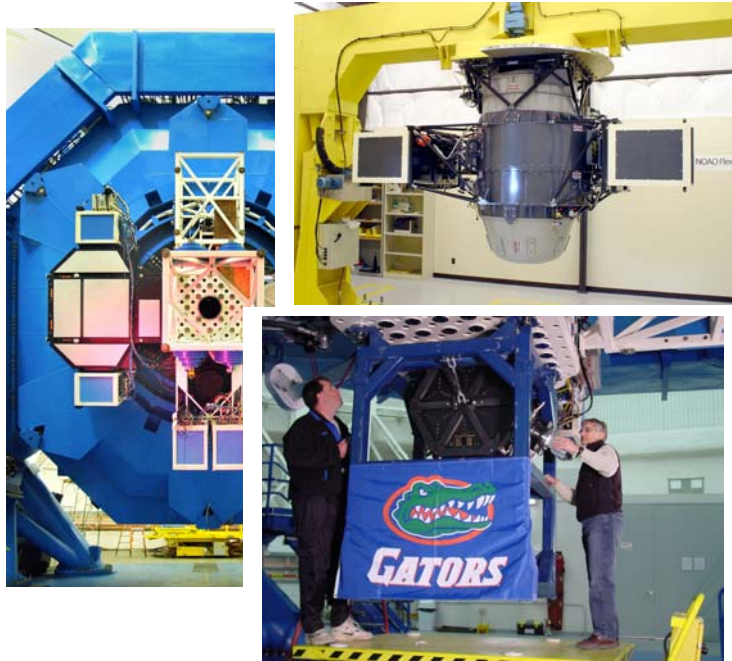


Future Instrumentation for the Gemini 8-m Telescopes: U.S. Perspective in 2003



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Introduction

Submitted by Taft Armandroff

The International Gemini Observatory began a process in early 2002 to identify the key science drivers for Gemini in the period 2008-2010. These key science questions, to be identified by the Gemini partner communities, would lead to a set of required observations that would guide future instrument development at Gemini. It has become apparent that these scientific themes that will guide future Gemini instrumentation development must be extremely compelling and broad based. Several of the scientific questions are likely to connect with expected facility developments at other wavelengths or in space-based initiatives.

Gemini Observatory will hold an international meeting to facilitate this science and instrumentation planning process on 27-28 June 2003 in Aspen, Colorado. The goal of the meeting is to define the scientific frontiers for users of Gemini during the period 2008-2010. A new suite of instruments will be built within the Gemini Partner countries, which are expected to become available in 2008-2010. The previous Gemini instrumentation-planning meeting was held in Abingdon U.K. in January 1997. It is hard to overstate the strategic importance of the Aspen Workshop in Gemini's future evolution, as the plan that emerges from the Aspen meeting will essentially define the next generation of instruments developed for Gemini through 2010.

The NOAO Gemini Science Center (NGSC) organized a workshop for the U.S. community in preparation for the international Aspen meeting: "Future Instrumentation for the Gemini 8-m Telescopes: U.S. Perspective in 2003" on May 30-31 in Tempe, Arizona. This U.S. workshop mirrors meetings held in several of the Gemini partner countries. The goals of this U.S. meeting were to:

- Explore important science questions that will be addressed via Gemini next-generation instrumentation in the period 2008-2010
- Discuss, in general terms, the observing capabilities required to address these science questions

Forty U.S. astronomers participated in the Tempe workshop (as listed in Appendix 1). This group represented diverse scientific interests and institutional affiliations.

Both the international Aspen meeting and the U.S. meeting in Tempe feature four science breakout groups:

- Stars, the Solar System, and Extra-Solar Planets
- Star Formation Processes and the ISM
- Structure and Evolution of the Milky Way and Nearby Galaxies
- Formation and Evolution of Distant Galaxies and the High-Redshift Universe

Prior to the Tempe meeting, there were e-mail discussions between the members of each breakout group, and in some cases teleconferences. These interchanges laid the groundwork for the discussions in Tempe on what are the most compelling and appropriate science questions for Gemini to address in the period 2008-2010. Each participant in the Tempe meeting was also sent a preparatory reading packet; this included, among other items, a description of the current and under-construction Gemini observing capabilities.

The Tempe participants also discussed the growing realization within the U.S. astronomical community that the full complement of telescopes and instruments accessible to U.S. astronomers is being used as an observing system. Thus, any Gemini instrumentation additions or enhancements should be thought of in the context of the U.S. observing system (*Report of the First Workshop on the Ground-Based O/IR System*, October 2000, Scottsdale, Arizona).

The participants in the Tempe meeting worked hard and defined high-impact scientific questions for Gemini to address in 2008-2010. These scientific questions were justified and placed in context. In addition, the observations required to address the questions were defined in general terms. The next four sections of this report contain the reports of the four Tempe science breakout groups. Each section is filled with important science questions, where Gemini has the potential to make critical contributions in the coming years. In the final section of this report, we explore commonalities and themes over the science investigations proposed. Commonalities are present both in the basic questions of astronomical origins and evolution, and also in the types of observing capabilities required to answer the scientific questions.

Stars, Solar System, and Extra-Solar Planets

Compiled by Jeff Valenti

Participants: Laird Close, Steve Eikenberry, Jian Ge, Suzanne Hawley, Ken Hinkle, Bruce Macintosh, John Stauffer, and Jeff Valenti (chair)

Preface

This report summarizes conclusions of the “Stars, Solar System, and Extrasolar Planets” group, which met on May 30-31 at the “Future Instrumentation for the Gemini 8-m Telescopes: U.S. Perspective in 2003” workshop in Tempe, AZ. Our mandate was to identify exciting science opportunities that would be enabled by supplementing the currently planned instrument suite for the Gemini 8-m telescopes. Based on introductory talks, we assumed that new instruments would be deployed in the time frame 2008 to 2012.

We discussed dozens of interesting research topics relevant to stars and planets, but our conclusions were necessarily biased by the scope of our expertise. For each research question, our entire group discussed the observational data needed to make significant scientific progress. In many cases, we decided that the required data could be obtained with existing or planned instrumentation. In other cases, the required observations did not seem feasible, even with new instrumentation. Neither of these extremes constrains the scientific potential of new observing capabilities. In keeping with our assignment, we instead focused mainly on science questions that could be addressed with plausible new observing capabilities beyond those already planned for Gemini.

A fairly comprehensive suite of instruments is already planned for the Gemini telescopes. In particular, our group noted that Gemini will have high-resolution optical (bHROS) and low- to moderate-resolution 1-5 μm (GNIRS) spectrographs within the next couple of years. Phoenix is currently providing high-resolution 1-5 μm spectroscopy over a narrow wavelength interval, but this “visitor” instrument is expected to leave Gemini in the next couple of years.

We identified a few plausible observing capabilities that do not seem to be supported on any large telescope. No high-resolution 1-5 μm spectrograph offers multi-object capability or full simultaneous wavelength coverage. No high-resolution spectrograph (optical or infrared) can be fed by a polarimeter. No multi-object spectrograph has a field of view greater than a square degree. No imager or coronagraph has a Strehl ratio high enough to image companions at separations of $4\lambda/D$ with contrast ratios of 10^6 . We mainly considered applications of these potential new observing capabilities.

ALMA is expected to be operational around 2008. In late 2011 JWST is scheduled to deliver very sensitive 1-28 μm spectroscopy at $R=100$ and $R=1000$. Similarly, LSST would be well suited to certain photometric survey projects. When these facilities would best address a

particular science question, we tended to give less weight to potentially redundant Gemini instruments, but we did not completely dismiss such possibilities.

Detecting and Characterizing Extrasolar Planets

The discovery of the first hundred extrasolar planets has captured the imagination of astronomers and the public. Precision radial velocity measurements have yielded the masses and orbital properties of these extrasolar planets, but many important questions remain unanswered. What are the surface characteristics of extrasolar planets? How was our solar system formed? How do planetary systems evolve? How common are habitable systems like our own? These questions will be the subject of intense research over the next decade. Space missions like SIM, JWST, and TPF will eventually address aspects of these questions, but ground-based instrumentation has an important role.

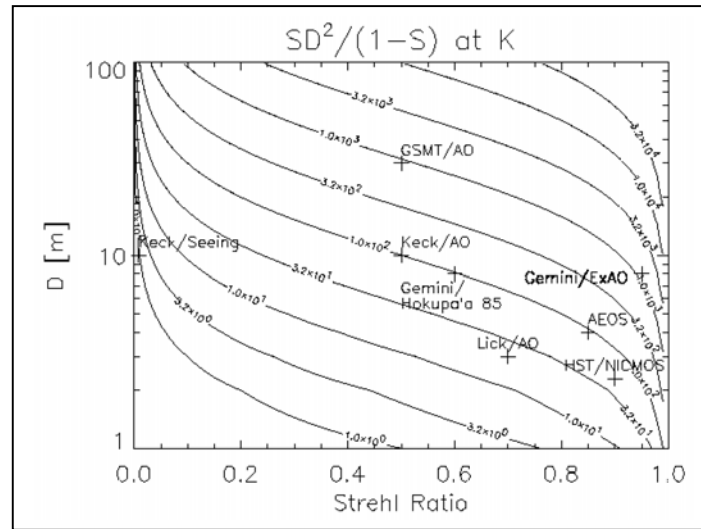


Figure 1: To first order, the signal-to-noise ratio (SNR) achieved in AO scales with telescope diameter (D) and Strehl ratio (S) as $SD^2/(1-S)$. The figure shows contours of constant SNR, with each contour corresponding to a factor of ten in exposure time. High-contrast AO ($S > 0.9$) on Gemini can be a 100 times faster than conventional AO on an 8- to 10-m telescope and comparable to conventional AO on a 30-m telescope.

