Future Gemini Instrumentation

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ABSTRACT

The following capabilities have been identified as high priority for future Gemini instrumentation.

1) A Natural Guide Star/Laser Beacon Adaptive Optics (AO) system at Cerro Pachon, and laser beacon capability for the Mauna Kea AO system
2) A Near IR Coronagraph/Imager for Cerro Pachon
3) 1 - 2.5μm Multi-object spectroscopic capability, including IFU and multi-slit capability for use with AO corrected images, and wide field multi-object capability over at least 5 arcmin field of view.
4) Polarization modulators for Optical and IR wavelengths at both Mauna Kea and Cerro Pachon
5) A High Stability Lab Optical Spectrometer for Cerro Pachon, with resolutions around 120K and $\geq$300K.

1. INTRODUCTION

The Gemini telescopes on Mauna Kea in Hawaii and Cerro Pachon in Chile are designed to excel in the key areas of imaging quality, throughput and IR emissivity, with the capability to exploit the best observing conditions through innovative scheduling. The capabilities of the initial complement of instrumentation (Table 1) were designed to allow the Gemini communities to undertake a broad range of scientific programs when the Gemini telescopes come online. The future instrumentation program is intended to further exploit the telescopes' key capabilities, beyond those offered by the Phase I instrumentation, to keep the Gemini facilities at the forefront of astronomical research well into the 21st century.

Table 1: Gemini Phase I Instrumentation

Mauna Kea	***Cerro Pachon***
▪ Multi-Object Spectrograph (GMOS-N)[1]	▪ Multi-Object Spectrograph (GMOS-S)
▪ Near IR Imager (NIRI)[2]	▪ High Resolution Optical Spectrograph (HROS)[4]
▪ Near IR Spectrograph (NIRS)[3]	▪ Mid-IR Imager[5]
▪ NGS Adaptive Optics System (Altair)[6]	▪ Near IR High Resolution Spectrometer (Phoenix)[8] shared with NOAO
▪ Mid IR Imager/Spectrograph (Michelle)[7] shared with UKIRT	

In order to ensure the continuing relevance of the Gemini Future Instrumentation Program, international scientific workshops will be held every few years. This will provide our partnership an opportunity to reevaluate the content and direction of the instrumentation program from a scientific and technical perspective, taking into account changing scientific opportunities and the evolution of technology. The first of these international workshops was held in Abingdon UK in January 1997[9].

This Workshop addressed four broad areas: 1) Stars and Planetary Systems; 2) Star Formation and the Interstellar Medium; 3) Galactic Structure and Nearby Galaxies; and 4) Formation and Evolution of

Galaxies and Cosmology. The goal was to identify the key instrumentation capabilities based on illustrative problems from these broad areas to ensure that Gemini would enable observations addressing these as well as many other scientific opportunities.

Two broad perspectives emerged from the workshop discussions as the basis for future instrumentation for the Gemini telescopes. The first is the ability to obtain near diffraction-limited imaging capabilities at near IR wavelengths, on both Gemini telescopes. The implementation of adaptive optics (AO) was considered of paramount importance to effectively address key scientific issues over the whole range of topics. Recent advances demonstrating the scientific utility of AO and of Laser Guide Star (LGS) capabilities have highlighted the timeliness of this capability. Gemini's priority is to use LGS AO technologies to maximize sky coverage. With this capability, the Gemini telescopes will complement and extend HST performance at Near-IR wavelengths, and will provide spatial and spectral resolution capabilities in the 2-20μm atmospheric windows far superior to the capabilities of ISO and those planned for SIRTF.

The second perspective focused on technological advances in Near-IR arrays that enable new innovative instrumentation capabilities that will fully exploit the images delivered by the Gemini telescopes at wavelengths longward of one micron. The development of high performance 1kx1k and 2kx2k Near IR arrays, leading possibly to 4kx4k focal planes, open new possibilities for addressing many key scientific issues using Integral Field Units (IFU), multislit, and multi object spectroscopic capabilities at Near IR wavelengths.

The new instrumentation capabilities that were highlighted during the workshop, and have been approved for future development, are summarized in Section 2.

