HIRES: The High Resolution Echelle Spectrometer on the Keck Ten-Meter Telescope

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ABSTRACT

We describe the high resolution echelle spectrometer (HIRES) now in operation on the Keck Telescope. HIRES, which is permanently located at a Nasmyth focus, is a standard in-plane echelle spectrometer with grating post dispersion. The collimated beam diameter is 12″, and the echelle is a 1 × 3 mosaic, 12″ by 48″ in total size, of 52.6 gr mm^{-1}, R–2.8 echelles. The cross disperser is a 2 × 1 mosaic, 24″ by 16″ in size. The camera is of a unique new design: a large (30″ aperture) $f/1.0$, all spherical, all fused silica, catadioptric system with super-achromatic performance. It spans the entire chromatic range from 0.3μ to beyond 1.1μ, delivering 12.6-micron (rms) images, averaged over all colors and field angles, without refocus. The detector is a thinned, backside-illuminated, Tektronix 2048 × 2048 CCD with 24-micron pixels, which spans the spectral region from 0.3μ to 1.1μ with very high overall quantum efficiency.

The limiting spectral resolution of HIRES is 67,000 with the present CCD pixel size. The overall 'throughput' (resolution × slit width) product achieved by HIRES is 39,000 arcseconds. Peak overall efficiency for the spectrograph (not including telescope and slit losses) is 13% at 6000 Å. Some first-light science activities, including quasar absorption line spectra, beryllium abundances in metal-poor stars, lithium abundances in brown-dwarf candidates, and asteroseismology are discussed.

1 INTRODUCTION

The W.M. Keck Ten-Meter Telescope, a joint project of the California Institute of Technology and the University of California, has begun operating atop Mauna Kea in Hawaii under the auspices of CARA, the California Association for Research in Astronomy. A complement of five first-light instruments for the Keck I telescope are currently under construction or being commissioned. One of these is HIRES, a high resolution echelle spectrometer. HIRES was designed and built at UCO/Lick Observatory, with S. Vogt as Principal Investigator. The HIRES project was formally started in September, 1988, and achieved first-light on July 16, 1993. The cost-to-completion for the 'core' version of HIRES was $4.1 million.

 0-8194-1493-X/94/$6.00

The HIRES design is the result of several years of design evolution. Previous discussions leading up to the final concept can be found in Vogt (1983)[4] and Vogt & Penrod (1987).[5] A detailed summary of the mechanical design of HIRES was published by Osborne and Bigelow (1993).[6] A HIRES user's manual[7] is also available from UCO/Lick Observatory. This paper presents a brief technical overview of the HIRES design, and gives examples of its performance by presenting some of the first-light science activities now underway. Space limitations do not permit a complete discussion here of the many scientific and technical considerations which determined the final HIRES design, nor of many of the technical details of the instrument. The interested reader is referred to Vogt (1992)[1] for more detail.

2 SCIENTIFIC DESIGN CONSIDERATIONS

Early in the design process, a number of high-resolution spectroscopic projects were identified as high priorities for first-light of the Keck. These include stellar abundances and chemical composition, studies of narrow absorption lines in QSO's, asteroseismology, and projects involving precision stellar line profiles and radial velocities. For a more detailed discussion, the reader is referred to the HIRES Phase B proposal,[2] and to Nelson, Mast, & Faber (1985).[3] Most of these projects are especially well-suited to the large aperture and anticipated excellent seeing of the Keck since they require quite high dispersion and thus lots of photons. They are projects which cannot be dealt with adequately using existing telescopes because the photon collection rate is too small. These key areas of research played an important role in defining the spectrometer, and in balancing the inevitable cost and performance trade-offs.

In designing a spectrometer with a cross-dispersed echelle format, there is almost always a trade-off between order separation and spectral coverage per observation. HIRES was designed with the belief that in many (perhaps most) cases, it is scientifically more useful to have relatively large order separation than to get the maximum wavelength span per observation, at least for a very large telescope like the Keck. The Keck, for a while the world's largest telescope at one of the world's best sites, is first and foremost a threshold instrument. At any given resolution and S/N, it should be able to go significantly fainter than any existing telescope. For high-resolution work, it may often be expected to do this in conditions of bright moonlight, and mediocre seeing, since the best bright-time seeing may well be largely used for IR imaging. Hence, sky subtraction (for faint objects) and image slicing (for brighter objects, at high S/N and resolution) become essential. For both, considerable order separation is necessary; extreme wavelength coverage, however, is less important.

3 INSTRUMENT DESCRIPTION

HIRES is a rather conventional in-plane, grating post-dispersed, echelle spectrometer. It is optimized for use with CCD's 50 to 60 mm in size. Its first-light detector is a Tektronix TK2048 CCD (2048x2048 format of 24-micron pixels). Larger and more sensitive CCD arrays are under development at UCO/Lick which will give both higher resolution and more spectral coverage. HIRES is designed for fairly high spectral resolution, wide (but not extreme) wavelength coverage in a single exposure, and good performance in average conditions on Mauna Kea. The instrument is designed to be modular and easy to add onto. The core instrument (that part funded by the initial CARA allotment and delivered at first-light) is a general purpose, 'no frills' instrument. Later enhancements, such as image rotators, ADC's, image slicers, and other cross-dispersers will be added as required by the scientific priorities of the user community.

Figure 1 shows top and side schematic views of HIRES. Since it is somewhat difficult to follow the light path in this figure, we present in Figure 2 a highly-simplified functional diagram of the instrument and light path. Figure 2 is actually the graphical user interface `xhires`, through which the observer controls HIRES. It is schematic only and not drawn to any constant scale.

