuss how optical observations of galaxies at similar redshift will provide complementary data on the physics of massive star formation, galactic winds, and the intergalactic medium; see Section 2.5.8 for a discussion of CELT observations of the "dark ages" prior to z ~ 5.

Instrument Requirements
A summary of the requirements for AO-fed faint galaxy science:

- **Deployable IFUs**: Most of the sky is blank at CELT/AO resolution and there will be perhaps tens of objects per square arcmin within the sensitivity range of CELT spectroscopy. Each IFU need only sample perhaps 1 to 2 arcsec "patches" of sky, feeding a moderately high dispersion R ~ 5000 spectrograph. One does not know a priori how finely one would want to sample spatially on the detector or with the IFU spatial element. In many cases full diffraction-limited resolution may be overkill; depending on the detector characteristics, one might want to have options for spatial sampling to feed the spectrograph.

- **Imaging mode**: An imaging mode covering the 1-2 arcmin AO-corrected field (envisioned to be the maximum in the 1-2 μm range) would be potentially very interesting, but probably less important than the ability to efficiently feed a spectrograph. The "deployable IFU imager" discussed in Section 10.5.3 seems particularly attractive in this regard.

- For faint galaxy science, capabilities beyond 2.5 μm are not deemed important.

2.5.7 Wide Field Science with CELT

The baseline design for CELT provides access to a ~ 20 arcmin field with good images, similar to the Keck telescopes. While at first glance it would seem that the largest gains provided by CELT would be in the near-IR where AO can provide diffraction-limited images, there is a large body of exciting science that takes advantage of the huge gain in spectroscopic throughput (particularly in the 0.3-0.8 μm range where the background is low even at low-to-moderate spectral resolution) afforded by the order-of-magnitude gain in collecting area. If the challenge of building instruments that can take in the whole of the CELT 20 arcmin field can be met, there are huge leaps forward to be made, particularly in our understanding of the evolution of the large-scale structure of the universe.

There is a rich variety of science programs where seeing-limited (or perhaps ground level turbulence-corrected) observations over the full CELT 20 arcmin field will be extremely important. The 30-m aperture of CELT brings objects roughly ten times fainter within reach for moderate-to-high dispersion spectroscopy in the optical; there are many classes of objects whose surface density on the sky is 100 or more times larger at CELT limits compared to (e.g.) Keck. These are the areas where CELT will truly revolutionize wide field spectroscopy. We explore one of these areas below, in order to motivate by example the kind of wide-field instrumental capabilities desirable for CELT.

Galaxy/IGM Connection at High Redshift
By the end of the current decade, we will have very robust constraints on the distribution of galaxies over the redshift range $0 \le z \le 1$, largely through ambitious surveys on 4-8-m class telescopes (e.g., the Two Degree Field Redshift Survey, the Sloan Digital Sky Survey, the Keck DEEP survey, the VLT VIRMOS survey, etc.). CELT will enable us to extend this kind of detailed mapping of the universe to the redshift range $2 \le z \le 4$, an epoch during which we believe a large fraction of the stars presently seen in galaxies were formed, and where the structures seen at $z < 1$ will be in the early stages of assembly. As we describe below, the insight into the evolution of the entire baryonic component of the universe, and its connection to the underlying distribution of dark matter, may be best attained at these high redshifts, using the unique capabilities of CELT.

Most of the baryons in the universe are believed to be distributed in the form of diffuse gas in the intergalactic medium, a component that has not been observed in its own emission but can be very sensitively observed using background probes in whose spectra the Lyman α line of hydrogen is recorded in the rest-frame UV. Lyman α absorption line studies can detect quantities of neutral hydrogen that are more than seven orders of magnitude smaller than required for detection via emission in the 21 cm line. The Lyman α line is observable from the ground for redshifts $z \geq 1.6$. The undulations in the neutral hydrogen content of the universe along each line of sight to a suitable background source are recorded in the form of a spectrum of the so-called “Lyman α forest.” At present, sensitive probes of this dominant intergalactic baryonic component are limited to rare high redshift QSOs, whose surface density on the sky at magnitudes attainable using Keck is very low (much less than 100 per square degree), so that at best only one-dimensional information is accessible. Key to the huge amount of progress that could be made with CELT is that the surface density of suitable background probes depends extremely sensitively on apparent magnitude, and that with a 30-m aperture the number of background targets increases by more than two orders of magnitude. This high density of background probes allows tracing of the three-dimensional distribution of diffuse gas at high redshift. When combined with faint galaxy surveys in the same cosmic volume, which are also enabled with CELT and a 20 arcmin field, a nearly complete census of cosmic baryons, and deep insight into the galaxy formation procåCs and its connection to large-scale structure in the universe, comes within reach.