2. NEW INSTRUMENTATION CAPABILITIES

The mapping of science programs onto instrumentation capability is summarized in Table 2 and illustrates the broad use of these capabilities among the different scientific areas. These perspectives and the scientific discussions led to the identification of the following components of the future Gemini instrumentation capability:

- A Natural Guide Star/Laser Beacon Adaptive Optics system (AOS) at Cerro Pachon, and LGS capability for the Mauna Kea AO system
- A Near IR Coronagraph/Imager at Cerro Pachon
- 1 - 2.5μm Multi-object spectroscopic (MOS) capability, including IFU and multi-slit capability for use with AO corrected images, and wide field multi-object capability over at least 5 arcmin field of view.
- Polarization modulators for Optical and IR wavelengths at both Mauna Kea and Cerro Pachon
- A High Stability Lab Optical Spectrometer for Cerro Pachon, with resolutions around 120K and $\geq$300K.

Table 2 - Science Drivers for New Instrumentation Capabilities							
SCIENTIFIC PROGRAMS	**LGS/ NGS AOS**	**IR Coronagraph/ Imager**	**IR MOS**			**Polarization Modulator**	**Hi Stab Lab Spec**
			>3’ FOV	**AO**	**IFU**		
A. Stars & Planetary System							
--BD & giant planets	X	X			X		X
--physics of nearby stars			X	X			X
--stars in other galaxies	X	X	X	X	X		
--surface structure/active processes	X					X	X
B. Star Formation & ISM							
--initial mass function	X	X		X			
--molecular clouds & cores							
--disks & envelopes	X	X			X	X	
--young substellar objects	X	X			X		X
C. Galactic Structure & Nearby Galaxies							
--massive stars	X			X	X		X
--star clusters	X	X		X	X		
--galactic nuclei	X	X		X	X		
D. Formation & Evolution of Galaxies/Cosmology							
--evolution of galaxies	X		X	X	X		
--studies of AGN’s	X	X		X	X	X	
--galaxies probes of HiZ structure	X		X	X			
--QSO’s as probes of HiZ universe	X	X			X		X

In the following sections each of these instrument capabilities is briefly discussed, including illustrations of scientific drivers and Performance Guidelines established for the capability. The Performance Guidelines are intended to provide guidance for conceptual design activities, and it is anticipated that modifications and extensions to the Performance guidelines will occur during and at the end the conceptual design activity as the technical issues, opportunities and cost tradeoffs become better understood. Performance requirements will be established prior to the start of the completion phase of each instrument.

A. Laser Guide Star (LGS)/Natural Guide Star (NGS) AO Systems

The Cerro Pachon telescope will be a superb facility for Adaptive Optics (AO) observations. A combined LGS and NGS AO system will extend and complement the AO capabilities on Mauna Kea. The combination of AO implementation at Cerro Pachon, together with the Laser Guide Star upgrade to the Phase I NGS AOS for Mauna Kea will constitute a powerful integrated AO program for the Gemini telescopes. These capabilities combined with the recommended Near IR coronagraph/imager and near IR spectroscopic capabilities will enable new scientific programs throughout the whole scope of scientific issues addressed by the workshop. Combined with our Near-IR Wavefront Sensors (WFS) for tip/tilt and fast focus correction, a LGS AO system would enable high performance AO imaging and spectroscopic observations in dark clouds - one of Gemini’s key science drivers.

Our first task is to adequately characterize Cerro Pachon for AO, quantifying such parameters as $C_n^2(h)$ and wind velocity profiles. Specific site measurements, including SCIDAR measurements and a series of balloon borne atmosphere soundings, are currently underway.

On Mauna Kea, a Laser Guide Star upgrade will boost AO sky coverage very substantially at moderate Strehl ratios in the near-IR. The intent is to upgrade the initial NGS AOS (Altair) for use with a Sodium Laser beacon in order to achieve moderate Strehl ratios (around 0.5) in the near-IR over most of the sky.