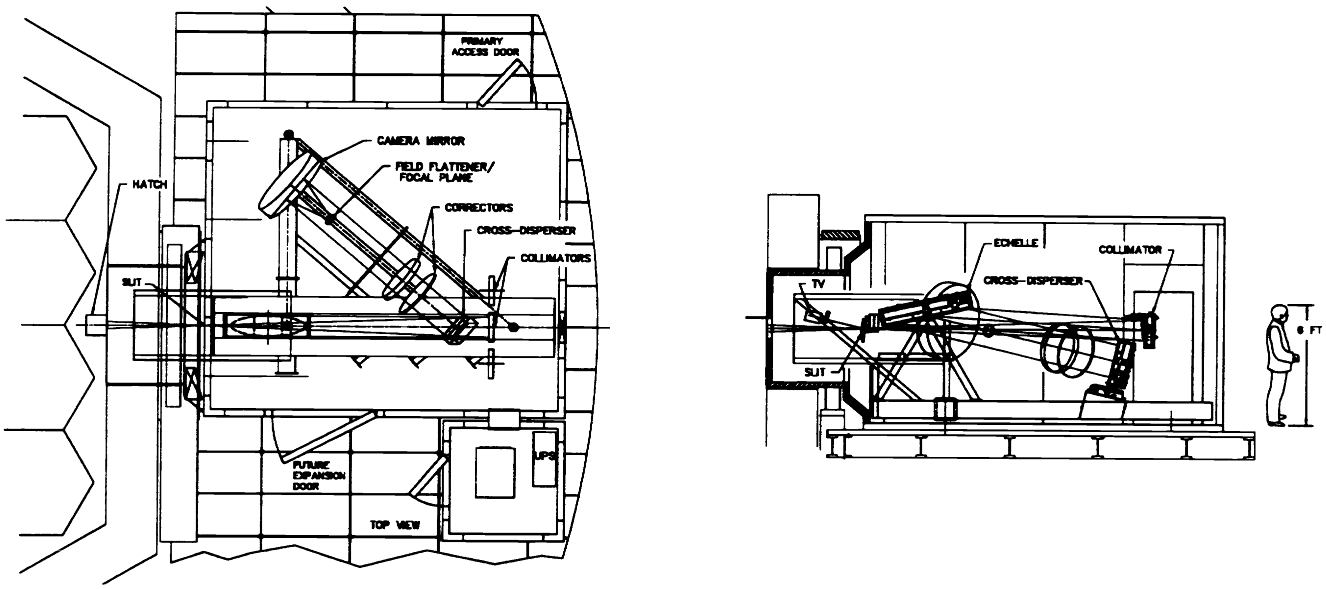

Figure 1: Top view and side view schematics of the HIRES Spectrometer. Light from the telescope enters from the left.

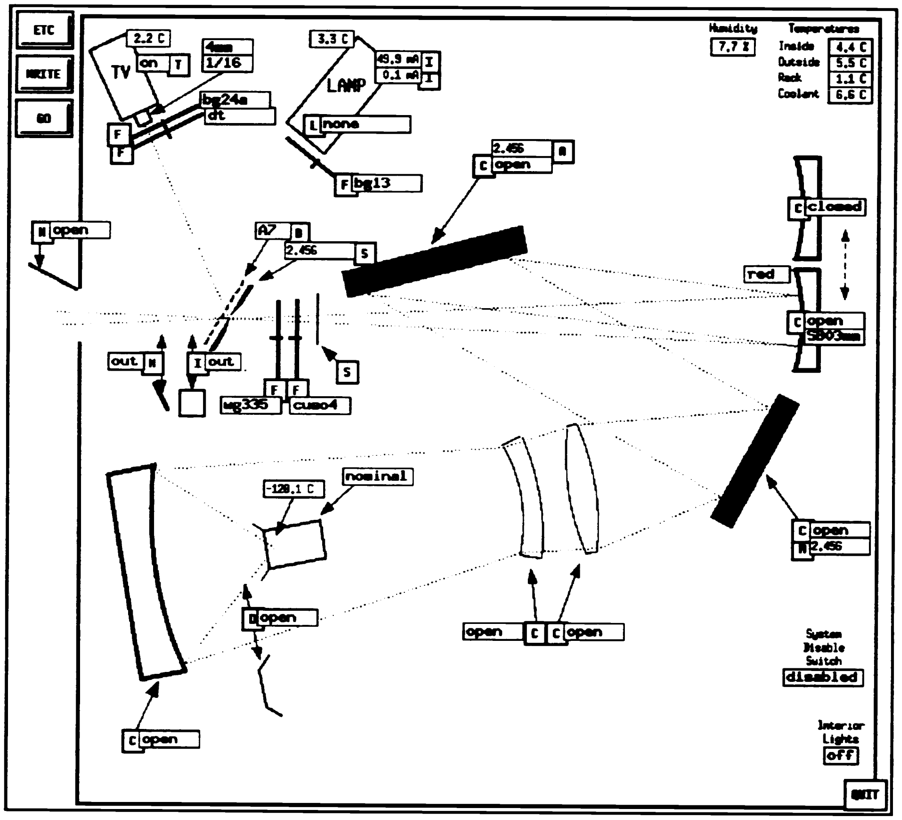

Figure 2: Simplified functional schematic of the HIRES optical system. This is actually the **xhires** graphical user interface

The instrument is permanently located on the 'right' Nasmyth platform. Light from the telescope enters from the left, coming to the $f/13.7$ Nasmyth focus at the slit. The slit area features a fairly standard complement of guiding and calibration devices. Ahead of the slit are various components for sending calibration light into the spectrograph and for finding and guiding on objects off the tilted polished slit jaws of the spectrograph. The slit is horizontal, and the slit plane is tilted 7.5° to deviate light reflected off the slit jaws by 15° up to a Photometrics CH250-L CCD-TV target acquisition and guiding camera. A Canon 200 mm $f/1.8$ lens provides a 45 by 60 arcsec field-of-view. The TV system includes two 8-position filter wheels for brightness and color control. One wheel holds neutral density filters, and the other holds colored filters. The TV system, with neutral density filters and aperture control, has a dynamic range in excess of 20 stellar magnitudes.