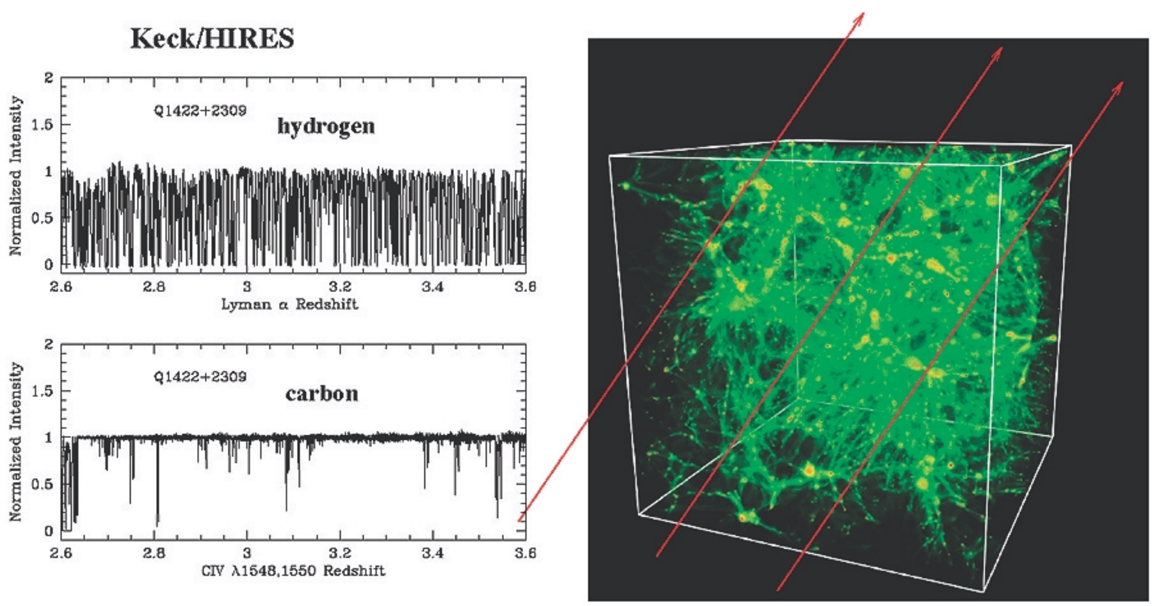

Figure 2-21. An illustration of how multiple lines of sight through a volume of the universe at high redshift (in this case, a hydrodynamic simulation produced by the Princeton cosmology group) can be used to map out the 3-dimensional structure. Each line of sight yields detailed 1-D maps of the H I in the IGM, as well as the associated metal lines, as shown in the panels on the left. CELT allows dense sampling of the IGM because background galaxies can be used, rather than QSOs (which are much rarer).

In Figure 2-21, we sketch a program of observations with CELT that would be capable of surveying both the galaxy distribution and the diffuse intergalactic medium over volumes that are large enough to provide an accurate measure of clustering statistics and characterize the largest structures at $z \sim 2\text{-}3.5$. The program would provide a huge range in environment, enabling detailed testing of assertions that the Lyman α forest traces mass fluctuations and that galaxies trace the same fluctuations but in a much more biased way (the level of bias can in principle be measured directly from these observations, as well). The survey will also allow a detailed map of where the metals are relative to the galaxies, testing ideas about the baseline metallicity in the IGM and where it originated.