The first goal is to discover new extrasolar planets, using techniques that complement existing precision radial velocity surveys. Direct imaging of nearby stars may be able to detect self-luminous planets in the planet-forming region 5-50 AU from the star. Such planets cannot be detected by current radial velocity techniques or by SIM, due to low velocity amplitude and long orbital periods. Figure 1 shows that a high contrast imager on Gemini would beat all existing systems. Current models of extrasolar planets predict significant self-luminosity for massive planets as old as 1 Gyr. Nonetheless, detecting such planets will require 1-5 μm imaging with very high contrast (10^{-7}) at separations down to 0.1 arcsec.

A radial velocity survey of L dwarfs would potentially reveal how the frequency and characteristics of planets depend on mass of the primary. Because L dwarfs are so faint in the visible, 1-2.5 μm spectra are required. High spectral resolution ($R=50,000$) is needed to measure sufficiently precise radial velocities (10-100 m/s). Even in the infrared, these objects are faint, so high sensitivity will be needed.

Direct imaging of nearby stars may be able to detect self-luminous planets that are well separated from the star. Such planets cannot be detected by current radial velocity techniques, due to low velocity amplitude and long orbital periods. Current models of extrasolar planets predict significant self-luminosity for massive planets as old as 1 Gyr. Nonetheless, detecting such planets will require 1-5 μm imaging with very high contrast (10^{-7}) at separations down to 0.1 arcsec.

Precise measurements will be required to characterize the surface properties of extrasolar planets. The atmosphere of a transiting planet can absorb a minute fraction of the stellar spectrum. Comparing high S/N (10^5) spectra in and out of transit yields the absorption properties of the planetary atmosphere. For the one known transiting system, HD 209458, HST obtained a marginal result. The HST experiment should be repeated at high spectral resolution (10^5) in the red and infrared (0.6-5 μm), where key molecular features are located. Ten transiting systems are predicted to exist down to $V=10$. Very high S/N (10^5) photometry would constrain the radius of the transiting planet and possibly reveal the presence of rings or moons.

Several groups have failed to detect reflected light from giant planets orbiting very close to the stellar surface. The spectrum reflected by the planet is a Doppler-shifted version of the stellar spectrum, possibly with absorption features superposed by the planetary atmosphere, especially from 1-5 μm . High S/N (10^5) spectra at high spectral resolution (10^5) are required to detect such signatures. Reflected light will be linearly polarized at quadrature, whereas direct starlight will be only weakly polarized. Moreover, the signatures of trace atmospheric constituents can be accentuated in polarization spectra. Spectropolarimetry may be the best way to study light reflected by extrasolar planets.

Self-luminous planets detected directly by high contrast (10^{-7}) imaging can be studied further without having to decompose composite spectra. Photometry and/or spectroscopy ($R=10-100$) of such resolved systems would reveal the temperature and molecular composition of the planetary atmosphere, providing important constraints on planetary evolution models. TPF is supposed to accomplish this goal, but certainly not within the next decade.

Planets are believed to form in circumstellar accretion disks, but details of the process are still subject to debate, given the lack of observational data. Recent 3-5 μm spectra of 1-10 Myr old stars have revealed circumstellar disk emission in the molecular species CO, H₂, and H₃⁺. High S/N spectra (10^4) at higher spectral resolution ($R \geq 50,000$) could reveal the presence of gaps in the gas disk, due to the formation of planets. More generally, the timescale for giant planet formation is strongly constrained by the presence or absence of circumstellar gas as a function of stellar age.

Debris disks around warmer stars have been detected in scattered light. These debris disks may provide clues about the planet formation process. SIRTf is likely to detect the spectral signature of such debris, but direct detection requires high contrast (10^{-7}), diffraction limited imaging from 1-20 μm . Dual linear polarization would potentially enhance the scattered light signal.

Brown Dwarfs

Brown dwarfs are the link between stars and planets. How are stars, brown dwarfs, and planets related? What physical processes do these objects share? Isolated brown dwarfs are relatively common, but solar-mass stars rarely have brown dwarf companions. How do brown dwarfs form? These questions can be addressed by new observing capabilities.

As with planets, the first task is to search for brown dwarfs using new techniques that extend or complement existing techniques. Deep 1-3 μm imaging over a very wide field is the most effective way to find isolated brown dwarfs. Binary brown dwarfs can be resolved with HST. The remaining challenge is to search around solar-type stars for brown dwarf companions, as in the original discovery of Gliese 229B. Such a survey would require 1-5 μm imaging at moderately high contrast (10^{-4}) imaging at separations down to 0.1 arcsec.

Understanding the physics of brown dwarf atmospheres requires infrared spectroscopy and supporting photometry. Interesting sources are typically no brighter than $K=15$. Temporal monitoring over the course of a night would show any 1-5 μm photometric or 1-3 μm spectroscopic variations due to clouds being carried across the surface by stellar rotation. Observed changes in spectral features would diagnose cloud composition. Moderately high spectral resolution ($R=20,000$) is required to minimize the impact of telluric features. Analysis of time-averaged 1-5 μm spectra ($R=20,000-50,000$) would test atmospheric chemistry models.

Flares and X-rays have been observed on some brown dwarfs. This suggests that some brown dwarfs may have strong surface magnetic fields, possibly created in a turbulent dynamo. It is not clear why only some brown dwarfs are active. Surface magnetic field measurements would provide a quantitative basis for understanding observed activity. Zeeman broadening is most pronounced in the infrared, so magnetic field measurements require high-resolution spectroscopy ($R=50,000$) at 1-2.5 μm , using Zeeman sensitive diagnostics like FeH.

Recent evidence suggests that some brown dwarfs are surrounded by an accretion disk, possibly providing clues about how brown dwarfs form. The properties of these disks could be measured directly with a 1-2.5 μm high contrast (10^{-5}) imager, especially if the imager was sensitive to linear polarization induced by scattering off the disk surface.

Origin of the Elements

Elemental abundance patterns in stars of different ages record the chemical enrichment history of our Galaxy. Interpreting these abundance patterns requires an understanding of stellar mass loss. Many important questions remain unanswered. For example, what is the composition of the earliest generation of stars? What do abundance patterns tell us about nucleosynthesis? What

causes mass loss from stars? What are the abundances of high-mass stars throughout our Galaxy?

Surveys continue to discover very metal-poor stars that probe conditions very early in the history of our Galaxy. Measuring elemental abundances of trace species requires $S/N > 50$ and high spectral resolution ($R=50,000$), but very metal-poor stars tend to be very faint. Thus, a very sensitive spectrograph would be useful.

The details of mass loss are not well understood, especially for cool giants. ALMA will map outflows from AGB stars in a variety of molecular species, but complementary 2-4 μm imaging is needed to trace the key species H_2 and H_3^+ . To see the ejecta, high contrast (10^{-6}) imaging is required. For unresolved outflows, 0.6-5 μm spectra with very high-resolution ($R=150,000$) spectra are needed to resolve very narrow components in spectral lines. Linear polarization measurements would help constrain shell geometry.

High-resolution ($R=20,000$) spectroscopy at 1-5 μm would also enable abundance determinations for high mass stars discovered by SIRTf/GLIMPSE throughout our Galaxy. Slightly higher resolution ($R=50,000$) spectra of the He I 10,830 \AA line would allow measurement of wind terminal velocity, which provides a strong constraint on stellar mass and luminosity. Similar observations of stars in the LMC and SMC would explore the effect of metallicity on mass-loss processes in high-mass stars.

Additional Science Themes

In addition to the three science themes highlighted above, we identified other major science themes of interest. The *Fundamental Stellar Physics* theme included issues such as the origin of magnetic fields and stellar activity, the physics of surface granulation, stellar interior structure as diagnosed by stellar seismology, orbital determinations of stellar mass, and refining models of supernovae. The *Solar System* theme included atmospheric studies of planetary satellites and studies of material from the planet formation epoch, e.g., comets, asteroids, and Kuiper Belt objects. The *Galactic Census* theme envisioned a survey of the dynamics and intrinsic properties of stars within 100 pc the Galactic center, and a survey to detect young stellar associations within 500 pc of the Sun. We acknowledge that even these additional themes do not cover all the potentially interesting science topics that could be addressed by Gemini with new instrumentation.

Many of the specific projects within these additional science themes call for the same set of observing capabilities emphasized throughout this report, namely, high-contrast imaging, high-resolution IR spectroscopy, and linear and circular spectropolarimetry. Some of the fundamental stellar physics topics also require high throughput $R > 100,000$ optical spectroscopy. The search for young associations in the solar neighborhood would require a wide-field spectroscopy capability.

Star Formation Processes and the ISM “Gemini Capabilities in 2010: From Baryons to Beings”

Compiled by Michael Meyer & Bob Blum

Participants: J. Bally (Colorado), R. Blum (NOAO), J. Elias (NOAO), J. Graham (UC-Berkeley), L. Hartmann (CfA), D. Jaffe (Texas), M. Meyer (UofA), J. Morse (Colorado), J. Najita (NOAO), K. Sellgren (OSU), J. Stauffer (SSC)

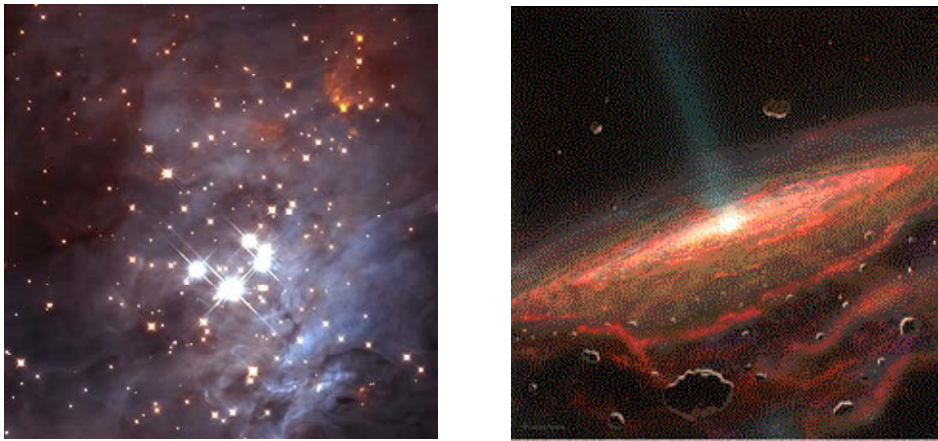


Figure 2: Left, Trapezium Cluster observed with NICMOS on HST (Luhman et al. 2001). Right, artist conception of a protoplanetary disk (courtesy of William Hartmann, Planetary Science Institute).