Calibration lamps are housed in a light-tight, thermally-insulated enclosure above the slit area. Light sources provided are a Th-Ar hollow cathode lamp, and a 3400°K quartz-halogen incandescent bulb. A filterwheel provides color balance control for the calibration lamps. The calibration lamp optical system was designed to ensure that calibration light enters the spectrograph as similarly as possible as that coming in from the telescope, at all wavelengths. This is crucial for accurate measurement of instrumental profiles and flat-fielding. The calibration light is fed into the spectrometer off a small flat mirror which slides into place in front of the slit during calibrations.

An iodine absorption cell can be moved in directly ahead of the slit for very precise stellar radial velocity work. This cell was built in collaboration with Drs. G. Marcy and P. Butler of San Francisco State University and follows their previous design.[8] The cell produces a large number of extremely sharp absorption lines between 0.48μ and 0.6μ, and impresses this calibration signal, free from systematic effects caused by imperfect spectrograph optics, directly onto the stellar spectrum. With such a cell, radial velocity precision of better than a few meters per second is routinely achievable.

A selection of deckers is available, carried in a 4-position tray on a linear slide in front of the slit. A combination of slit with overlaying decker, or fixed aperture plates are available. Some longslit capability is available if interference filters are used to isolate single echelle orders. The maximum usable slit length is about 70 arc-seconds. An image rotator and an atmospheric dispersion compensator (ADC) will also eventually be provided, but are not currently funded for first-light.

Directly behind the slit are two 12-position filter wheels containing filters necessary for blocking unwanted orders from the cross-disperser grating. Standard size 2″ by 2″ filters are used for ease of availability. All filters are AR-coated. Behind the filterwheels is a shutter which provides exposure control. This location is nearly the smallest place in the optical train, and thus convenient for a fast timing shutter.

After passing through focus at the entrance slit, the $f/13.7$ light cone is collimated into a 12″ diameter beam by a simple tilted spherical mirror. At the small tilt angle (1.75°), the sphere gave better performance, as averaged over a long slit, than an off-axis paraboloid, and was much less expensive to make. HIRES offers two optimally-reflective collimators. One is coated with the UCO/Lick 'holy grail' sapphire-overcoated silver recipe,[5] and is optimized for the 0.34μ to 3μ region. The other collimator features a 2-layer enhanced overcoated aluminum surface for the 0.3μ to 0.55μ region. The twin collimators sit side-by-side on a translating table. Both collimator mirrors are made oversized to accommodate the square beam produced by Richardson-type image slicers which may be added in the future if very high resolution work is required.

The collimated beam is then passed to a large echelle grating. This echelle is 12″ by 48″ in size, and was formed by mosaicing together three of the largest ruled echelles available from Milton Roy Co.. A more detailed description of the echelle mosaic is given below. The echelle is used in-plane with a collimator-to-camera angle of 10°.

The diffracted beam is then sent to a cross-disperser grating located below and slightly ahead of the collimators. The cross-disperser turns the beam 40° and into a large fast prime-focus catadioptric camera. This camera has a two-element corrector, a spherical light-weighted $f/0.76$ primary mirror, and a thick singlet field-flattener lens.

The field-flattener also serves as the vacuum dewar window. A more detailed description of the camera is also given below.

The optics are all mounted on a stiff steel optical bench which is attached kinematically to the Nasmyth weldment structure. The attachment is done such that differential expansion between the spectrometer bench and the Nasmyth weldment structure does not introduce stresses into the spectrometer. The entire instrument is housed in a light-tight, dust-tight, thermally-insulated enclosure. The electronics are housed in a separate enclosure which is thermally isolated from the spectrograph, and cooled via the Observatory's circulation coolant system.

3.1 Spectral format

The spectral format for the instrument is shown in Figure 3. This format is for the 1st order of the cross-disperser which is normally used redward of about 0.4μ. For work blueward of 0.4μ, the 2nd order of the cross-disperser is used and the order spacing doubles. The free spectral range of each order is shown by the bold central portion of each echelle order. The format of the Tektronix 2048 x 2048 CCD at three different locations on the echelle format is shown by the inset boxes. As can be seen, the present CCD is not large enough to cover the entire spectral format, so the desired spectral region to be observed is brought onto the CCD by rotating the echelle and/or cross-disperser. An echelle format simulator[9] aids in this task.