The 3-dimensional structure of the IGM has become a focal point for much cosmological theory because the gas giving rise to the Lyman α forest is expected to provide a nearly direct mapping of the total matter distribution (see Figure 2-21). This assertion is based on the application of the so-called "fluctuating Gunn-Peterson approximation," the idea that diffuse baryons in the Lyman α forest trace regions within a factor of ~10 of the mean density of the universe. The "equation of state" of this diffuse H I is simple enough that the H I optical depth should be a monotonic function of the line-of-sight mass density. In this way, "tomography" of the IGM (via multiple lines of sight through any survey volume) should be capable of tracing out the overall mass distribution on all scales larger than about 0.5 Mpc (co-moving). This simple idea of diffuse baryons tracing mass would be extremely powerful, if true. At present, it has not been adequately tested. A clear test of most ideas about galaxy and structure formation would require observations of galaxies and of the relative distribution of the diffuse IGM. These observations are expected to trace the same undulations in the matter distribution, albeit in a "biased" manner. The details of this relationship would constitute crucial constraints on the process of galaxy formation and its connection to large-scale structure. Very recent observations have suggested that the galaxy formation process is so energetic at high redshifts that individual galaxies strongly affect the physical state of the IGM within ~ $500h^{-1}$ kpc (co-moving) through the influence of large-scale winds, which move gas mechanically and shock-heat much of the surrounding medium. This calls into question the simplest assumptions inherent in the current picture of the Lyman α forest; however, the IGM then becomes a powerful tool for understanding the energetics of galaxy formation. In any case, it is clear that the simultaneous study of the diffuse IGM and forming galaxies is fundamental to understanding both.

The same spectra that would be useful for quantitative probes of the IGM distribution would also be of high enough S/N to detect very weak metal lines associated with the same Lyman α forest systems. This would provide probes of metals distribution in the IGM, and allow for detailed chemical and kinematic analyses (of the galaxies themselves) from the high quality rest-frame far UV spectra. Taken together, these observations will provide a three-dimensional mass distribution and a map of the location of gaseous regions that have been enriched in metals.

While the diffuse baryons are probed using intermediate resolution spectroscopy, the details of the galaxy distribution are best obtained through wide-field faint galaxy spectroscopy, capable of obtaining redshifts for objects ~ 10 times fainter than the faint limit for the IGM probes. A low-dispersion optical spectrograph on a 30 m telescope would have the capability of obtaining identification-quality spectra of extremely faint galaxies at z ~ 2-4 (to R ~ 26.5 with high level of completeness (based on scaling of experience from Keck), reaching faint enough to sample the equivalent of the L* galaxy density in the present-day universe. This is a critical aspect of the CELT survey; as it would allow making evolutionary connections with substantially higher validity. Present day galaxy evolution studies, particularly at high redshifts ($z \geq 2$), are hindered by the fact that only relatively rare objects are detectable.

The uncertainties in photometric redshifts are, unfortunately, much too large to allow their use for this part of the project. Accurate redshifts are necessary for examining the three-dimensional galaxy distribution and for establishing galaxies' effects on the IGM. Typical photometric redshift uncertainties at these redshifts would result in distance uncertainties of several hundred Mpc, although they would clearly be useful in *pre-selecting* the spectroscopic sample. For the sake of illustration, the combination of survey volume and apparent magnitude limits is chosen to approximate the SDSS redshift survey, tuned to the cosmic epoch $2 \le z \le 3.5$. There are many reasons for focusing on this redshift range, including the practical ease of obtaining redshifts where the night sky is quite dark (3500-6000 Å), accessibility of the Lyman α line of H I, and the ease of applying photometric pre-selection using *optical* wide-field photometry.

Survey Details

Based on the scaling relative to Keck/ESI, with CELT the apparent magnitude limit for obtaining R = 8000 (seeing-limited) spectra with continuum S/N ≥ 30 per resolution element will be R ~ 24 (for 10-hour integrations). This resolution is high enough that structure in the Lyman α forest is resolved down to velocity scales of ~ 40 km s^{-1}(~500h^{-1} kpc). Inside of this the approximation of the gas as a fluid that closely traces mass fluctuations (the fluctuating Gunn-Peterson approximation described above) must break down due to thermal- and hydro-dynamical effects. While the surface density of QSOs in the required z ~ 2-4 redshift range to R ~ 24 will be about 75 per square degree (estimated from the QSO rate in current Lyman break galaxy surveys reaching similar magnitude levels with high completeness), the corresponding surface density of compact high redshift galaxies will be about 5000 per square degree. While galaxy spectra are somewhat more complex than those of QSOs, it is clear that they can be used as probes since the intrinsic lines are easily separable from the intervening systems because of the large velocity width of the interstellar features in the galaxy spectra. An example of the quality that could be achievable for typical probes is given in Figure 2-22. This surface density places about 1 line-of-sight probe of the IGM at every co-moving square h^{-1} Mpc at z ~ 3, or a spatial sampling rate of one probe per few hundred proper Kpc (and so just about the right spatial resolution to match the spectral resolution).