Stars are responsible for most of the observable light in the Universe. As a result, understanding the formation of galaxies, and the origin and evolution of our own Milky Way requires understanding the evolution of the ISM and the physics of star formation. Furthermore, life is thought to have originated on planetary surfaces through complex organic chemistry. As a result, knowing whether or not it is common or rare in the Universe requires an understanding of the origin of planetary systems and the evolution of complex organic molecules through the phases of the ISM to their incorporation into forming solar systems. To summarize, our panel is concerned with the transformation of baryons into beings!

We focused our deliberations on three key issues that highlighted new capabilities required for the Gemini telescopes:

- 1) How do stars form across the stellar mass spectrum?
- 2) How do planets form and evolve?
- 3) How does the ISM evolve over the lifetimes of stars?

These three areas of investigation comprise an inter-dependent cycle of star formation and its impact on the evolution of the ISM.

1) How do stars form across the stellar mass spectrum?

What is the IMF in “extreme environments” such as those of high or low stellar density, metallicity, or galactic environment (inner/outer galaxy or dwarf irregulars in the Local Group)? Here we envision imaging surveys of high-mass star-forming regions in the inner galaxy (high metallicity spiral environment) including the Galactic center where conditions for star formation are unique in the Galaxy, outer galaxy (lower metallicity spiral environment), as well as clusters often referred to as “star burst analogues” in the LMC/SMC (low metallicity dwarf irregular environments). This would require 1-5 μm imaging over $\sim 2'$ FOV sampled at the diffraction limit (DL), perhaps including observations to 10 μm in the more nearby, thus less crowded, regions. The next step is multi-object spectroscopy in these clusters to characterize the IMF in the outer regions of the clusters down below the hydrogen-burning limit (HBL). While these precursor studies can be undertaken with existing or planned capabilities, measuring the IMF down to the HBL in the *cores* of these dense rich clusters will require spectral imaging at $R = 300\text{-}3000$ with the highest possible spatial resolution (diffraction limited) over 4"-5" FOVs in order to overcome confusion which currently limits observations above $0.5 M_{\text{sun}}$. This requires an IFU spectrograph (1-2.5 μm) that properly samples the diffraction cores produced by the Gemini AO systems, ideally spatial sampling 0.03 arcsec or less. We have completed calculations which show that current or planned instruments do not take full advantage of the Gemini DL images in the crowded cluster cores. Coarser sampling over a larger FOV can help fill the gap between the MOS observations and the DL IFU observations.

These high angular resolution studies will allow us to explore the detailed process of high-mass star formation in the context of massive stellar clusters for the first time. By observing a large sample of clusters including the youngest ones (< 1 Myr), we will be able to determine where, as a function of radius, stars of a given mass form. This will provide clues to whether or not such processes as mergers are important in the formation of the most massive stars.



Figure 3: Example target clusters such as W31 (left, with ZAMS O stars and massive YSOs) in the inner Galaxy (Blum et al. 2001) and R 136A in the 30 Dor region of the LMC (right; Walborn et al. 2002).

In addition to characterizing the shape of the IMF, which we hope will point toward critical scales in star formation, detailed studies of the collapse of individual objects can provide us with “snapshots” of the actual process. How do protostars of all masses collapse from individual cloud cores to form star+disk systems? In order to pierce through veils of extinction up to 200 visual magnitudes, near- and mid-infrared imaging and spectroscopic studies are required. In particular, new capabilities required for Gemini include $R > 30,000$ spectra from 2-17 μm in order to study important molecular constituents of this gas (100-1000 K) which traces material between 0.1-5 AU. At these distances, the Keplerian velocities vary from 100-10 km/sec requiring high spectral resolution to study the coldest, slowest moving gas found in the outer protostellar envelopes. For the most massive stars, lines of ionized H and He and atomic species such as FeII and molecular lines of CO will be key in exploring the circumstellar environments (i.e., geometry) of the objects, providing important constraints on the formation processes. While these objects are already burning hydrogen in their cores, they are “newly born” and near-infrared studies with precise radial velocities can provide key information on the circumstellar geometry of the material which played a role in their formation. Large wavelength coverage is essential to calculate line ratios used to derive physical parameters like the ionization state of the surrounding ultra compact HII region.

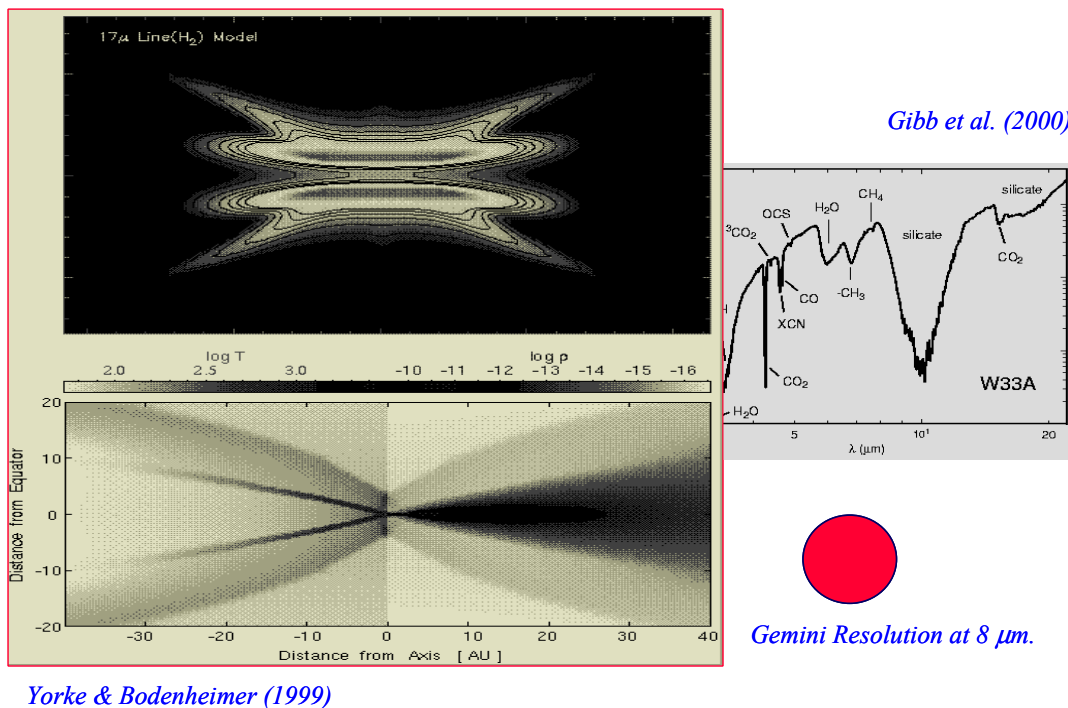


Figure 4: Simulation of an accretion shock of molecular hydrogen from Yorke and Bodenheimer (1999) shown along with a sample ISO absorption spectrum towards the protostellar sources W33A (Gibb et al. 2000). The diffraction limit of Gemini at 10 microns is shown for scale projected to the distance of the Taurus dark clouds.

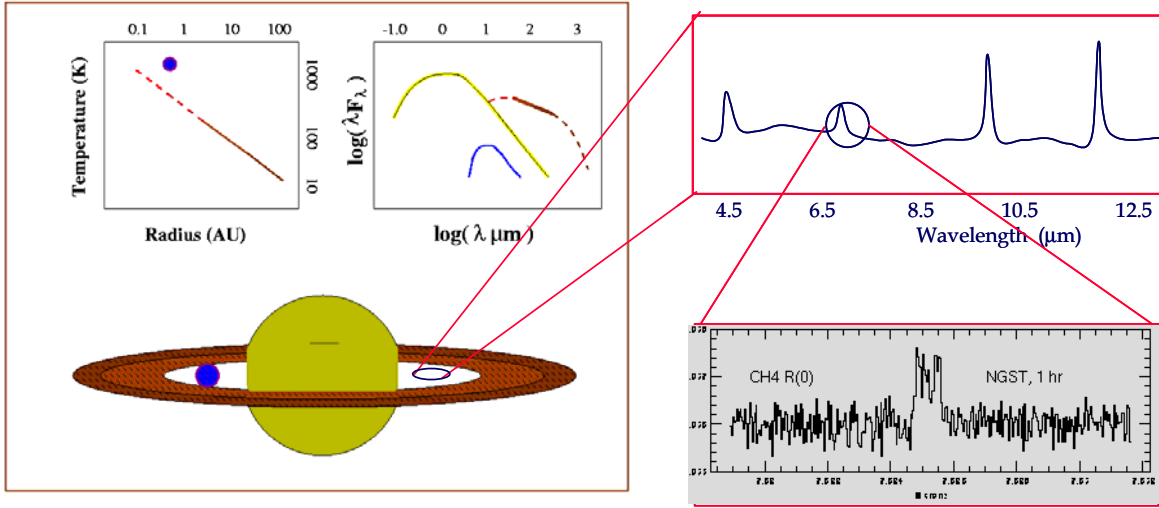
In order to trace shock diagnostics as material crashes down onto the star+disk system from the envelope, a DL $R > 3000$ IFU over 4-5" FOV to perform imaging spectroscopy in the 1-5 μm region is required. These high spectral and spatial resolution studies take us from collapse through star formation. As the systems evolve and shed their natal birth material, planet-forming disks and planets just become visible at very high contrast near the parent star. Our studies transition from capabilities which require the most out of Gemini's current (or planned) excellent image quality into those which require "extreme" solutions as described next.

2) How do planets form and evolve?

