CELT Science Priorities

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As discussed at some length in the Green Book, Volume 1, Chapter 2, the new science opportunities provided by a 30m-class optical/IR telescope operating from 0.3-28.5 microns are very broad, ranging in scale from the solar system to the high redshift Universe. We firmly believe that the scientific impact of CELT will go far beyond what we envision today, and, as was the case with the Keck Telescopes, CELT will enable discoveries that we cannot anticipate. Also as has been the case with Keck, new facilities on the ground (e.g., ALMA) and in space (e.g., NGST, Constellation X) will provide exciting new directions where the CELT observatory will be uniquely placed to make crucial contributions.

Nevertheless, there are some key science goals that drive the technical capabilities of CELT. In our view, the telescope capabilities must enable these goals. We note that most of the science requirements suggest multiple telescope capabilities. Many of the science requirements have already been folded into the Telescope Requirements section (Chapter 3) of the Green Book. Here we prioritize these more explicitly, concentrating on what we view as being among the highest priority science goals currently envisioned. The conversion of the science goals into detailed observatory technical requirements will be a primary phase 2 CELT activity; the intention of this document is to present a broad outline that can be used as a starting point for those activities.

The scientific priorities for CELT are based on the guaranteed performance of a 30m telescope as a seeing-limited spectroscopic telescope and as a (diffraction-limited) thermal-IR spectroscopic complement to SIRTF, NGST, and ALMA. As we have emphasized, diffraction-limited near-IR performance need not be a first-light capability for CELT to have a profound and instant impact on astronomy. Nevertheless, this capability, when it is achieved, will make CELT truly revolutionary.

Top Level Science Goals for CELT

1. The Epoch of Galaxy Formation

CELT will be the most powerful facility envisioned at the present time for addressing the development of structure in the post-reionization Universe. Redshifts $1<z<6$ encompass more than 35% of the age of the Universe, but perhaps 80% of the total star and heavy element production in the history of the Universe. Initial forays into this “epoch of galaxy formation and assembly”, using present-generation 8-10m class optical/IR telescopes and ground-based radio and sub-mm telescopes, have already indicated a very broad-brush picture that makes clear the gains that can be made with a significant increase in sensitivity. There is an opportunity, using CELT, to bring this phase of the Universe's history into as sharp a focus as the present view of the nearby Universe.

This particular science goal requires two broad CELT capabilities: wide-field, seeing-limited optical spectroscopy and near-IR, moderate dispersion, diffraction-limited spectroscopy. The details are described in sections 2.5.6 and 2.5.7 of the Green Book. It involves direct observations of the development of large scale structure, the mass assembly of galaxies, and the tomographic reconstruction of the otherwise "invisible" intergalactic medium. The necessary observations are a combination of wide-field faint object spectroscopy, powerful integral-field spectroscopy to measure small-scale kinematics, chemistry, and morphology, and high dispersion spectroscopy of high-surface density background sources that will probe the primary reservoir of gas available for galaxy and star formation before it has been incorporated into galaxies. The science here ranges from the structure of the dark matter distribution to the environmental effects on the assembly and evolution of galactic systems, to the chemistry of early galaxies and the production and dispersal of the heavy elements that would eventually form stars capable of harboring planetary systems. CELT provides the first real opportunity to observe simultaneously all of the baryons, both diffuse and "collapsed" into galaxies, and the complex physical processes connecting them, during the most eventful period of time in the Universe's history.

1.1 Observatory Requirements

- Near-IR, diffraction-limited, integral field spectroscopy in the 0.8-2.5 micron range for spatial dissection of faint galaxies for measuring dynamical masses, chemical abundances, and quantitative morphology.
- Wide-field, seeing-limited spectroscopy in the 0.36-1 micron range for tomography of the intergalactic medium and for massively multi-plexed spectroscopy of very faint galaxies at z=2-4.

2 . The "Dark Ages" and Re-Ionization

The *spectroscopic* investigation of the "epoch of re-ionization" and the formation of the first stars and heavy elements in the universe will require large ground-based telescopes operating in the near-IR. While addressing this scientific question is the primary mission of the Next Generation Space Telescope, it is already clear that the tremendous power of a giant ground-based telescope will be essential to fully understand this period in the history of the universe (which most theoretical models expect will correspond to the redshift range $6<z<20$) As for the "epoch of galaxy formation", the power of CELT will lie in its unprecedented power for astrophysical spectroscopy. While NGST will be very effective in discovering bright $z>6$ objects that may be used as probes of the re-ionization era, the spectroscopic capabilities of NGST will be limited to low-dispersion measurements. The principle diagnostics of the reionization era will be in the astrophysics of resonance lines of metallic species that fall in the rest wavelength range

122-164 nm, which at z=6-10 fall in the 0.9-1.6 micron wavelength range. The required spectral resolution will be R>10,000. This is an example where a CELT near-IR spectrograph fed by diffraction limited images will have far greater sensitivity than NGST.