The survey volume assuming z ~ 2–3.5 will be about 3 x 10^6 Mpc^3 per square degree ($\Omega_m = 0.3$, Ω_λ = 0.7) co-moving. Assuming a faint galaxy magnitude limit of R ~ 26.5, from the known luminosity distribution of UV-selected galaxies at these redshifts, there will be about 50,000 galaxies per square degree in the redshift range of interest. A survey of 10 square degrees would thus contain a volume of a few times 10^7 Mpc^3 (co-moving) and would contain 500,000 galaxies, both numbers very similar to SDSS in the local universe. The sample space density would be ~ 2 x 10^{-2} Mpc^{-3}, or roughly an L^* density in the present universe. The survey should consist of four to six ~ 2.5^o x ~ 1^o fields, each spanning regions ~ 200-100h^{-1} Mpc (co-moving) transverse to the line of sight, roughly what would be wanted to adequately sample the largest structure that could possibly have existed at those cosmic epochs. There would be hundreds of protoclusters in such a volume.

The point of these numbers is that it would be possible to perform a Sloan-like redshift survey in the $2 \le z \le 3.5$ universe, with the added benefit of more than 50,000 “skewers” through the IGM in the same cosmic volume in about one year of observing time with CELT (detailed below). The survey products would include:

- extremely good spectra of 50,000 bright high redshift galaxies (c.f. Figure 2-22), allowing for studies of chemical abundances, detailed kinematics of gas associated with the galaxies, and massive

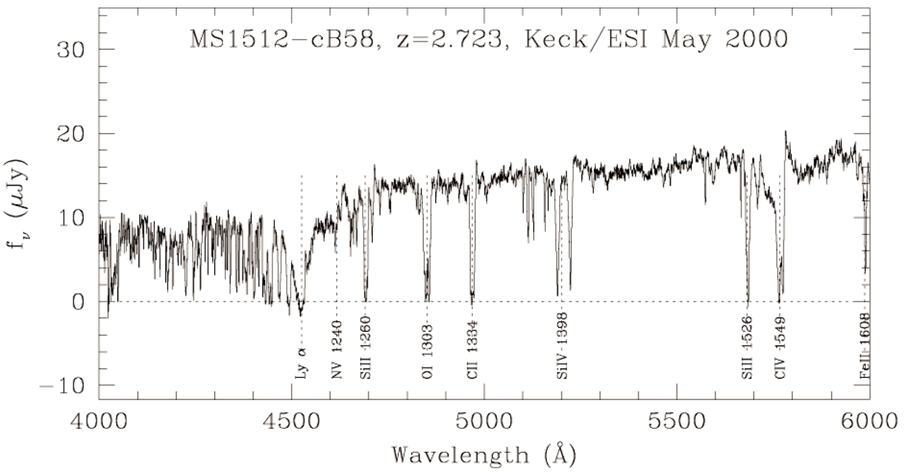

Figure 2-22. Example spectrum of a lensed (by a factor of ~ 30) high redshift galaxy (z = 2.732) obtained using ESI on the Keck II telescope. This is approximately the average quality spectrum that could be expected for R = 24 galaxy probes of the diffuse IGM at high redshift (R ~ 8000). The unmarked doublet features near 5120 Å and 5160 Å are an intervening Mg II doublet at z_{abs} = 0.828 and an intervening C IV doublet at z_{abs} = 2.331, respectively. There are at least 4 additional intervening C IV doublets identified in the spectrum. This spectrum has yielded the gas-phase chemical abundances of 5 different elements and provides our only current glimpse at the detailed physics of high-redshift star forming galaxies. Such spectra will be routine with CELT.

stellar populations from the UV spectral features (this is in addition to the utility of the spectra for tracing out the IGM distribution);

- a densely sampled volume that would contain a snapshot of structure formation progress at only 15% of the universe's current age (the volume is large enough to contain hundreds of protocluster environments, which could be observed conveniently with a small investment of time at other wavelengths because it is contained within fairly small angular scales on the sky, owing to the high redshift);

- constraints on the evolution of galaxy clustering, feedback between galaxies and the IGM, 3-D structure of the IGM, and the relative structures traced by galaxies all with unprecedented precision (compared to *any* redshift); and

- a vast array of follow-up projects using high spatial and spectral resolution, background sources for weak lensing studies at high redshift (*z* ~ 1-1.5), NGST chemical abundance studies, etc.