Having followed the star formation process from collapse of the parent cloud to an emerging stellar system in the preceding section, we now ask, "how do planets form?" What is the relationship between the constituents of the gas and dust in circumstellar planet-forming disks? What processes lead from the condensation of solids to the formation of planetesimals? There is rich chemistry in circumstellar disks where melting dust grain mantles and large, cometary bodies inject the gaseous medium with material processed on grains. There are a wide variety of molecular species of interest in studying the gas content of disks (OH, CO, H₂O, H₂, CH₃OH, NH₃, CH₄, C₂H₂, HCN, OCS, OCN⁻, NH₄⁺, ¹³CO, C¹⁸O) as well as solids (silicates, polycyclic aromatic hydrocarbons, nanodiamonds, and aliphatic hydrocarbons), and other hydrocarbons in the L-band at 3.6 μm as well as O-H and C-H and N-H stretches that populate the 2.9-4.0 μm region of the spectrum. Further to the red there is the $v=1-0$ CO fundamental in the M-band at 4.8 μm , H₂O in the N-band at 10 μm , and $v=0-0$ H₂ J=3-1 at 17 μm , J=4-2 at 12.3 μm , J=6-4 at 8.0 μm . Methane and acetylene, like H₂, are inaccessible at mm/submm wavelengths. At progressively longer wavelengths, one is tracing colder material at larger radii where the Keplerian/thermal velocities are intrinsically small. Therefore, the highest resolution is required at the longest wavelengths to trace the slowest moving material. Experience with current spectrographs also shows that $R > 50,000$ is needed from 8-17 μm to avoid the confusion of many telluric lines in the 10 μm window (which leads to lower sensitivity) and to resolve non-optically thick lines in order to provide accurate abundances and excitation information. In summary, tracing molecular species which dominate the mass of the gas-rich disks from which planets form requires $R > 30,000$ spectroscopy from 2-5 μm and $R > 50,000$ spectroscopy of point sources from 8-17 μm .

Complementary observations of both remnant dust disks (both primordial and debris disks) and directly detecting the planets themselves will require very high contrast imaging ($> 10^{-7} < 2''$ from 1-2.5 μm) in the near-IR. This will require very high performance AO capable of delivering at the highest possible Strehl ratio with particular attention to stability and calibration requirements. Such a capability would enable: a) planet search at wide separations (> 5 AU) around the very youngest stars in nearby star-forming regions; b) characterization of dynamical structures in scattered light which could reveal inner holes, gaps, and warps in disks indicative of the presence of planets; and c) a complete census of gas giant planets surrounding young < 1 Gyr stars within 100 pc of the Sun. Such a program, combined with on-going radial velocity surveys, and complementary ground- and space-based studies would provide fundamental constraints on the formation and evolution of planetary systems around Sun-like or similar stars, enabling us to place our solar system in context.

Young giant planets are still contracting and cooling, and are therefore easier to detect than older objects. Initial extreme AO searches may be most fruitfully focused on younger systems; any characterization of the resulting census will also require age determinations. Prior surveys—both spectroscopic and astrometric—will increase the efficiency of planet surveys, by identifying 10-100 Myr stars located far from their birth sites. This may require wide-field spectroscopic surveys for post-T Tauri stars. Estimates of the source density of these stars can be made based on extrapolation of surveys for solar-type stars in the Gould’s Belt (Mamajek et al. 2002; Wichmann et al. 2003).



Carr & Najita (1998)

Figure 5: Gas content in disks as a function of radius and age.

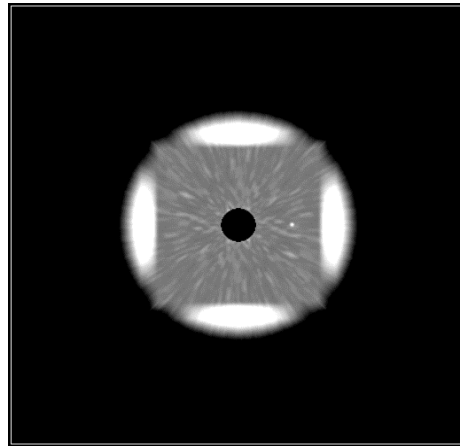


Figure 6: Simulation of high contrast AO capable of detecting an $8 M_{\text{jup}}$ planet surrounding a 500 Myr G star at a distance of 10 pc (Graham and Macintosh, 2003).

3) How does the ISM evolve over the lifetimes of stars?

Having addressed the collapse and formation of stars and planetary systems, we now close the cycle by asking how stars impact the ISM and its evolution. We have identified two specific questions that Gemini could make unique contributions toward answering. How do stars cycle material and energy into the ISM? This requires a wide-field ($> 30'$ FOV) seeing-limited ($< 0.5''$) emission line ($R=10,000$) imaging ($0.8-5 \mu\text{m}$) of regions where stellar outflows from a variety of stellar objects/remnants (young stars, evolved stars, and super-nova) are interacting with the surrounding ISM. A wide FOV on an 8-m telescope is needed for finding fainter targets. Pushing to $5 \mu\text{m}$ will enable probes for diagnostic lines such as Br alpha in the highest extinction regions, studying higher excitation lines like Mg IV and Ar V, and molecular features like CO $v=1-0$ and C_2 . Once target areas have been identified, follow-up modest-field ($> 1'$) diffraction-limited (DL) observations at higher spectral resolution ($R > 10,000$; the minimum for detailed kinematic studies and allowing the lowest background to be reached between OH lines in the near infrared) in selected bands $0.8-17 \mu\text{m}$ are required to measure changes in temperature, density, and composition across shock fronts in order to investigate the injection of kinetic energy into the surrounding ISM and look for changes in abundances from region to region. Such shock studies will enable us, for the first time, to quantify the extent to which outflows from young stars are responsible for driving turbulent support of molecular clouds in star-forming regions. Gas-phase abundance studies on a few arcminute scales for many targets will permit us to study the process by which heavy elements are injected into the ISM through mass-loss from evolved stars and supernova remnants.

A second question we hope is addressed in the next 5-10 years is: what is the detailed composition of the interstellar medium from which stars, planets, and life emerge? This requires spectra at ultra-high resolution (up to $R = 1,000,000$) of field stars observed through the ISM at wavelengths $< 1 \mu\text{m}$. The goal here is to probe atomic and molecular abundances (through electronic transitions in the visible) and kinematics of the cold, diffuse ISM. Vibrational transitions of important molecules in the gas and solid phases (CO, H_2O , H_2 , CH_3OH , NH_3 , CH_4 , C_2H_2 , HCN, OCS, OCN^- , NH_4^+ , ^{13}CO , C^{18}O , silicates, polycyclic aromatic hydrocarbons, nanodiamonds, and aliphatic hydrocarbons) observed along the line-of-sight toward background field stars shining through denser material would provide estimates of the column density of absorbers and constraints on the physical state of the gas enabling abundance estimates. This requires an $R > 30,000$ capability optimized for the $2-5 \mu\text{m}$ spectral region and $R > 50,000$ capability optimized for the $8-17 \mu\text{m}$ spectral region for point source spectroscopy. These studies must include observations of lines from a wide variety of molecular and atomic species, under varying excitation conditions, so large regions of the spectrum (ideally, a full octave) must be covered simultaneously.



Figure 7: Outflow associated with the massive protostellar object known as Ceph A (Hartigan et al. 2000). [SII] is blue, H α is green, and H $_2$ emission at 2.12 μm is red, illustrating that both atomic and molecular tracers are required over $> 1'$ FOV in order to fully understand complex outflow sources.

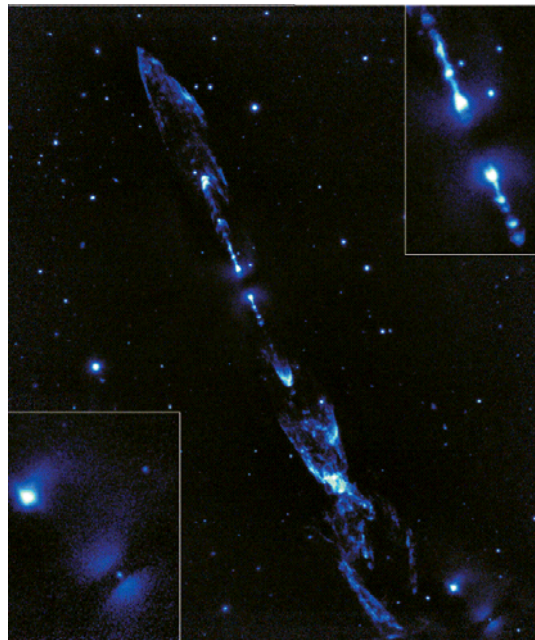


Figure 8: VLT image of the HH object 212 in Orion (McCaughrean et al.). Wide-field surveys are needed to provide targets for high-resolution follow-up work where full-field kinematics can be used to investigate the accretion process and the injection of energy into the surrounding medium.

Connections

The studies outlined here (formation of stars across the stellar mass spectrum, formation and evolution of planetary systems, and evolution of the ISM) are inter-related. The formation of massive stars has a profound impact on the surrounding ISM as well as providing the raw material for dusty disks and planets to form through the formation of the elements. The ISM sets the initial conditions of star and planet formation, and planetary systems may help mediate disk accretion and therefore outflow processes as well as provide a “storehouse” of refractory elements that could be liberated during the late phases of stellar evolution or not at all. Rather than three separate investigations, these studies can be thought of as a single theme encompassing the star and planet formation process in the context of star clusters themselves which are embedded in the ISM. The vast majority of stars do not form in isolation!

In addition, there are natural links to the science themes considered on the other panels. The study of nearby galaxies as well as galaxy formation at high redshift requires understanding of how the IMF varies as a function of metallicity and environment. Furthermore, “feedback” is a crucial input to models of how protogalactic fragments are assembled and any empirical constraints that we can provide could represent a significant breakthrough in understanding hierarchical models of galaxy formation. In addition, our connections to stars and planets are obvious. Both panels are concerned with the fundamental question: when, where, and how frequently are planets formed around Sun-like stars? Furthermore, we wish to know how planetary systems might evolve. Finally, all studies of stellar astrophysics on the main sequence use the outcome of the star formation process as the “initial conditions.”