Current theory predicts that the first substantial star formation in galaxies occurred within $\sim 10^8$ solar mass galaxies undergoing the first atomic cooling at redshifts z=10-15. The expected flux densities of such objects are in the nano-Jansky regime (AB>31 mag), and the sizes are expected to be on the order of 100 pc, i.e., very nearly the diffraction limit of a 30m telescope in the 1-2.5 micron range. The expected low masses of these first objects suggest kinematic line widths of ~20 km s^{-1}. Thus, maximum spectral sensitivity to these objects will be achieved with spectral resolution of R~5000-10,000 and spatial resolution of ~20 milli-arcseconds. As argued below, a 30m telescope at the diffraction limit can reduce the effective spectroscopic near-IR background to AB~29 per first-light galaxy "footprint". Thus, CELT will be the primary means of extracting physical understanding from the earliest galaxies discovered with NGST, in much the same way that Keck has provided astrophysical context to Hubble Space Telescope images.

2.1 Observatory Requirements

- Near-IR diffraction-limited, integral field spectroscopy in the 0.8-2.5 micron range for maximum sensitivity for very faint, nearly unresolved galaxies at redshifts z=6-20

- Near-IR, diffraction limited moderate-to-high resolution spectroscopy for the physics of a partially re-ionized intergalactic medium at z~6-10. The limits of the Keck Observatory have already been reached. Higher sensitivity, reduced background spectroscopy of fainter sources observed in the near-IR above the rest-frame Lyman alpha must be made.

3. The Physics of Star Formation and the Connection to Planet Formation

Understanding the complex physical processes of star formation has been a forefront research area of astronomy and astrophysics for three decades. The observational challenges are formidable. In the nearest star formation regions, proto-stellar and proto-planetary disks are a few to tens of milli-arcseconds in size, star formation regions typically are strongly obscured at optical wavelengths, and many of the gas motions that are crucial for understanding dynamical processes are small, requiring high spectral resolution observations. For thestudy of planets around other stars, the observational challenges are even greater. The angular size subtended by one AU (the distance between the Earth and the Sun) at the distance of the nearest star formation region is 7 milli-arcsecond, comparable to the diffraction limit of a 30m telescope at a wavelength of 1 micron. CELT will revolutionize our ability to study star and planet formation processes on scales as small as 1-30 AU in the nearest star forming regions, coupled with velocity resolution of ~1 km/sec. These capabilities will directly complement ALMA, which will probe the cool outer regions and the most deeply embedded and obscured regions with comparable spatial and spectral resolution in the sub-mm and mm regime..

There are several key areas in this field which have associated CELT capability drivers. First, there is the need for raw sensitivity in the optical and near-IR for the exploration of the earliest phases of star formation via scattered light. As discussed below, this sensitivity is achieved in the near-IR by means of the extremely high spatial resolution for observations at the diffraction limit of a 30m aperture. Disks around single stars extend to hundreds of AU (which is the reason that HST has been able to resolve a handful of the largest and nearest). However, the planet-building regions are expected to be <30AU in radius. Powerful indicators of planet formation are gaps in proto-planetary disks, which can be detected either through direct imaging, or through thermal-IR spectroscopy. Direct imaging of disks/gaps will be possible down to 1AU scales (at 1 micron) in the nearest star-forming regions (150 pc) and surveys for young planetary systems will be possible to ten or fifteen times that distance, dramatically increasing the volume of space and the range of stellar ages over which such a census will be possible. A very exciting CELT capability (see Green Book 2.5.2) will be direct imaging, in the thermal IR where young planets are easiest to detect against the glare of the parent star, of a subset of planetary-mass companions of nearby stars allowing determination of bulk composition properties, size, albedo, and surface temperature.

Star-formation and extra-solar planet studies using CELT's spectroscopic capabilities will also be revolutionary. Spatially-resolved near- and mid-IR spectroscopy at the diffraction limit of proto-planetary disks will make it possible to study the chemistry of planet-forming material and to constrain kinematics of infall, outflow, and rotation from close to the central star out to the distance of the solar system Kuiper Belt.

3.1 Observatory Requirements

- Diffraction-limited thermal-IR (3-30 micron) imaging and high resolution (R~100,000) spectroscopy for surveys and detailed study of proto-planetary disks.
- Diffraction-limited (6-20 milli-arcsecond) near-IR (0.8-2.5 micron) imaging and R~1000-30,000 spectroscopy for high spatial resolution studies of the physics of young stars.