Performance Guidelines for the Cerro Pachon LGS/NGS AOS:

- Wavelength Range: 1-2.5μm required; 0.5-5μm as a goal
- Operating Zenith Angle: 1-60°
- Switchable NGS ↔ LGS modes
  - Emphasis on LGS but must support on-axis NGS as well
- Strehl Ratio (SR)
  - NGS - at a minimum achieve the same level as Altair
  - LGS - ≥SR and sky coverage at H achieved by Altair in the LGS mode
- General Spectroscopy Performance
  - LGS - TBD% sky coverage at TBD% slit throughput in a 0.1" slit at H
- Preserve location of telescope focal plane
  - Feed any instrument mounted on the Instrument Support Structure (ISS)
- Design studies may be for either altitude or telescope conjugated systems
  - Prefer capability to handle either mode
  - Issue will be sorted out when Cerro Pachon site characterization work is completed
- Optimized to support AO instrumentation
  - Coronagraphic Imager
    - Low scattering
    - Waffle mode rejection
    - Apodized mask possibly integral to AO unit
  - Multi-slit/IFU Spectroscopy
    - Slit throughput
    - Boost sky coverage
    - Short wavelengths
  - ~2 arcmin field of view
  - Maintain at least the same throughput and emissivity specifications as Altair

B. IR Coronagraph/Imager at Cerro Pachon

1-5μm imaging will be a "workhorse" capability for Gemini, exploiting the superb image quality and extremely low emissivity of the telescopes. Furthermore, Gemini will be a unique platform for coronagraphic observations because of the exceptionally smooth primary mirror, rigorous mirror cleaning program, thin secondary vanes, and small telescope obscuration ratio.

Performance Guidelines for the IR Coronagraph Imager:

- Wavelength range: 0.8-5μm

- Pixel scales: 0".01, 0".02, 0".05
- Array format(s): 1kx1k with goal of 2kx2k
- Optimized coronagraphic mode
- Assume facility AO
- Near IR On Instrument WFS (OIWFS) for tip/tilt and fast focus correction
- Studies to evaluate coronagraphic performance and mask requirements and consider role of AOWFS within instrument.

Science Illustrations:

A small field imager with pixel scales and optics designed to exploit AO performance and tip/tilt corrected images with optimized near-IR coronagraphic imaging capability will address a very wide range of science topics. Not only will the Gemini Telescopes and this imager provide some of the clearest views yet of the most distant galaxies, they offer a golden opportunity to search for the faintest and most elusive of nearby objects, brown dwarfs and planets. A high performance coronagraph on Gemini would allow a statistically significant census of brown dwarf companions to distances of ~100 parsec. Any detections of low-mass companions would provide precise astrometry which, with radial velocities, would yield masses, absolute magnitudes, and temperatures, all basic to understanding the sub-stellar mass function, and ultimately the transfer of angular momentum in star formation, and the universal proportion of matter bound up in sub-stellar companions.

An AO optimized IR imager with coronagraphic capability is essential for observing high contrast ratio scenes in star formation regions, including YSO envelopes, the origins of outflows, and studies of disks and superplanets around forming stars. High spatial resolution imaging in spectral lines probing shock-ionized gas (e.g. [FeII] 1.6 microns) will enable observation of energetic jets emerging from the inner regions of accretion disks and the shocked regions which mark the interaction between jets and/or neutral winds and circumstellar material. Such observations are critical to understanding the role played by high energy outflows in terminating infall and determining stellar masses. High angular resolution is crucial in order to probe regions 5-10 AU from the stellar surface -- where the wind/cloud interactions should be revealed.

Research on nearby galaxies would benefit greatly from AO systems which are capable of at least moderate Strehl ratio imaging in the near IR. The centers of galaxies are the sites of two of the most widely-studied phenomena in astrophysics: starbursts and AGN. These two mechanisms for energy generation power the high luminosities of several celebrated classes of galaxies - "ultra-luminous infrared" galaxies, Seyfert galaxies, "radio" galaxies, and quasars. However, despite intensive and voluminous studies over the past two decades, most of the fundamental issues and controversies remain unresolved. A proper exploration of compact, dusty astrophysical systems also requires the best-possible angular resolution near-IR imaging.

C. IR MOS

The continuing development of large format Near-IR arrays, 2kx2k HgCdTe arrays[10] for the 1-2.5μm and possibly buttable 1kx1k InSb arrays, provides an opportunity for three powerful new capabilities in the area of 1-2.5μm Multi-Object Spectroscopy (MOS).

One key Near-IR MOS mode would be a high spatial resolution Integral Field Unit (IFU)[11] that adequately samples AO corrected images, possibly equipped with coronagraphic capability. An IFU with a FOV of 5-10" and 0.05-0.1" sampling is required for studies in crowded regions and of galactic nuclei.