The Bottom Line

We struggled with a list of most important requirements. Although it was difficult, and not all were in agreement, we came up with a (small) list of desired capabilities. Our top five requirements (not in order of preference):

- (i) $R = 300-3000$ 1-2.5 μm 4" FOV IFU (diffraction limited sampling not currently available or planned)
- (ii) $R > 30,000$ 2-5 μm optimized cross-dispersed echelle (covering at least one octave in one observation)
- (iii) $R > 50,000$ 8-17 μm high sensitivity echelle (cross-dispersed if array formats become sufficiently large)
- (iv) Ultra-high contrast near-IR imager ($> 10^{-7}$ 0.1-1", Strehls $\sim 95\%$)
- (v) MCAO $> 1'$ FOV near-IR $R > 10,000$ tunable narrow-band spectrophotometric imaging capability (possible to achieve space-like sky backgrounds below 2.4 microns).

We are still working toward developing quantitative examples of our science case and refining (and better justifying) the list of required capabilities. We look forward to comments on this document.

Structure and Evolution of the Milky Way and Nearby Galaxies

Compiled by Rosie Wyse

Participants: Rosie Wyse (chair), Taft Armandroff, Jean Brodie, Eileen Friel, Jay Gallagher, Karl Gebhart, Terry Herter, Kris Sellgren, Verne Smith

Overall Science Theme identified was ‘Quantitative Astrophysics: Determining the Power Spectrum of Dark Matter on Galactic Scales.’

Rationale: Through recent large-scale structure surveys such as those of the SDSS, the 2dF galaxy redshift survey and the Wilkinson MAP Satellite, we now have a robust characterization of the important cosmological parameters such as the various contributions to the energy density and the present expansion of the Universe. These observations are well described by the formation of structure via gravitational instability governed by Dark Matter with a power spectrum as expected if the dark matter is Cold. However, several potential problems with the CDM power spectrum have arisen, all on scales of galaxies and their satellites (e.g., too many predicted satellite haloes; too steep predicted cores of galaxies; too much late merging for large disk galaxies; too late disk formation . . .). The solutions to these problems that have been proposed maintain the dark matter, and rather use astrophysics to modify the observed galaxies, and as such can be tested by astrophysical observations.

We propose four aspects to this overall theme:

- 1) How do observed galaxies relate to their dark matter haloes?
- 2) What are the most important processes in the build-up of galaxies as they form and evolve?
Collapse or quiescent accretion or mergers with systems of significant mass ratio?
- 3) What determines the star formation process at a given place and time?
- 4) What is the role of supermassive black holes in galaxy evolution?

Thus we propose to analyze how galaxies form and evolve through the determination of the properties of the stellar populations, of the supermassive black holes, and of the ISM in as many different galaxies as possible. The tracers used will vary with the distance of the target galaxy, with more luminous tracers (e.g., globular clusters) and integrated light used in more distant galaxies. The required properties are the age distributions, the chemical elemental abundance distributions, the kinematics—both mean streaming and random motions—all as a function of radius. These will be used to determine the merging histories, star formation histories, chemical evolution, and the importances of gas flows into and out of the system. We propose to test galaxy formation using a range of galaxies from the Milky Way, for which the most detailed information and stringent tests are possible, to the other members of Local Group, then to more distant members of galaxy clusters and the field.

1) How do observed galaxies relate to their dark matter haloes?

Determination of the dark matter content of galaxies comes from the kinematics and spatial distributions of tracers such as individual stars. Full three-dimensional kinematics (radial velocities and proper motions) is best; the astrometric satellites GAIA (launch before 2012) and SIM will provide proper motions throughout the Local Group. The analysis of line-of-sight velocities alone is complicated by a degeneracy between mass and orbital anisotropy. However recent investigations have demonstrated that radial velocities with an accuracy of a fraction of the overall potential well and covering the face of the target galaxy can be modeled to break this degeneracy between mass and orbital anisotropy, given a large enough sample (1000s) and sufficient areal coverage (Wilkinson et al 2002, MNRAS 330, 778). For more distant galaxies for which only integrated spectra are available, analysis techniques using the full line-of-sight velocity distribution are sophisticated enough also to provide mass and velocity dispersion tensor separately (e.g., Gebhart et al. 2003, ApJ, 583, 92). Galaxies in a variety of environments should be observed. Use globular clusters for radial velocities and integrated field stars for more distant systems (out to Coma). Note that the kinematics by themselves offer tests of hierarchical clustering models, since these predict significant angular momentum transport during major mergers, with the outer parts of elliptical galaxies supposedly containing most of the angular momentum—this should be observable in the kinematics of e.g., outer globular clusters.

Requirements:

For nearby galaxies MOS in the optical, reasonable FOV (tens of arcmin)—natural seeing. For dwarf galaxies, need velocities to a few km/s, or R =several thousand (nominal 0.1 pixel accuracy). Note that optimal system would also allow good metallicities for stars, and (relative?) age/metallicities for globular clusters and integrated light, from absorption line indices.

For more distant galaxies, IFU, IR AO-fed.

2) What are the most important processes in the build-up of galaxies as they form and evolve? Collapse or quiescent accretion or mergers with systems of significant mass ratio?

Merging histories and chemical evolution can be constrained by chemical elemental abundances and age distributions; Figure 9, taken from Tolstoy et al. (2003, AJ, 125, 707) shows that the elemental abundances in satellite galaxies of the Milky Way (large colored symbols) are very different from those in stars of the Milky Way (small symbols), implying that if mergers of subsystems did form the Galaxy, the subsystems were not like those satellites we see now.

The age distribution in the halo/bulge/thick disks of galaxies determines the merging history through providing lower limit to time of last merger that heated the thin disk (cf Wyse 2001, in ASP Conf ser 230). The fossil record in long-lived stars provides complementary constraints to looking directly at high redshift.

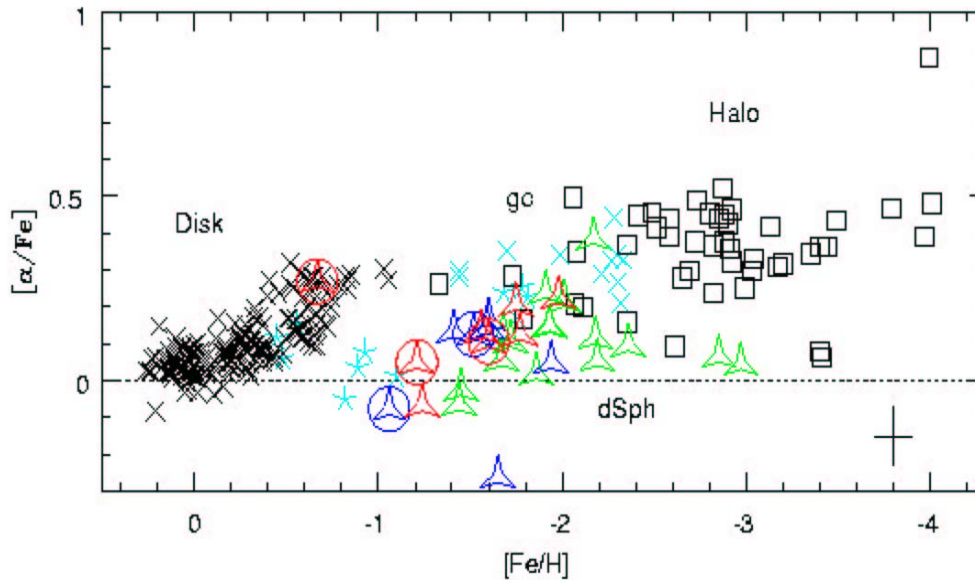


Figure 9: α -element abundances vs. $[\text{Fe}/\text{H}]$. The colored symbols represent stars in the Galactic dwarf spheroidal companion galaxies. The black crosses represent Galactic disk stars, and the squares show Galactic halo stars.

A fundamental aspect of this is to determine the detailed chemical abundance and metallicity distribution functions of stars in the different components of the Milky Way. At present we know only the mean and first moments of the distribution functions, based on small samples of stars, whereas much of the merging history is in the fine structure in chemical abundances and in kinematic phase space. Signatures of mergers may be long lived, particularly if one looks in parameters that are approximately conserved, such as angular momentum and elemental abundances. This investigation—mining the fossil record with Galactic Archaeology—can be carried out at two levels, the first obtaining straightforward ‘metallicities’ from medium resolution spectra—also sufficient for good kinematics—and the second determining detailed elemental abundances, providing much more information. Requires large samples (quantify!). Different elements are produced by stars of different masses and hence different timescales. Thus chemical evolution models can constrain star formation histories and gas flows, etc. more rigorously with elemental abundances.

Requirements:

Note that elemental abundances and indeed simply overall metallicity determinations require that sensitivity below 4000\AA be maintained, to reach Calcium H&K and also $[\text{OII}]3727$ (for HII regions).

Elemental abundances require high S/N, high-resolution spectra. Figure 10 from V. Smith shows how derived $[\text{O}/\text{H}]$ degrades in quality as decrease both S/N and resolution, as a function of oxygen abundance, for a typical red giant target star. Clearly $R=40,000$ is preferred, but $R=20,000$ suffices for some circumstances. (other elements?) At these resolutions, we are targeting stars with $V < 18$, or main sequence within a few kpc in the Milky Way, red giants in the Milky Way halo, and red super-giants out to M33. Different elements contain different information since they are created in stars of different main sequence masses and evolutionary

timescales. And different elements have useful transitions in different parts of the spectrum, requiring both IR and optical MOS capabilities. More straightforward metallicities and kinematics can be done with $R=5,000$, reaching $V=23$. Large samples of stars are needed to define the distribution functions, and at these apparent magnitudes, wide FOV is best.