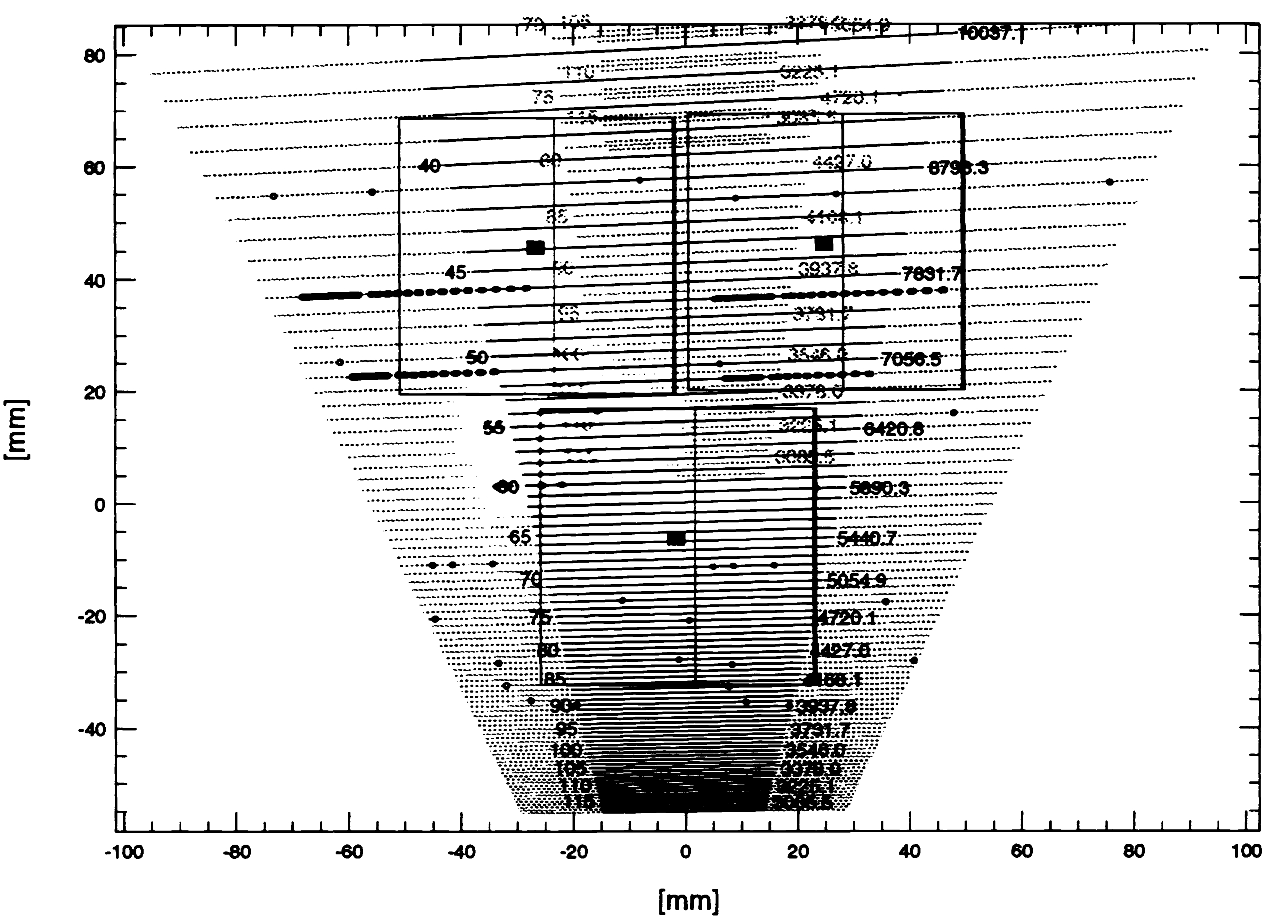

Figure 3: HIRES spectral format.

3.2 System efficiency

The overall efficiency of the HIRES instrument plus Keck telescope is shown in Figure 4. These curves represent the combined efficiency of the telescope, the HIRES optical train, and the HIRES CCD. They do not include losses due to a slit, or to atmospheric extinction. The solid curves are actual measured values obtained during commissioning through observations of spectrophotometric standards using a wide slit. The dotted curves are predicted efficiencies for other wavelengths (not yet measured) obtained by extrapolating from the standard star curves, using the measured efficiency curves for each surface.

The solid (measured) curves show some variation as expected from differing observing conditions on different nights. But they basically demonstrate that the instrument plus telescope combination peaks at about 6-8% near 0.6μ. The HIRES instrument by itself peaks at about 13%, but the telescope has three aluminum mirrors which each perform at about 85% efficiency. Thus about 39% of the light is lost to the Keck telescope mirrors.

All the HIRES optics transmit or reflect quite efficiently all the way down to the atmospheric cut-off at 0.3μ. The rapid fall-off of HIRES efficiency in the ultraviolet is due mostly to the roll-off of the Tektronix CCD's quantum efficiency. While this CCD features very high overall quantum efficiency from the blue through the near-infrared, it drops sharply below 0.4μ, achieving only about 7% QE at 0.3μ. Other more uv-sensitive CCD arrays are currently under development at UCO/Lick to improve this.

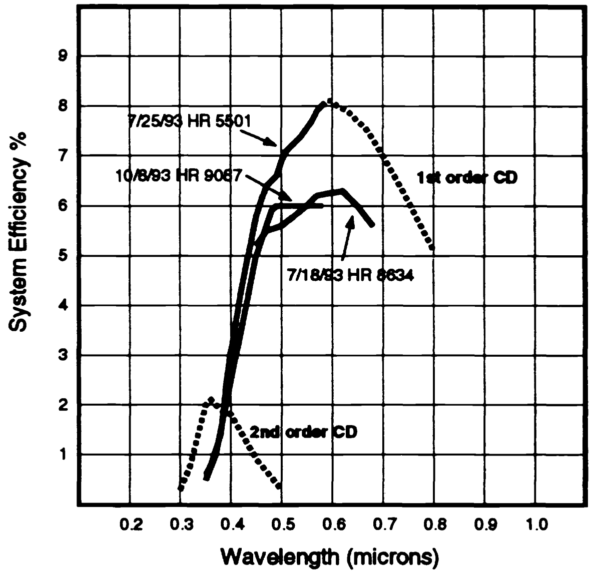

Figure 4: (HIRES + Keck) efficiency.