4.0 New "discovery space" for CELT

It has become customary to highlight the "new discovery space" of any new astronomical facility, particularly for space missions because of their high cost and limited lifetimes. For CELT, this "discovery space", or the capability that represents the largest advance in sensitivity, will be in diffraction-limited performance in the near-IR (0.8-2.5 microns). Because almost all observations in the near-IR on Keck are severely limited by the background, it is not just the gain in collecting area, but the decrease in the relevant background by the same factor, that leads to entirely new regimes of sensitivity as well as angular resolution. Many of the most important scientific questions we can conceive of at present will hugely benefit from this capability—from planetary studies to stellar population studies to cosmology and galaxy formation--- but we also expect that CELT will make many discoveries that are currently unforeseen; it is quite likely that the capability that will maximize the new discoveries will be based in the near-IR provided that diffraction limited spatial resolution, for both imaging and (especially) spectroscopy.

Drivers for a 30m Aperture

There are always strong science drivers toward the largest telescope aperture possible given the current technology and the budget. However, there are particularly interesting thresholds that are crossed in going from 10m to 30m apertures. Here we summarize the arguments that a 30m aperture should be the CELT goal.

- **Spatial resolution .** The goal is driven by the desire to 1)Resolve down to 1 AU spatial scales at the distances to the nearest star-forming regions harboring significant numbers of young stars, 2) resolve the scales of individual giant HII regions in young star-forming galaxies at high redshift, matching the expected sizes of the first star-forming galaxies for maximum spectral sensitivity in the "dark ages" of the Universe and 3) resolve in the near-IR the equivalent of the highest spatial resolution mode of ALMA in the far-IR / sub-mm.

- **Sensitivity.** Two considerations weigh heavily in driving one toward 30m apertures from the current Keck 10m state-of-the-art. One is the order of magnitude increase in sensitivity for all wide-field seeing-limited programs, a prime example of which is the high redshift large-scale structure study outlined above; the second consideration, which is tightly linked with the concomitant increase in spatial resolution afforded by the 30m aperture, is the tremendous gain in sensitivity for imaging and spectroscopy in the near-IR behind AO.

The order of magnitude increase in seeing-limited sensitivity in the optical is essential for the first of the highest priority science goals outlined above. This order of magnitude increase in aperture leads to a 2 order of magnitude increase in the surface density of background galaxies and QSOs bright enough to achieve S/N~20 at R=8000 for AB =24-24.5 in the optical in 10 hours, and allows for sampling the IGM on <1 Mpc co-moving scales. It is also needed to achieve a high level of completeness in the galaxy spectroscopy to R_{AB} =26.5 in 2 hours. Such faint objects are important to achieving the dense sampling of the galaxy distribution necessary for an SDSS-like (i.e., ~10^7 Mpc^3) structure survey at z=2-4.

More generally, this increase in collecting area is essential for progress on all moderate-to-high resolution optical spectroscopic applications that are currently photon-starved using the Keck telescopes. The coupling of the large aperture with instruments designed to take advantage of a field of view of ~20 arc minutes makes CELT more powerful when brought to bear on the high redshift Universe than the Sloan Digital Sky Survey in the local Universe (20' at z=2.5 is the equivalent of a 3.4 degree field at z=0.15). The opportunity to simultaneously study the distribution and physics of diffuse intergalactic gas would make the proposed CELT study the most comprehensive study of the large-scale structure of the universe at any redshift.

In the near-IR (0.8 –2.5 microns), the potential gains of the 30m aperture are spectacular, when combined with the diffraction limit of 6-17 milli-arcseconds. Here one gains both the factor of ~10 in light gathering power with a factor of ~700 reduction in the average background "beneath" an unresolved object. A more concrete way of thinking about the background reduction is that the sensitivity in the 1-2.5 micron range, assuming modest Strehl ratios, is reduced to the equivalent of obtaining 0.3" "seeing" in the optical V band (~25.0 AB mag per resolution element on the sky). Another way of stating this is that near-IR imaging and spectroscopic sensitivity can be made equivalent to that achieved by CELT in the optical on nights with the best natural seeing, with the added benefit of 20-40 times higher spatial resolution, with a 30m aperture. For the first time, the faint near-IR Universe would be in reach from the ground. As discussed above, we believe that this mode represents the largest "discovery space" for CELT, and is the region with the largest potential synergy with NGST and ALMA

Together with the optical part of the spectrum (where the natural background is already very low) a 30m CELT provides nano-Jansky (AB~31.5) sensitivity from 0.35-2.5 microns. For context, reducing the CELT aperture from 30m to 20m would reduce the near-IR sensitivity to being the equivalent of an ~8m telescope operating in the optical.