Technical and Instrumental Issues

Ideally, a multi-fiber spectrograph with 400-500 fibers over a 20 arcmin field would allow spectra of all of the available R ≤ 24 IGM probes, in the spectrograph field of view, simultaneously. Assuming integration times of 10 hours per pointing, a 10 square degree survey could be completed in 1000 hours (~125 nights). The ideal wavelength range covered would be 3500-7000 Å, with a minimum spectral resolution of R ~ 5000.

The faint galaxy portion of the survey would be slightly more time consuming. Here we assume an *imaging spectrograph* (R ~ 500) using the full 20 arcmin field, with 20 arcmin total slit length and 4 banks of slits across the dispersion direction (so that about 500 spectra could be obtained simultaneously). An integration time of about 2 hours should be sufficient for about 80% spectroscopic completeness and observing 500,000 galaxies would then require 2000 hours, or 250 nights. A less ambitious imaging spectrograph (i.e., a smaller field of view) would require smaller fields, sparser sampling, or both.

2.5.8 CELT and Exploration of the "Dark Ages"

At the time of this writing, very little is known about cosmic epochs prior to $z \sim 4$; there is a handful of known QSOs with $z \geq 5$, and a similar-sized handful of faint galaxies identified, mostly from the Hubble Deep Field. At present, this is one area where the discovery space is still very large, since we do not know at what redshift detectable star formation in galaxies began. The redshifts explored so far do not clearly indicate an absence of star formation well beyond $z \sim 5$. As detailed above, the NGST mission is being optimized for exploration of the $z \geq 5$ universe; however, there are several areas in which CELT may figure prominently for "dark ages" science:

- **Spectroscopy of probes of the re-ionization epoch:** There are currently indications that the highest redshift QSOs are beginning to pierce the re-ionization epoch, when neutral hydrogen in the intergalactic medium was ionized and when the IGM was heated to a temperature of ~ 10^4 K. Re-ionization is expected to occur in a "patchy" manner, with initially isolated ionized regions interspersed with regions that remain optically thick in H I. The detailed structure of the IGM requires quite high spectral resolution in order to resolve regions that are optically thin in H I during this transition period. There are estimated to be only 20 $z > 6$ QSOs in the entire Sloan survey, so that clearly a detailed understanding of the physics of re-ionization (and the nature of the ionizing sources responsible for it) will be severely limited. It is likely that many more, much fainter $z \geq 6$ objects (both galaxies and AGN) will be discovered in the intervening decade, but spectroscopic follow-up *at the requisite moderate to high resolution* (R ~ 10,000) will not be possible with either Keck or NGST for these faint objects. CELT may be the only telescope capable of high enough quality spectra to observe the details of re-ionization.

- **The physics of the first galaxies**: Even if the re-ionization epoch is near $z \sim 6$ as we are currently led to believe, the predictions for the formation epoch of the objects responsible for the reionization is not completely clear. Most theory based on hierarchical structure formation predicts that the first objects that can significantly affect the equation of state of the IGM are objects of total mass ~ $10^8 M_{Sun}$. These would be predicted to have rest-UV luminosities at the nano-Jy level (i.e., $m_{AB} \geq 30$) at $z \sim 10$. Depending on the nature of these sources (sizes surface brightness, spectral features, etc.) and which redshift is most important, CELT's superior performance at the diffraction limit using moderately high spectral resolution (~ 5000) in the 0.0 to 2.5 μm range may be a crucial capability in the NGST era.

- **Narrow-band imaging:** NGST will be limited in what it can do by the filters that go into space with it, necessarily a very finite number. It may well be that narrowband imaging, tuned to (for example) the Lyman α emission line for the highest redshift sources, may reveal interesting physics of reionization. The Lyman α line can be observed up to redshifts $z \sim 19$ using a narrow-band imaging system on CELT constrained to l < 2.5 μm.

Technical and Instrument Issues

The area of **spectroscopy of probes of the re-ionization epoch** would benefit from high dispersion, high efficiency spectroscopy in the 0.8-2.5 μm range. It may be that this can be accomplished using the deployable IFUs behind the AO system for the z = 1-5 program. However, it is possible that a normal slit spectrograph optimized for faint near-IR work would be superior, and perhaps even be required to attain the desired spectral resolution of ~ 10,000.