3.3 Echelle and cross-disperser mosaics

In order to achieve an adequate 'throughput', or resolution times slit width product, with a telescope as large as the Keck, it was necessary to use a large path length for interference at the echelle. This was done by using a relatively steep echelle blaze angle (70.5°), with a relatively large collimated beam size (12″ diameter), and then mosaicing three of the largest commercially-available echelles (12″ by 16″ from Milton Roy Co.) to get the required length of ruled area. Conventional 1:2 aspect ratio R-2 or higher echelles, are not long enough to accept a circular input beam of same diameter as the echelle's width, leading one historically to overfill the echelle and vignet light for 'optimum' performance. The HIRES echelle mosaic aspect ratio properly matches the elliptical input beam footprint. There is no vignetting of light at the echelle, and no need to overfill the echelle.

The ruling density of the echelles was chosen to be 52.676 gr mm^{-1}. This choice was based on the desire to match the echelle free spectral range (FSR) to the width of a 61 mm by 61 mm mosaic of Ford 2048^2 (15-micron pixel) CCD's, the detector format originally intended for HIRES. The echelle ruling density was set such that the FSR would have begun to exceed the detector width at about 6856 Å, at the atmospheric B-band, an area of the spectrum where there is generally little spectral information and lots of contamination from atmospheric lines. The gaps in the spectrum which then result from overfilling the detector in any single exposure would have occurred mostly in uninteresting and/or contaminated regions of the spectrum. As it turned out, despite this fine-tuning of the echelle format, we reached first-light with a smaller CCD format (49mm by 49mm), and thus the placement of holes in a single-shot spectrum is presently less than optimum, and gaps begin redward of about 5200 Å. This situation will improve when a larger focal plane format is installed.

The three echelle gratings were mosaiced together by kinematically mounting the blanks (minimally constrained) onto a granite support slab. Each grating sits on three zerodur washers, and the washer thicknesses were adjusted through fine grinding to adjust the tilt of each grating. Side supports provided adjustment for rotation (about the grating normal). In aligning the mosaic, the center grating was the reference and did not need adjustment. We checked the relative grating alignments with a Zygo interferometer, counting fringes and measuring fringe tilt to iterate on washer thicknesses and adjust rotation about the grating normals until adequate alignment was achieved. Since there are three echelles and two cross dispersers, one actually has 6 independent echelle spectra overlapping at the focal plane. Thus adequate alignment is required to preserve spectral and spatial purity in the data. Typically, with our 6″ diameter interferometer, we were able to align the gratings to an accuracy of about 0.6 arcsec, which corresponds to shifts at the focal plane of 3–4 microns. This is much less than the size of our typical 15 to 24-micron detector pixels and thus deemed adequate. In the future, if we install smaller pixel CCD's and image slicers to achieve very high resolutions, the mosaic alignment may need finer tuning.

Since we do not intend to use the instrument at resolutions higher than that theoretically available ($R = 750,000$) from any single echelle in the mosaic, we made no attempt to phase the mosaic's components, nor even to control piston misadjustment. Rather, we intentionally pistoned the gratings such that half of each mosaic gap is shadowed, thereby reducing the 3.25% light lost in the gaps to 1.6%. While this savings may not seem like much, it amounts to about one-half the area of a Keck primary segment, and seemed worth doing.

There is only one cross-disperser at first light, though others can be added in the future as science needs dictate. The cross-disperser is a 2 by 1 mosaic of 12″ by 16″ gratings. The gratings are mosaiced along the ruling length direction such that the effective length of each ruling is 24″ and the width of the ruled area is 16″. This geometry nicely matches the anamorphic beam from the echelle. The mosaic concept is essentially identical to the echelle mosaic. The cross-disperser ruling density was chosen by first selecting the echelle ruling density (as described previously), and then adjusting the cross-disperser ruling density until the maximum amount of spectral coverage obtainable per exposure in the cross-disperser's second order (in the ultraviolet/blue) maximally filled the vertical dimension of the CCD detector. This approach then yields the maximum allowable order separation at the maximum allowable spectral coverage per exposure in the UV/blue. That established the cross-disperser ruling density as 250 $\mathrm{gr\,mm^{-1}}$. The cross-disperser is blazed at 7000 Å (first-order) and will be used in either first or second order, with filters to block unwanted orders.

It has now been over one year since the instrument was first assembled, and HIRES has been in use at the telescope for the past 8 months. So far, the mosaics have remained in alignment within specification, and thus seem to be a successful solution for making large passively-mounted grating mosaics.

3.4 Camera

The optical design of the camera was one of the most difficult design challenges of HIRES. A more detailed discussion of the HIRES camera problem and our ultimate solution has been published.[10] Basically, we required an $f/1.0$ (polychromatic) camera with a 30″ diameter clear aperture, and an entrance pupil displaced well ahead of the camera mouth. Furthermore, this large camera had to be able to provide 10–15 micron diameter images with high efficiency over the entire spectral region from 0.3μ to beyond 1.1μ, and to a flat focal surface without refocussing.