Site Characteristics Versus Scientific Priorities

The 3 most important site characteristics for a ground-based optical/IR telescope are

- **Image quality** (seeing). As discussed in detail in chapters 9 and 13 of the Green Book, the suitability of atmospheric properties, at a number of different altitudes, are strongly site-dependent and are quite complex. However, these characteristics are the single most important ones for achieving diffraction- limited performance using adaptive optics systems, and for obtaining the best possible sensitivity for seeing-limited observations.

- **Percentage of clear nights.** The percentage of time that sites have completely cloudless nights is important for many reasons. Most obviously, nights with opaque cloud cover render the telescope useless. However, anticipating that adaptive optics using laser guide stars will be an essential component a large fraction of the time with CELT, even partial cirrus cloud cover (quite common, e.g., on Mauna Kea) may have a deleterious effect on the quality of the AO correction or may even prevent the use of lasers altogether. We need to better understand the effects of thin cloud cover on AO performance; we should soon get some direct experience with this on the Keck LGS facility (on-sky integration in late 2002/early 2003).
- **Thermal IR transparency.** As detailed in chapter 2 of the Green Book, the water vapor content of the atmosphere strongly affects the transparency in certain regions of the near and mid-IR spectral ranges. The water vapor content is a strong function of altitude, with the very best known sites being Antarctica and the high Andean plateau in Chile (e.g., Chajnantor). A secondary effect of high altitude is smaller diurnal temperature variations and lower night-time temperatures, which can lower the near-IR thermal background and mitigate locally-induced seeing problems.

In the view of the CELT Science Working Group, the first two characteristics should be optimized at the (possible) expense of the third. (The most profound effect of larger water vapor content will be increased difficulty in working at wavelengths longer than 15 microns). The site image quality must meet minimum requirements (TBD) before it should be considered, even if the percentage of clear nights (a statistic that is now well-known for most interesting sites in Chile and in the southwest portion of North America, and will soon be similarly characterized for Mauna Kea) is high.

Optical Coatings

As discussed in the Green Book, we believe that optical coatings for CELT must be optimized for the near-IR and visual with durable coatings requiring much less maintenance than the Al coatings on the Keck segments. We noted that significant improvements in the UV (wavelengths less than 380 nm) can be obtained at the same time as excellent IR reflectivity using hybrid coatings such as those currently under development at LLNL. While there is important science in the deep near-UV (and the terrestrial background reaches a minimum), we recognize that the coatings development for both the telescope mirrors (primary/secondary/tertiary) and for the science instruments are significant technology and cost risks. We believe that the hybrid coatings should be studied carefully for suitability and feasibility, but the natural fall-back (with acceptable scientific implications) would be over-coated silver. We understand that even durable over-coated silver needs significant development either within the Caltech/UC system or with potential vendors. Bottom line: we may be forced to modify the telescope wavelength requirements to 0.36-30 microns, from 0.30-30 microns. It would be a scientifically-acceptable de-scope option.

Summary

We have outlined the primary science objectives that drive the CELT telescope requirements. In brief, these science areas are:

- Exploration of galaxies and large-scale structure in the young universe, during the violent era in which most of the stars and heavy elements were formed and the galaxies in today's universe were being assembled.
- Exploration of the "dark ages" when the first sources of light in the universe were forming and when the universe, which had recombined at z~1000, becomes re-ionized by these sources of light. Here CELT and NGST will work closely together, with complementary capabilities.
- Exploration of the physics of star formation and the connection to the birth of planetary systems.

Weighting by these scientific issues and the new discovery space created, the most important CELT capabilities, in order of their priority, are:

- Diffraction-limited imaging and spectroscopy in the 0.8-2.5 micron wavelength range. The highest priority is spectroscopic capability, with integral field units deployable over a 1-2' AO-corrected field of view.
- Wide-field, seeing-limited spectroscopic capabilities in the optical. This capability is made most powerful by taking advantage of the 20' field afforded by the initial CELT concept.
- Diffraction-limited imaging and spectroscopy in the 3-30 micron range.

The second two capabilities are seen as relatively low technological risks and should be available for first-light; the first is expected to continually improve over the lifetime of the observatory.

We have argued that the telescope aperture is a crucial factor in obtaining the desired sensitivity in the 0.36-2.5 micron wavelength range, for both seeing-limited and AO-corrected applications. The telescope aperture is essential for realizing the spatial resolution necessary for the science in the thermal-IR regime.

We have made recommendations for the scientific impact of various site selection criteria, and for the choice of optical coatings.

The CELT Steering Committee and the CELT Science Working Group is prepared to engage in more detailed studies of all of the above should it become necessary for any scientific, technical, or financial reason.