A second mode would be the capability to select numerous objects for spectroscopic study within a FOV consistent with AO isoplanatic patch size, about 20-30" diameter. Many applications for this type of MOS will be in crowded complex fields, so multi-slits or even multi-2D capability would be required.

The third key capability is simultaneous spectroscopy of objects over a FOV comparable to that of GMOS, particularly for studies of the distant universe.
For many science applications the spectral resolution needs to be optimized to work between the OH airglow lines, between 5000 and 8000, while abundance measurements will require spectral resolutions around 30,000. This capability supports a range of scientific applications, many of which follow the themes of GMOS science to higher redshift or probe dusty environments.

The NIRS is designed to have significant space in front of the cold slit for an IFU. Because of the "small" 1kx1k format of the NIRS detector, an image slicer concept for the IFU, which maps slices of the image plane into a single long slit, would provide efficient use of the array and require no additional blocking filters. Two plate scales are of interest; the first of 0.12-0.15 arcsec/spatial element for non-AO use and the second of 0.03-0.04 arcsec/spatial element for use with AO.

Performance Guidelines for the IR MOS Capability:

- Wavelength range: 1-2.5μm
- Array Format: minimum of 2kx2k, goal of 4k in at least one dimension
- Resolution: R~6000 requirement, and ~30K goal
- Pixel scale/FOV:
  - IFU with 0".05 pixels, FOV 5” (or as large as practical)
    - Minimum spectral coverage of ~1000 pixels
  - Multi-slit with 0".05 pixels over minimum 30" FOV - flexibility in number, location, size, length of slitlets is highly desirable
  - Multi Object with 0".15 pixels over minimum 5'.5 FOV
- Goal to combine two or more of the above modes in a single instrument
- Slit masks or other object selection mechanism should be changeable during an observing session without warming the spectrometer or significantly interrupting operations
- Mode changes should not require warming instrument
- NIR OIWFS for tip/tilt and fast focus correction
- Study should determine optimum choice of spectral resolution for working between OH airglow lines.

Science Illustrations:

Near-infrared (JHK) photometry and moderate resolution near-infrared spectroscopy (R~6000) enables determination of stellar effective temperature, interstellar extinction and stellar luminosity of forming stars in a wide variety of environments. In practice, however, these quantities are difficult to determine, particularly in the rich, dense stellar clusters which are presently thought to dominate star formation in the Milky Way, because of source confusion and the irregular background owing to the combined effect of complex reflection and emission nebulosity. To probe the initial mass function over the full range of masses -- from the hydrogen burning limit to the Eddington limit requires high spatial resolution in order to obtain accurate photometry and spectra in confused regions.

Gemini will enable detailed study of the structure of YSO envelopes and the processes of infall and outflow in the immediate vicinity (distances ranging from 10 to 1000 AU) of the star/disk system from analysis of adaptively-corrected infrared images and high resolution infrared spectroscopy. Studies of embedded YSOs in crowded regions with complex, irregular background emission requires multi-object spectroscopy over the isoplanatic patch at 2 microns using slits or optimally-designed integral field unit(s). Similarly, an equally important capability for the detailed study of nearby galaxies is a near IR IFU/multi-slit spectroscopic capability for small fields at high angular resolutions.

Moderate resolution near-infrared spectroscopy of very faint galaxies very close to bright QSOs at $1<z<4$ will allow measurement of Balmer lines (Hα or Hβ) and/or [OII] to determine redshifts and star formation rates. Integral field spectroscopy in the near infrared (JHK bands) with the high spatial resolution of AO-corrected images is needed to explore lines of sight as close as possible to the QSOs (the impact parameter of damped Lyman-alpha absorbers is expected to be very small).

Clusters of galaxies are the largest gravitationally-bound structures in the Universe, and their abundance and properties can provide strong constraints on cosmological parameters and the power spectrum of the mass fluctuations that give rise to large scale structure. Moreover, the study of cluster galaxies over a very large look-back-time baseline will substantially contribute to our understanding of the formation and evolution of galaxies. Near-infrared spectroscopy of the cluster galaxy candidates will determine galaxy redshifts and cluster velocity dispersions. Multi-object near-infrared spectroscopy over a field of view of several square arc-minutes is needed. Resolutions of 6000 or so are required to effectively subtract the OH sky lines, for redshift and velocity dispersion determination and to obtain information on star formation rates and galaxy ages. Galaxy surveys now show that the $1 < z < 3$ region is critical to our understanding of galaxy evolution (as it appears to be for QSOs), hence multi-object 1-2.5μm band spectroscopy over as large a field as possible (>5') is vital to identify and study the characteristics of the galaxy population at these redshifts.