To meet these requirements, we designed a unique new type of large, very fast, highly achromatic camera. It is shown in Figure 5. This camera is an $f/1.0$ (polychromatic) prime focus catadioptric system with two fused silica corrector lenses, an $f/0.76$ primary mirror, and a fused silica field flattener which also serves as the dewar vacuum window. It has a 29.5″ diameter input aperture, a focal length of 30.0″, and covers a 6.7° diameter field of view. The camera is optimized for use with an entrance pupil which lies 85.0″ ahead of the corrector, as required for HIRES. Moreover, this family of camera designs is relatively insensitive to pupil location, and can be

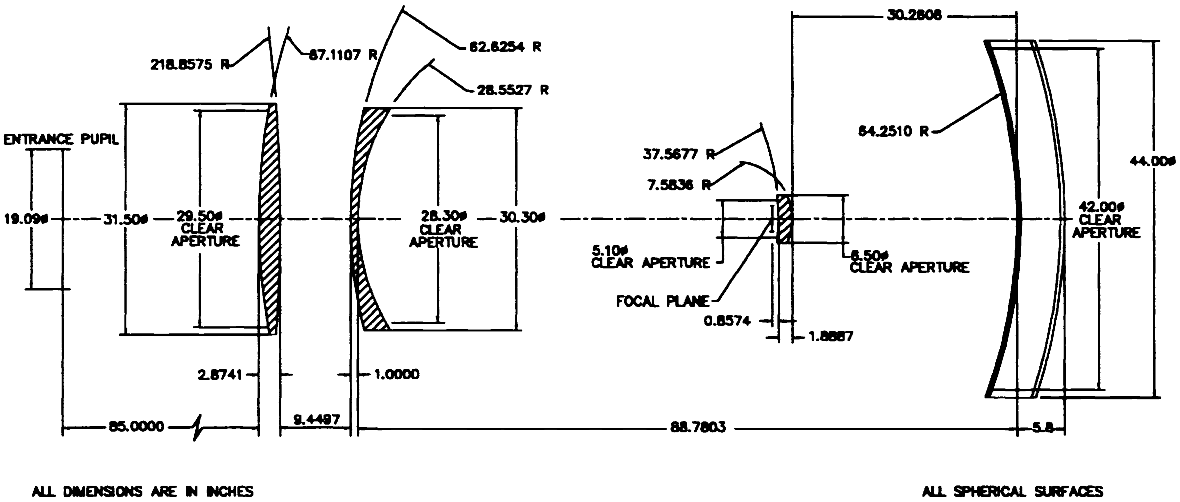

Figure 5: HIRES camera design. This is a 6.7° diameter field of view $f/1.0$ all-spherical system with a simple fused silica field flattener which also serves as the dewar window.

re-optimized to accommodate other pupil distances. The camera uses all-spherical surfaces, so it can be fabricated easily in the large size required. Its refracting elements are all fused silica, with very high transmission from 0.22 to 2.0 microns. All air/glass surfaces of the camera are Sol-Gel AR-coated. The large lenses are sufficiently thin that they sag under their own weight. Finite-element analysis was used to design lens support cells which remove this sag. The mirror of the camera uses a Hextek light-weighted blank. The camera focus was athermalized by incorporating Delrin spacers of the correct length in the mirror mount. These spacers exactly compensate for thermally-induced expansion/contraction of the steel camera frame and thereby remove focus changes due to temperature variation. The camera never needs re-focusing. To optimize instrumental throughput, there will eventually be two separate camera mirrors with reflectances optimized for visible and ultraviolet.

Spot diagrams and ray trace analysis show that the camera delivers 12.6 micron rms image diameters (averaged over all colors and field angles) over the entire chromatic range from 0.31μ to 1.1μ, without refocus. Further achromatism is possible beyond both blue and red extremes of the design range with design re-optimization and/or some refocus, with little penalty in overall image quality. In practice though, if an infrared array is installed in this camera, it will reside in its own separate dewar, and we will accordingly optimize its field flattener (which is also the dewar window) to obtain peak performance in the infrared.

3.5 Detector

The CCD installed at first-light is a Tektronix TK2048 CCD (2048 x 2048 format of 24 micron pixels). These devices are quite expensive (about $100,000) and still quite hard to get, but are properly thinned for backside illumination and AR-coated. They thus feature very high average QE over the entire 0.3μ to 1.1μ region. The QE is about 11% at 3200 Å, 60% at 4000 Å, rising to a broad maximum of about 70% near 6500 Å, and then rolling off to 63% at 8000 Å, and 28% at 9500 Å. With the temperature held at -120 C and operating in MPP-mode, the TK2048 CCD has a dark current of 1-2 electrons per pixel per hour and a readout noise of 5-6 electrons. The 24-micron pixels are a bit larger than desired, but will be quite acceptable for much first-light science. For low S/N work on very faint objects, the larger pixel will even be preferable.

It should be pointed out that Tektronix TK2048 CCDs are not flat. Measurements of several mechanical and engineering-grade samples showed a roughly spherically convex surface with a radius of curvature of about 65″. The HIRES camera was originally designed for a *flat* focal surface, and this amount of focal surface curvature on such a fast camera would have been quite unacceptable, leading to significant loss of spectral and spatial resolution. Fortunately, we were able to re-optimize the field flattener to remove most of the effect without changing any other parameters of the optical prescription.