The **physics of the first galaxies** would benefit from near-IR deployable IFU spectroscopy behind AO.

Narrow-band imaging calls for capabilities at optical and near-IR wavelengths. This might be accomplished by a number of different instruments. There is probably a strong science case to be made for "tunable filter" imaging for a wide variety of science applications.

REFERENCES

Blandford, R.D. 1999. "Origin and Evolution of Massive Black Holes in Galactic Nuclei." ed. Merritt, Valluri and Sellwood, in press. Astro-ph/9906025.

Burrows, A., W. B. Hubbard, D. Saumon, and J.I. Lunine. 1993. *Astrophysical Journal* **406**, 158.

Charbonneau, D., R.W. Noyes, S. G. Korzennik, P. Nisenson, S. Jha, S.S. Vogt, and R.I. Kibrick. 1999. *Astrophysical Journal* **522**, L145.

Ciotti, L., and J.P. Ostriker. 1997. *Astrophysical Journal* **487**, L105.

Ciotti, L., and J.P. Ostriker. 2001. *Astrophysical Journal* **551**, 131.

Drilling, A.U., and J.S. Landolt. 1999. *Astrophysical Quantities*, 4th edition, ed. A. N. Cox. Berlin: Springer-Verlag.

Ferrarese, L., and D. Merritt. 2000. *Astrophysical Journal* **539**, L9.

Gebhardt, K., et al. 2000. *Astrophysical Journal* **539**, L13.

Gillette, F., and M. Mountain. 1998. Science with the NGST, eds. E. Smith and A. Koratkar, ASP Conference Series v. **133**, 42.

Gilliland, R.L., et al. 2000. *Bulletin of the American Astronomical Society* **196**, 202.

Gonzalez, G., G. Wallerstein, and S.H. Saar. 1999. *Astrophysical Journal* **511**, L111.

Henry, G.W., G.W. Marcy, R.P. Butler, and S.S. Vogt. 2000. *Astrophysical Journal* **529**, L41.

Jha, S., D. Charbonneau, P.M. Garnavich, D.J. Sullivan, T. Sullivan, T.M. Brown, and J.L. Tonry. 2000. *Astrophysical Journal* **540**, L45.

Karkoschka, E. 1994. *Icarus* **111**, 174.

Kormendy, J. 2000. "Galaxy Disks and Disk Galaxies." Astro-ph/0007401.

Marcy, G.W., and R.P. Butler. 2000. *Publication of the Astronomical Society of the Pacific* **112**, 137.

Marcy, G.W., R P. Butler, and D.A. Fischer. 1999. *Bulletin of the American Astronomical Society* **194**, 1402.

Marcy, G.W., R.P. Butler, S.A. Fischer, and S.S. Vogt. 2000. IAU Symposium 202, in press.

Marcy, G.W., R.P. Butler, and S.S. Vogt. 2000. *Astrophysical Journal* **536**, L43.

Marcy, G.W., R.P. Butler, S.S. Vogt, D. Fischer, and J.J. Lissauer. 1998. *Astrophysical Journal* **505**, L147.

Mayor, M., and D. Queloz. 1995. *Nature* **378**, 355.

Merritt, D., and L. Ferrarese. 2001. To appear in "The Central kpc of Starbursts and AGN," in press. Astro-ph/0107134.

Queloz, D., A. Eggenberger, M. Mayor, C. Perrier, J.L. Benzit, D. Naef, J.P. Sivan, and S.Udry. 2000. *Astronomy and Astrophysics* **395**, L13.

Sagan, C., and E.E. Salpeter. 1976. *Astrophysical Journal Supplement* **32**, 737.

Sanders, D.B., and I.F. Mirabel. 1996. *Annual Review of Astronomy and Astrophysics* **34**, 749.

Santos, N.C., M. Mayor, D. Naef, F. Pepe, D. Queloz, S. Udry, and A. Blecha. 2000. *Astronomy and Astrophysics* **361**, 265.

Sarzi, et. al., 2000. "Super Massive Black Holes in Bulges." Astro-ph/0010240.

Silk, J., and M.J. Rees. 1998. *Astronomy and Astrophysics* **331**, L1.

Vogt, S.S., G.W. Marcy, R.P. Butler, and K. Apps. 2000. *Astrophysical Journal* **536**, 902.

Wolszczan, A., and D.A. Frail. 1992. *Nature* **335**, 145.