Having access to Hα at z's as high as possible is of great importance for studies of SFR history in the universe. Having access to the K band MOS would cover the all important z~2 era. For example: studies of lenses and lensed objects, AGN and normal galaxy nuclei, the properties of groups and clusters of galaxies as f(z) and the study of galaxies close to QSO lines of sight.

D. Polarization Modulator / Optical & IR - Mauna Kea & Cerro Pachon

While polarimetry is a powerful diagnostic tool, it requires a large number of photons. The gains that can be realized by coupling the Gemini telescopes to efficient polarimeters should be quite spectacular; both reducing the time that many observations currently require and making other observations possible for the first time.

Polarization measurements will require implementation of a polarization modulator in the Acquisition and Guiding (A&G) unit above the bottom port of the Gemini Instrument Support Structure (ISS). The NIRI and NIRS Phase I instruments can accommodate Wollaston prism polarization analyzers, however, implementation of polarizing capability in GMOS and HROS will require upgrades to the Phase I instruments.

Performance Guidelines for the Polarization Modulators:

- Optical/IR polarization modulator plates mounted in the A&G unit in front of up-looking ISS port.
- Implementation must be remotely retractable and allow for unvignetted use of bottom port over a minimum 7 arcmin diameter science FOV with a goal of 9 arcmin
- Wavelength coverage: 0.3 - 1.2μm for GMOS, HROS and 1-5μm with a goal of 0.3-2.5μm with a single waveplate
- FOV: minimum of 1 arcmin. Extended FOV for OIWFS must be maintained
- Assessment of possible operating modes with GMOS and HROS
- A minimum of two modulator wheels that can be used in series
- Calibration capability

Science Illustrations:

Spectropolarimetry is highly 'photon-starved' since the percentages of linear polarization are typically a percent or so even for Be stars presenting nearly edge-on discs. In the past this has meant that polarimetry has mostly been applied at broad-band rather than high spectral resolution. Spectropolarimetry at echelle resolution can be a routine option with Gemini.

Magnetic fields almost certainly play a central role in the star formation process. They are important in all stages from the collapse of molecular clouds to the formation and evolution of disks and envelopes. The component of the field in the plane of the sky can be traced through the effects of aligned non-spherical dust grains on the transmission, emission and/or scattering of light. The study of magnetic field directions at high (arcsec) resolution has been confined to the brightest star forming regions. For example, dichroic extinction measurements have been made with imaging polarimetry towards the diffuse unpolarized H_2 emission at 2μm in Orion and through observations of polarized emission and absorption at 17 microns in Orion. As with all polarimetric measurements, Gemini offers very substantial gains but the advantages at these infrared wavelengths are particularly large.

Imaging- and spectro-polarimetry observations can be powerful diagnostics of the emission mechanism(s) and geometry of extragalactic sources (Seyfert galaxies, broad absorption line quasars, Ultra-luminous IRAS sources, and high redshift radio galaxies). The detection of polarized radiation from a source is an indication that either synchrotron emission, scattering (by dust and/or electrons) or dichroic extinction by dust grains is occurring.

E. High Stability Lab Spectrograph - Cerro Pachon

The High Stability Lab in the telescope pier provides a stable environment for precision radial velocity measurements. A fiber-fed, bench-mounted optical spectrograph with R=120,000, usable with an absorption cell in 500-600 nm range, would provide the greatest sensitivity currently for detection of low mass companions. A higher resolution mode, R>300,000 over the 380 to 1000 nm range, would enable many studies in stellar physics, including convection and magnetic fields, and also sufficient resolution for detailed studies of the ISM.