** check surface densities of target stars.

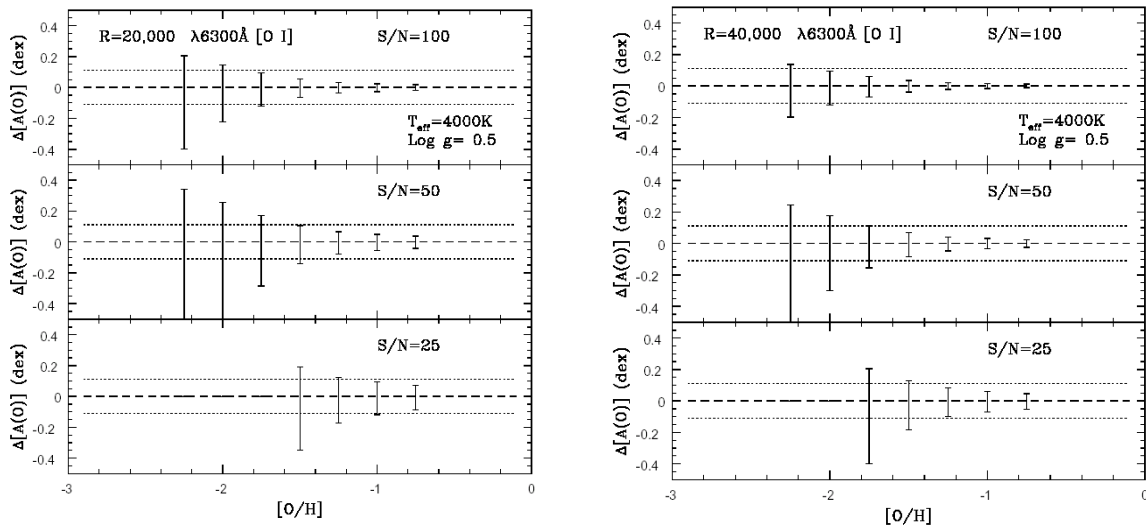


Figure 10: Errors introduced in an oxygen abundance analysis arising from noise in the observed spectrum for a variety of spectral resolutions, signal-to-noise ratios, and oxygen abundances; these test calculations are for the [O I] line at 6300\AA . Two spectral resolutions are shown: $R=20,000$ and $40,000$, with the two R -values set by a 2-pixel resolution element. The horizontal dotted lines represent errors in the abundance analysis produced by uncertainties in the stellar parameters of effective temperature ($\pm 70\text{K}$), $\log g$ (± 0.2 dex), and microturbulence (± 0.3 km/s). In the case of the lower S/N 's, the lack of points at low oxygen abundances means that the [O I] line falls within the noise.

3) What determines the star formation process at a given place and time?

The Stellar IMF is constrained by direct imaging (LF–MF) of individual stars and again—particularly for massive stars, precursors of Type II supernovae—by elemental abundances (stars of different masses produce different yields of different elements). Very low metallicity stars in the Milky Way and external satellites and M31 can be identified through large survey for follow-up with higher spectral resolution (if too faint for 8-m, then with future facilities, e.g., 30-m) to look for signature of Pop III enrichment. The mode of star formation—whether or not Super Star Clusters form, and with what mass function (of stars as well as of clusters!) can be determined by imaging followed by spectroscopy of the integrated light of a given cluster. This could be achieved out to the Coma Cluster. Break age-metallicity degeneracy of star clusters through combination of various spectral features.

Requires: The MOS and IFU unit.

4) What is the role of supermassive black holes in galaxy evolution?

It has become clear recently that feedback from black holes (BH) may be at least as important as feedback from massive stars in regulating the star formation of at least bulges/ellipticals. The Galactic Center can be used as a template here—what is the star formation process there? What are the chemical abundances? What are the properties of the stars in the stellar nucleus in M33? Why does M33 not fit the BH mass-velocity dispersion relation? What are the properties of the stars near SMBH in other galaxies?

Central regions tend to be dense and dusty, so need AO-fed IR spectrographs/IFU. Elemental abundances again require perhaps $R=40,000$.

Trade Studies Identified:

- (i) Multiplexing in wavelength coverage vs target number.
- (ii) Relative gains in science as increase sample size.
- (iii) Time to completion vs FOV.
- (iv) AO flavor vs FOV, sky background.
- (v) Investigation of the stability of (the distortions of) AO systems and their use for astrometry.

Formation and Evolution of Distant Galaxies and the High Redshift Universe

Compiled by Karl Glazebrook

Participants: Karl Glazebrook (chair), Mark Dickinson, Matt Bershad, Pat McCarthy, Richard Elston, Dan Eisenstein, Arjun Dey

We discussed the outstanding science problems in the field of high-redshift galaxy studies and cosmology, and identified three themes we thought were the most important:

- 1) The nature of dark energy
- 2) First Light in the Universe
- 3) The formation of galaxies

All of these have the potential for outstanding contributions to be made with new Gemini instrumentation.

1) The Nature of Dark Energy

The nature of the dark energy making up 70% of the Universe is THE most outstanding problem in modern cosmology and fundamental physics. We now have quite firm evidence that the Universe is close to the critical density from CMB experiments, and galaxy clustering from local redshift surveys indicate that matter (including cold, dark matter) is only one third of this. Further the distance-redshift relation from high- z Type Ia Supernovae implies the cosmological expansion has been accelerating since $z=1$. Taken together, these imply a missing component: either a classical cosmological constant (or vacuum energy) or something with a very similar equation of state.

But what is the nature of the dark energy? It is of 10^{120} orders of magnitude smaller than the Planck energy density and no compelling theory exists which can explain this. It is the central problem in Physics in this decade as identified by the Turner report (“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”). In the absence of theoretical understanding, we can make important experimental progress by mapping in more detail the expansion history of the Universe.

Gemini can contribute to this in several ways: firstly, it can contribute, as it is currently doing, to the effort to find many more type Ia Supernovae at high-redshift and follow them up. The $z>1$ epoch is critical as this is where the expansion transitions from deceleration to acceleration. Mapping the expansion with Supernovae requires finding many more of them and following their rest-frame optical emission into the near-IR. Scaling from GOODS, a deep J-band search, would yield ~ 1 SN Ia per pointing [2-4 hr exposure on 8-m to reach $J(AB)=25$] at $1.2 < z < 1.8$ for a $10' \times 10'$ FOV imager. A sample of ~ 1000 high- z Supernovae is within reach of Gemini and would enable us to measure the expansion history to 1% accuracy, improving our knowledge of the equation of state governing the dark energy by an order of magnitude.

Secondly, Gemini can contribute by studying the clustering pattern of high-redshift galaxies, in particular it could accurately measure the Baryon Oscillation signature left over from the epoch of re-combination. This is a promising new method which uses a ‘standard-rod’ approach to measure the distance-redshift relation. The standard rod is the sound horizon in the early Universe which is measured in the CMB to high precision. Its signature is imprinted in the galaxy clustering power-spectrum at low redshifts, effectively extending CMB precision to $0.5 < z < 4$. In particular, if the redshifts can be measured for $> 500,000$ high- z galaxies over $> 500 \text{ deg}^2$, one can measure the distance-redshift relation to $\sim 1\%$ accuracy comparable to the most ambitious future SNe studies (i.e., the SNAP satellite) and in a completely independent method with an absolutely calibrated standard rule (see Figure 11).

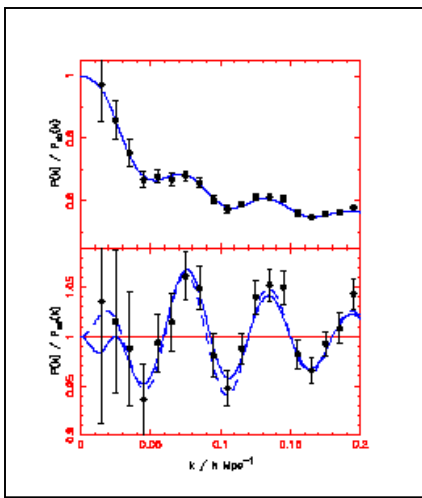


Figure 11: Power spectrum measurement for a simulated survey of $N = 2 \times 10^6$ galaxies over a volume $V = 6 V_{\text{Sloan}}$ at redshift $z \sim 1$. The power spectrum is divided by the zero-baryon model in the upper panel and the smooth reference spectrum in the lower panel. The solid line is the input (unconvolved) model power spectrum. [astro-ph/0301632, “Probing dark energy using baryonic oscillations in the galaxy power spectrum as a cosmological ruler,” C. Blake and K. Glazebrook, submitted to ApJ, 2003]

We also discussed other methods for probing dark energy: (i) weak lensing surveys over large areas, (ii) follow-up of high-redshift cluster samples (e.g., as detected by the forthcoming S-Z experiments) via the ‘growth of structure’ test.

Requirements:

Typically all the dark energy experiments require a wide-field capability in order to cover sufficiently large cosmological volumes. Supernova detections and weak lensing studies require wide-field NIR imaging. S-Z cluster follow-up requires NIR spectroscopy or multi-band photometry for photo- z 's. Probing the baryon oscillations requires redshifts of an enormous number of galaxies, at spectroscopic accuracy, over 100s of square degrees. Supernova spectroscopic follow-up is probably already covered by GNIRS + NIFS.

Trade studies needed:

- (i) NIR imaging and mapping speed on Gemini vs 4-m with bigger FOV. Relevance of GLAO to this, i.e., how big a field could we get with GLAO at what PSF?

- (ii) Effectiveness of wide-field NIR vs optical spectroscopy for baryon oscillation survey. Optical spectroscopy is much easier and cheaper per pixel, but maybe not as effective in the critical $1 < z < 2$ epoch?
- (iii) Effectiveness of wide-field NIR on 8-m vs ultra-wide field on 4-m for lensing science

Probable (new) instrumentation requirement:

- (i) NIR 1-2 micron imager with at least 10 arcmin FOV. Would really have to be 20-30 arcmin to give a big win over projected 4-m instrumentation.
- (ii) Spectrograph (very likely optical) capable of measuring redshifts ($R > 500$) of at least 20,000 $z > 1$ galaxies over 10 deg² per night.

2) First Light in the Universe

At $z=1000$ the Universe transitioned from ionized plasma to neutral hydrogen as it cooled. It remained this way until the first objects formed in the Universe and re-ionized the IGM with their UV radiation. Determining the epoch when this occurred and the nature of the very first objects in the Universe is now within the observational horizon of telescopes such as Gemini.