3.6 Enclosure

The spectrometer is housed in a light-tight, dust-tight, thermally-insulated enclosure. Thermal modeling studies of the spectrometer[11] showed that an insulated enclosure was necessary for adequate thermal stability of the instrument. The enclosure used provides at least a 9.5 hour time constant for the sealed spectrometer to track a 1°C temperature change in the dome air temperature, without active temperature control of the air inside the spectrometer. A clean room entrance trap is provided to collect dust, lint, etc, and to provide a place for technicians to put on clean gowns and boots. The air inside the spectrometer is slightly overpressurized with dried, filtered dome air to inhibit dust flow into the instrument. Every effort has been made to keep heat sources out of the spectrometer. Most moving devices are either air-piston actuated, or use DC servo motors which are powered off when not in use.

3.7 Electronics control system

The control system for HIRES is a VME-based system which uses only Keck Observatory standard modules. HIRES is one of five first-light instruments connected to a scientific instrument LAN at the mountaintop. Each instrument is controlled by its own VME-bus based Sparcengine-1E real-time controller running VxWorks, which connects over the scientific Ethernet LAN to either of two SUN Sparc-series instrument computers. Since there are two identical instrument computers, two separate instruments can be electronically on-line at the same time, as will often happen as one team prepares an observing run following another. One instrument computer also serves as a back-up for the other. The instrument computers are then connected to the Keck Observatory Ethernet LAN which provides a link with similar computers at the headquarters down in Waimea.

The HIRES VME chassis includes one Sparcengine-1E CPU card, eight Galil DMC 330-10 Motor controller cards, three XYCOM XVME-212 input port cards, three XYCOM XVME-220 output port cards, and one XYCOM XVME-540 Analog logic card. Most moving mechanical devices are driven by Galil DC-servo motors. Each optical instrument which uses a CCD has its own CCD controller system. The CCD controller[12] is based on the Leach[13] design and utilizes a programmable digital signal processor to generate timing signals and manage communication with the host computer, and allows remote programming of the timing waveforms and CCD clocking voltages. The CCD clocks are generated with digital-to-analog converters while a conventional preamplifier, dual slope integrator and 16-bit analog-to-digital converter process the CCD video signal. All of the electronics are housed in a separate thermally-insulated enclosure adjacent to the spectrometer. This electronics enclosure is cooled via the Observatory's recirculating coolant system. Since we were obliged to use standard observatory VME electronics modules which are not rated for use below 0°C, we actually hold the electronics enclosure at a temperature of 5°C.

3.8 Software control system

The software for instrument control at Keck Observatory is written in the C programming language and runs under UNIX on a network of Sun computers. The observer controls a given instrument through a user interface which allows both command-line input through keywords and scripts, and window-style graphical input using X11 windows with the MOTIF toolkit. Both types of input can be intermixed. The user interface also allows for multiple invocation of control processes, which is important for distributed observing. Here, the primary observer can be quite remote from the telescope (i.e. in Waimea or back in California), while graduate students and/or technical observers at other sites, or at the mountaintop, can cooperate in the set-up and running of the instrument during an observing run.

The astronomer's interaction with the HIRES instrument is mostly through the `xhires` graphical user interface. A description of this interface is given elsewhere in these proceedings.[14] Quick-look data reduction is done using the IRAF and/or FIGARO data analysis packages.

Operationally, HIRES is fully remotely-controlled, with minimal attention or maintenance required from mountain technical personnel. It is on-station and ready for observing 24 hours a day, 365 days a year. It has its own uninterruptable power supply system, and can ride out most power outages, even if one occurs during an exposure, without loss of any data. HIRES can be operated remotely over the Internet. It fills its own LN_2 dewar daily, and monitors a wide variety of environmental and instrument parameters such as temperatures, pressures, and humidities in various enclosures, positions of all moving components, dewar levels, voltage levels, line pressures, door-ajar, lights on, etc.. Anomalous readings generate audible verbal alert warnings in the control room on the summit, and email alert warnings over the Internet to personnel at CARA headquarters in Waimea and at UCO/Lick Observatory in Santa Cruz.

4 FIRST LIGHT SCIENCE

4.1 Quasar Absorption Lines

Much of the first-light science being done with HIRES concerns high spectral resolution observations of the absorption line spectra of quasars. The quasar studies include observations of the Lyman-alpha forest in high redshift quasars to $z = 4.7$, and accurate measurements of the abundances and velocity structure of intervening metal-line systems.

One of the first projects underway is a study of abundances in damped Lyman-alpha (DLA) systems. The first object studied was the archetype DLA system in PHL 957. This work is a collaboration between A. Wolfe, D. Tytler, K. Lanzetta, S. Vogt, and M. Keane. Figure 6 shows some detailed line profiles of Zn II and Cr II and in the DLA system at $z = 2.309$. The high resolution and high S/N are essential for resolving the multiple velocity components, and for measuring weak equivalent widths accurately. The low abundances derived from these data indicate that damped systems at $z \geq 2$ may be protospheroids which have probably not yet collapsed into protogalactic disks.

Another project underway is a detailed study of both the Lyman-alpha forest and the metal absorption lines in the relatively bright quasar PKS 2126-158. This work is being done by M. Keane as a Ph.D thesis research project. Observations covering the 3495–7060 Å region were obtained during HIRES commissioning in July and October of 1993. Figure 7 shows a section of the Lyman-alpha forest in this object at 9 $\mathrm{km\,s^{-1}}$, and $S/N = 30$. These data represent 8.5 hours of integration on this $V = 17.1$ object. The spectrum is now being analyzed to study many aspects of the Ly α forest such as the distributions of H I column densities and Doppler parameters, the velocity clustering amplitude, and the presence of weak heavy element lines. The observations also include several prominent metal line absorption systems which will be used for studying the dynamics, ionization state and abundances of clouds in galactic halos at $z \approx 2.5$.