Performance Guidelines for the High Stability Lab Spectrograph:

- Bench mounted in telescope pier; fibre fed from Cassegrain focal station
- Wavelength range: H&K lines to 1.1µm; simultaneous spectral coverage of at least 100 nm for 120K mode
- Resolution: 120 K required, with goals of 300k, 500k, & 1000k
- Stability: <0.01 resolution element/hr (3 pixels per resolution element)
  - Absorption cell for high stability wavelength reference
- Maintain throughput under poor seeing conditions
- Sky subtraction capability
- Study to determine throughput capabilities to High Stability Lab

Science Illustrations:

For a wide range of problems in the physics of stellar atmospheres, stellar line profiles must be resolved which, for late-type stars, demands <1 km/s or R>300,000, at optical and near-IR wavelengths. Observations covering a range of spectral types would also allow a realistic theory for the changes that depend on evolution, and differences in mass. Convective motions can be estimated from asymmetries in line bisectors derived from high-resolution spectra. These would provide new insights into turbulence and dredge up rates providing important data for the interpretation of surface abundances and for understanding the importance of rotation in mixing. For studies of infalling cometary bodies in post-planet-building disks, e.g. the ß Pic disk, a resolution of R=120K would be adequate for initial studies, with R~300K-500K for detailed work.

For stars with weak integrated magnetic fields like the Sun, Zeeman splitting cannot be resolved. On the other hand, stars with strong fields such as active M-dwarfs are generally too faint for observation with adequate spectral resolution. Thus, results to date are inconclusive. In particular the question of field strength vs. area coverage is ambiguous since it requires detailed modeling of the line profiles, particularly of many lines with different temperature sensitivities and continuum contrasts.

Abundances and luminosities of supergiants measured at R~120,000 in the nearest galaxies will impose limitations on estimates of fundamental stellar properties in different environments, particularly the Magellanic Clouds where accurate abundances and calibrated mass-loss rates as a function of luminosity can be determined. With Gemini, this technique could be extended to nearby galaxy groups.

A good way to disentangle dust depletion and abundances at the highest resdshifts is to measure FeII, which has a range of lines from 234-260nm, and the MgII doublet at 280nm. For redshifts above 2.7 the MgII lines are shifted into the infrared, and for z>3.3 all are. At the highest redshifts available so far, z=4.39, the MgII doublet is in the infrared H window and a number of the FeII lines fall in the J band. To unscramble effects of ISM gas temperature at high redshifts from any turbulent motions requires resolving the lines at about the level of the narrower ones, so R=100,000 or more is indicated. If these temperatures can be determined they provide a direct comparison with local conditions, and constraints on the heating/cooling at high redshifts. Knowledge of the true line widths also helps firm up abundance estimates.

The case for spectral resolution R=300,000 for quasar absorption has a common thread with that for the R=120,000, to resolve the lines and so measure temperatures and abundances. There is an expectation that there will be cold clouds at high redshifts because stars must have formed then, and there are already indicators in one or two cases of cold material in quasar absorption systems.

3. PROCUREMENT & SCHEDULES

The Gemini Observatory provides continuing support for the development of future instrumentation capabilities from its operations budget. Table 3 is a planning timeline for development of the new capabilities described herein, based on projected levels of support for instrumentation development in the Gemini operations budget, budgetary costs estimates for the new capabilities and for the completion of the current instrumentation development activities.

The priorities for development of these capabilities are 1) the early development of the A&G Polarization Modulation capability for use with the phase I instrumentation; 2) the timely development of the LGS upgrade to ALTAIR on Mauna Kea with a goal to be available within one year after delivery of ALTAIR; 3) the delivery of the LGS/NGS AOS capability on Cerro Pachon within one year of start of scientific operations; 4) Near-ir imaging capability at Cerro Pachon to support the commissioning of the AOS, followed as soon as possible by the IR MOSs and High stability Lab spectrograph.

The scientific instrumentation capabilities will be developed within the Gemini partnership communities, in cooperation with the Gemini National Project Offices. Groups interested in participating in the future Gemini instrumentation program are encouraged to contact their Gemini National Project Office.

Table 3: Future Instrumentation Schedule

	1997	1998	1999	2000	2001	2002	2003	2004	2005
MAUNA KEA				↓ *Start of scientific operations*					
A&G Polarization Modulators									
MK LGS Upgrade									
IR MOS (Large Field)									
CERRO PACHON					↓ *Start of scientific operations*				
A&G Polarization Modulators									
IR Coronagraph/Imager									
CP LGS AOS									
IR MOS (Small Field)									
High Stability Laboratory Spectrograph									

4. ACKNOWLEDGMENTS

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