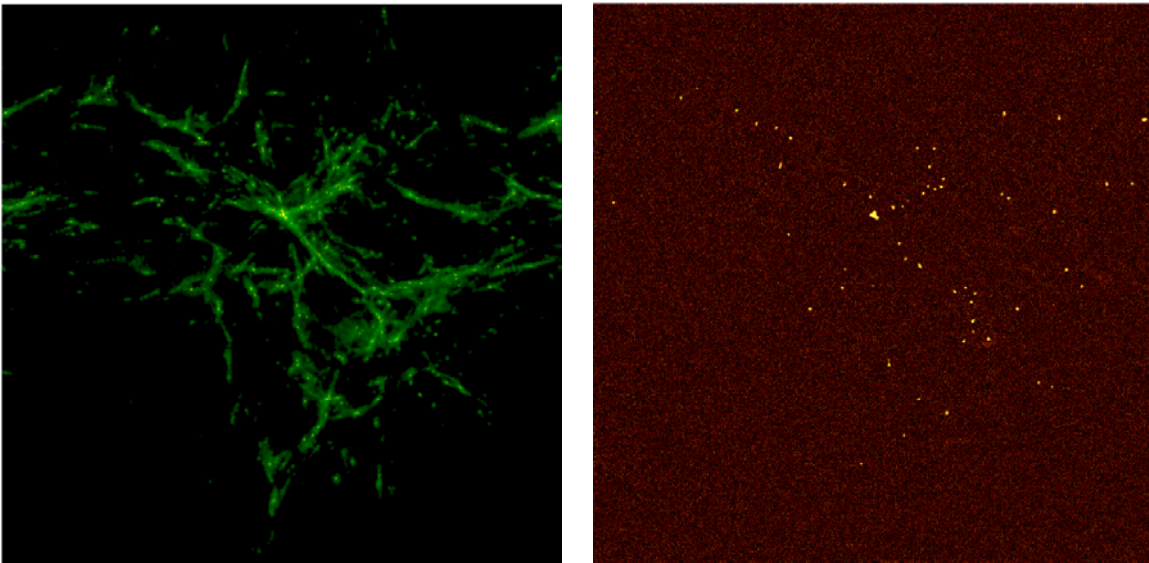


Figure 12: Left is the model Universe ($z=8$, 5.5 Mpc cube). Right is the Ly- α highlights Gemini could observe (3 arcmin FOV, $R=1000$, 30% throughput, 8-hr exposure). Courtesy of Elizabeth Barton Gillespie, Romeel Davé, J.-D. Smith, and Casey Papovich, based on simulations by Romeel Davé, Neal Katz, and David Weinberg.

The last 24 months has seen the first detections of $z > 6$ objects. The first of these were QSOs from the SDSS sample whose completely absorbed spectra below Ly- α have shown tantalizing evidence for a change in the state of the ISM at $z > 6$: a factor of ten increase at least in the fraction of neutral hydrogen, indicating perhaps the onset of re-ionization of the Universe at

slightly higher redshift. On the other hand, the CMB opacity indicates that the reionization epoch was closer to $z=17$, and it is possible that the Universe was ionized multiple times from early objects.

We have also found the first $z>6$ galaxies: a handful have been found by color and narrow-band imaging surveys. Typically these appear as i-z dropouts with strong Ly- α emission lines in the z-band. These may be the only reliable probe of the epoch of neutrality. The Gunn-Peterson trough in QSOs rapidly saturates for even a slight amount of HI; to measure the abundance of HI as it increases beyond $z=6$ we need to be able to find $z>6$ galaxies and measure the UV and Ly- α luminosity functions. The Ly- α line will be suppressed as HI increases. Re-ionization should be clumpy too; it is possible with sufficient statistics to detect this effect.

Requirements:

$z=6$ is right at the edge of the optical CCD window for Ly- α . To find galaxies to higher redshifts we need to move into the NIR bands. To detect such objects in the continuum we need to typically reach $J\sim 25$ —we would expect 50-500 objects per square degree selected by $z-J(AB)>2$. This imaging is a 10- to 20-h exposure on an 8-m telescope, so is not 4-m science.

Probable (new) instrumentation requirement:

- (i) NIR 1-2 micron imager with at least 10 arcmin FOV, sweet spot is 20-30 arcmin for order of mag gains over other facilities as for (1) above.
- (ii) NIR MOS spectrograph with at least 10 arcmin FOV, prefer much larger (20-30 arcmin) $R=4000$ for follow-up.

Trade studies needed:

- (i) What FOV would be useful? $z>6$ galaxies benefit tremendously from good image quality, but are also rare and need a large FOV. GLAO vs AO is of tremendous relevance here.

3) The Formation of Galaxies $1<z<5$

When and how did the massive galaxies we see today such as the Milky Way form? Did they form by a continuous build-up from smaller objects as predicted by the LCDM galaxy formation paradigm? How important is feedback in the formation of stars as a function of dark matter halo mass and time? When did spiral disks and bulges form? How did they assemble over time (inside-out?) and what environments did they form in? Many stellar populations today are very old; they would still be old at $z=2$. What galaxies are they in and can we see them?

We currently only have very cursory answers to these questions. The SFR of the Universe as a whole appears to have been *roughly* constant from $z=1$ to $z=5$, indicating a continuous build-up of the stellar mass. Massive disk and elliptical galaxies have been observed at $z=1$ in close to their modern abundance indicating they formed at higher redshifts. Various interesting examples of high- z galaxies populations have been found—many star-forming galaxies can be seen in ground-based images at $z>2$ by rest-frame UV selection and spectra have been obtained. HST

observations reveal irregular structures. The mass contained in these populations is small, perhaps 10% of the current global stellar mass density. Other tantalizing evidence exists for other high- z populations selected by optical/NIR colors which might contain more mass. However, spectroscopic follow-up has been limited. In particular spectroscopy of the oldest, reddest galaxies has been limited to $z < 1$ because of their lack of bright rest-frame UV emission.

Current techniques on 8-m telescopes have been pushing complete spectroscopic samples to $z=2$ using long (30-hr) integrations (see Figure 13). We can expect this to continue and new NIR instrumentation will allow rest-frame optical spectroscopy. In several years we can expect our dataset of the $z > 1$ Universe to consist of hundreds to thousands of objects with optical and NIR spectroscopy. We can certainly expect to be able to determine the history of galaxy formation to be mapped out at some crude level.

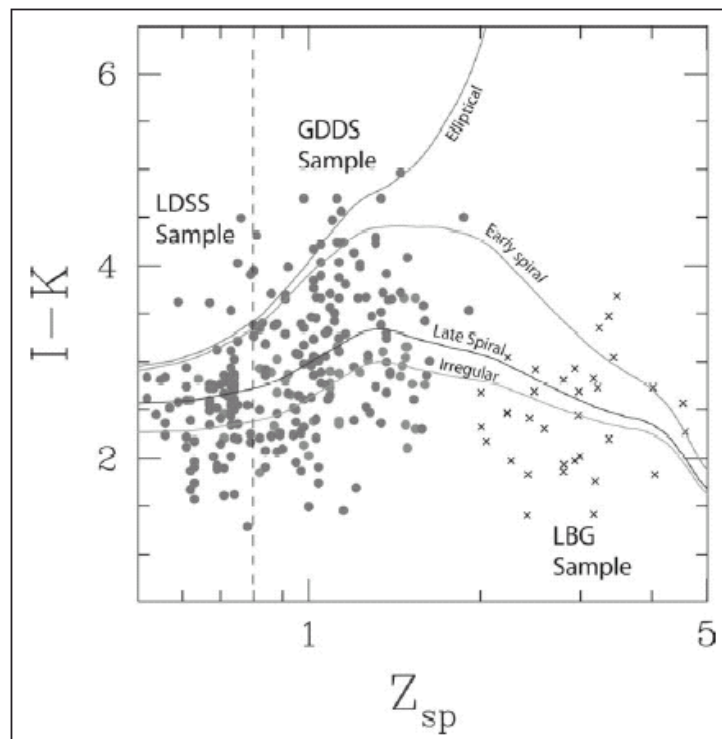


Figure 13: I-K color as a function of redshift for the GDDS (Gemini Deep Deep Survey) + LDSS (Low-Dispersion Survey Spectrograph) sample (solid circles) and for a sample of Lyman Break galaxies (crosses) in the HDF (courtesy of Mark Dickinson and collaborators). Note that the GDDS has few galaxies at $z < 0.8$, and the $z < 0.8$ points shown come from LDSS spectroscopy of the GDDS fields we have undertaken with Magellan. Conversely, almost all points at $z > 0.8$ are from the GDDS. Tracks correspond to the predictions of spectral synthesis models for a variety of star-formation histories. Note how the GDDS spans nearly the whole of the so-called redshift desert at $1 < z < 2$, and is sensitive to the full range of possible star-formation histories, including quiescent early-type systems that may hold substantial mass yet remain undetectable in other surveys. (*Gemini Newsletter* #26, June 2003)

However, in understanding galaxy evolution we are really playing a game of statistics in 5-dimensional space of mass, metallicity, star-formation history, environment, and time. To fully understand the high-redshift Universe, we need to be able to observe it in as much detail as the local Universe: i.e., samples of at least 10^4 and we need 10^5 objects to really do this right. If one wants 10% statistics in each bin, and about 5 bins each of mass, 3 bins of metallicity, 3 bins of star-formation history, 3 bins of environment, and 5 bins of time, that already multiplies up to a bit less than 10^5 . One can also add morphology as another axis (although it is clearly related to the mass axis) and that easily puts one over the 10^5 mark.

2dF and SDSS have revealed the complex nature of the galaxy distribution locally; this complexity encodes the detailed formation processes that went into these objects. To ‘wind back the clock’ on the local Universe and understand the processes that drive galaxy assembly we need similarly sized samples at high-redshift which require an order of magnitude increase in instrumentation capability.

Requirements:

- (i) Rest-frame optical & UV spectroscopy of $1 < z < 4$ large samples, $> 10^5$ objects over at least several deg^2 to enable determinations of stellar mass, metallicity and SFR as a function of environment.
- (ii) Moderate resolution (0.2-0.3") NIR imaging of similar sample.
- (iii) 2D spectroscopy of sub-samples to attempt to measure dynamical masses and correlate with stellar masses.

Probable (new) instrumentation requirement:

- (i) NIR 1-2 micron imager with at least 10 arcmin FOV. Prefer 20-30 arcmin very strongly.
- (ii) NIR MOS spectrograph with at least 10 arcmin FOV and large multiplex. Prefer 20-30 arcmin very strongly. $R \sim 1000$ for follow-up spectroscopy. (Though higher R might be necessitated by OH suppression.)
- (iii) NIR spectrograph capable of 2D spectroscopy of multiple objects (at least 10 in some FOV).

Trade studies needed:

- (i) What is the sky density of objects we can hope to get good 2D spectra of? Is it high enough to warrant a MOS capability or would we need a $\gg 10'$ FOV?
- (ii) NIR imaging and mapping speed on Gemini vs 4-m. Relevance of GLAO to this—i.e., how big a field could we get with GLAO at what PSF?

4) Implications for Future Gemini Instrumentation

Our panel identified one important instrumentation theme that runs through the three science themes presented here. All required wide-field capability. This is driven either by the requirement for large numbers for statistics and range of cosmic environment, or by the ability to

find and measure large numbers of rare objects, which nevertheless are extremely faint (e.g., galaxies at $z > 6$), requiring 8-m-class telescopes. In general we felt it was far more useful to be able to probe large fields (at least 10 arcmin) at natural seeing or perhaps GLAO enhanced resolution (e.g., 0.3 arcsec) than to have full AO correction over a field of < 1 arcmin.

IN PARTICULAR IT WAS STRONGLY FELT THAT GEMINI INSTRUMENTATION SHOULD BE AMBITIOUSLY WIDE-FIELD. WHILE 10 ARCMIN FIELDS WOULD REPRESENT PROGRESS, > 20 ARCMIN FOVS WOULD BE A REVOLUTIONARY ADVANCE ON THE STATE OF THE ART IN THESE SUBJECT AREAS

The other common theme was high-multiplex—high-redshift galaxy populations are very abundant. For example there would typically be several thousand $\sim L^*$ per square degree between $z=1$ and $z=2$. This translates into target densities of \sim several per arcmin² for typical science.

A strong NIR wide-field imaging and moderate resolution ($R < 10000$) IR spectroscopic capability is implied by galaxy evolution and first light science. This should be at least 10' to significantly improve on soon to be available capabilities, a field of say 30' would make Gemini ten times better than any other future facility for galaxy evolution science.

One big uncertainty was the issue of GLAO: the availability of this and the FOV vs PSF trade are currently very unknown. For example, a 10 arcmin FOV with 0.2" GLAO would win over a 30 arcmin FOV with 0.7" natural seeing.

PROBABLY THE STRONGEST ACTION ITEM IS FOR HARD NUMBERS ON GLAO FOV VS EXPECTED GAIN. ALSO WHEN CAN GLAO DELIVER?

Perhaps the most exciting science theme is the study of the dark energy using the baryon oscillations ('cosmic sound')—this requires a tremendous FOV (> 30 arcmin) and multiplex (> 1000) but is certainly do-able as the KAOS study demonstrates and represents a strong opportunity for Gemini to break out of its traditional funding regimen.

Major Science Themes

Contributed by Taft Armandroff

The preceding four sections are a rich compilation of frontline science questions for Gemini in the period 2008-2010. A number of big-picture science themes emerge as one reviews the science proposed by the four discipline groups. The following eight science themes encompass the vast majority of the proposed Gemini science:

- Formation and Evolution of Planetary Systems
- Formation of Stars & Brown Dwarfs over the Mass Spectrum
- Origin of the Elements
- Origin of the Hubble Sequence
- Dark Matter and the Formation of Galaxies from Substructure
- Effect of Feedback from Stars and AGN on Galactic Evolution
- Dark Energy and Cosmic Sound
- Reionization History of Universe

The proposed research encompassed in two of the themes, *Origin of the Elements* and *Dark Energy*, connect very closely with the recent report “Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century” (known widely as “The Turner Report”). The *Dark Energy* theme relates closely to the NASA initiatives in Cosmic Microwave Background (CMB) satellites, the proposed SNAP mission, and the Large Synoptic Survey Telescope (LSST). The *Formation of Stars & Brown Dwarfs over the Mass Spectrum* theme connects supportively with the science planned with the Atacama Large Millimeter Array (ALMA). Finally, the science contained in the *Formation of Galaxies from Substructure* theme closely relates to the planned astrometric satellites SIM and GAIA.

Viewed at the broadest level, the science questions posed by the U.S. community for Gemini’s future seek an understanding of the dominant physical processes that control the properties of the Universe at three very different scales. First, we seek to understand the physical processes that control star and planet formation and evolution. Second, we wish to understand how dark matter and feedback led to the population of galaxies observed today. Finally, we seek to understand how dark energy controls the evolution of the Universe as a whole. The U.S. community wishes for Gemini to play a major role in solving these three seminal problems in astrophysics. With the proper investment in future instrumentation, Gemini has the clear potential to contribute significantly to the solution of these major outstanding scientific questions.

Another set of commonalities among the proposed scientific investigations is the type of observations needed. The major investigations proposed by the four discipline groups have been organized in the following table around the type of instrumentation required on Gemini. Some generalizing has been done in order to simplify the presentation of the table. In examining the table, it is clear that certain types of instrumentation support several different scientific questions. For example, both the Nearby Galaxies and Distant Galaxies groups seek wide-field

spectroscopy in order to assemble the substantial samples needed to address the outstanding science questions in these areas. As another example, high-dispersion infrared spectroscopy is required for stellar physics studies proposed by Stars/Planets, ISM and protoplanetary disk investigations proposed by the Star Formation group, and abundance studies desired by the Nearby Galaxies group.

The science questions and proposed observations advanced by the U.S. community at the NGSC Tempe Workshop herald a bright and productive future for the twin Gemini Telescopes. It is clear that a properly targeted investment in instrumentation can make a huge difference in how a facility is able to address the key science questions of the day. The U.S. delegation will carry forward these science themes to Aspen for productive discussion with the other Gemini partners.

Connecting Proposed Science with Observing Capabilities

Capability	Stars and Planets	Star Formation	Nearby Galaxies	High Redshift
Adaptive Optics High-Contrast IR Imager	Extrasolar Planets; Circumstellar Disks	Planet Formation		
1-5 μm R = 50K Spectrograph Cross-Dispersed; MOS?	Brown Dwarfs; Origin of Elements; Magnetic Fields; Extrasolar Planets	ISM; Protostars; Protoplanetary Disks	Chemical Evolution	
Optical R = 5K Wide-Field 40' MOS Spectrograph			Substructure in Local Group; Dark Matter; Virgo/Fornax survey	Dark Energy; z=1-4 galaxies
Optical R = 40K MOS Spectrograph			Chemical Evolution	
Adaptive Optics IFU IR Spectrograph R = 3000 4" 20"	Planet Characterization	IMF; Protostars	Kinematics & dark matter	
Adaptive Optics IFU IR Spectrograph R = 20K-50K 3"			Super Star Clusters	
Wide Field IR Imager & MOS 20-30' R = 4000				Dark Energy; z=6,7,8,9 Galaxies; Supernovae Ia
MCAO >1' Near-IR Narrow Line Imager		Outflows		
8-17 μm R > 50K Spectrograph		Protoplanetary Disks; ISM		

Appendix 1: List of Participants

U.S. Gemini Next-Generation Instrumentation Meeting, May 30-31, Tempe, Arizona

Name	Institution	e-mail Address
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Appendix 2: Agenda
U.S. Gemini Next-Generation Instrumentation Meeting, May 30-31, Tempe, Arizona

Friday, May 30

Time	Topic	Presenter
8:00 am	Continental Breakfast	
9:00 am	Welcome, Introduction, and Logistics	T. Armandroff
9:10 am	Welcome from the NSF and U.S. Gemini Board Members	W. Van Citters
9:20 am	Context, Objectives of the Meeting, and a Route to the Objectives	T. Armandroff
9:40 am	Gemini Baseline Instrument Capabilities and the Aspen Next-Generation Instrumentation Process	D. Simons
10:30 am	Break	
10:45 am	Wide-Field Optical Spectroscopy Opportunities	A. Dey
11:15 am	High-Resolution Infrared Spectroscopy Opportunities	K. Hinkle
11:45 am	IR Multiplex Spectroscopy Opportunities	J. Elias
12:05 pm	Lunch	
1:15 pm	Ultra-High-Contrast Adaptive Optics Opportunities	J. Graham
1:45 pm	Multi-Object Spectroscopy with 2D Addressable Masks	A. Kutyrev
2:15 pm	Discussion of Science Sub-Group Mission	led by Armandroff
2:25 pm	Break into Four Science-Themed Subgroups	
2:30 pm	Discussion in Four Science-Themed Subgroups: <ul style="list-style-type: none"> • Stars, Solar System, and Extra-Solar Planets • Star Formation Processes and the ISM • Structure & Evolution of the Milky Way & Nearby Galaxies • Formation and Evolution of Distant Galaxies and the High Redshift Universe 	J. Valenti M. Meyer & R. Blum R. Wyse K. Glazebrook
5:30 pm	Adjourn	

Saturday, May 31

Time	Topic	Presenter
8:00 am	Continental Breakfast	
9:00 am	Initial Feedback from Four Group Leaders; Discussion	
10:00 am	Break	
10:20 am	Discussion in Four Science-Themed Subgroups	
12:00 pm	Lunch	
1:00 pm	Discussion in Four Science-Themed Subgroups	
2:20 pm	Break	
2:40 pm	Reports from Four Group Leaders; Discussion	
4:00 pm	Commonalities and Themes: Distilling a Preferred Set of Gemini Next-Generation Science Questions and Observing Capabilities	ALL, led by Armandroff
5:30 pm	Adjourn	