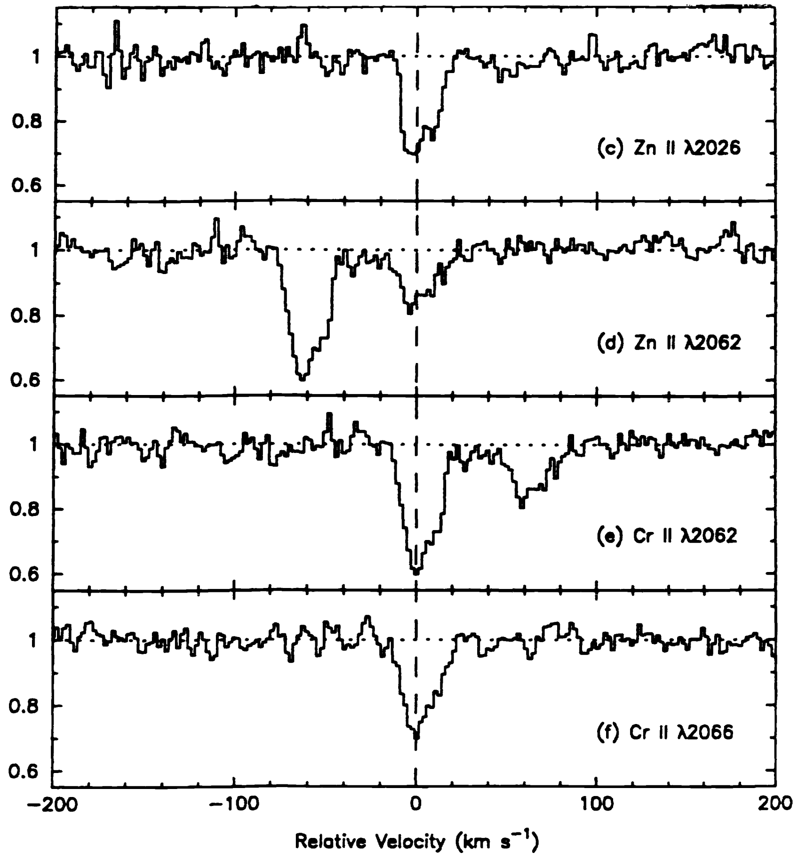

Figure 6: Metal lines in the damped Lyman alpha absorption system at $z = 2.309$. The typical S/N is ≈ 60 per 8 km s^{-1} resolution element in this 1.6 hr integration. Preliminary analysis of these data show [Zn/H] = -1.46 and [Cr/H] = -1.99 in agreement with previous work at lower resolution[15,16].

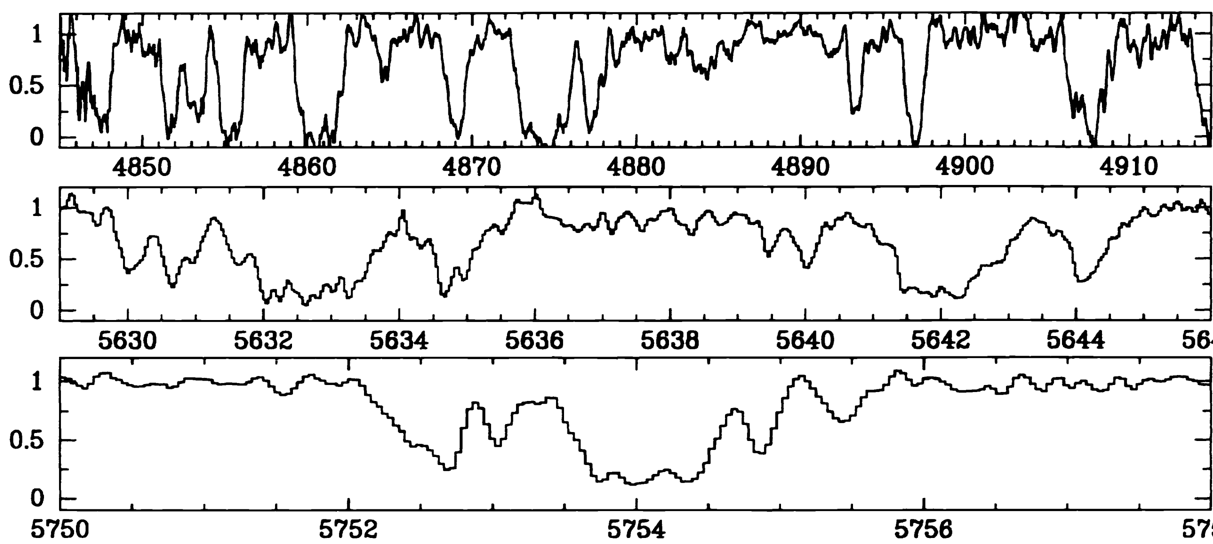

Figure 7: *Top*: A 70 Å portion of the Lyman-alpha forest at $z \approx 3$ in PKS 2126-158. *Center*: C IV λλ1548,1550 doublet at $z = 2.638$ in PKS 2126-158. *Bottom*: Si II λ1526 at $z = 2.769$ PKS 2126-158.

4.2 Beryllium in the Early Universe

Knowledge of the origin and evolution of beryllium (Be) in the early universe will improve our understanding of Big Bang nucleosynthesis (BBN) and cosmology, cosmic ray theory, and the chemical and dynamical history of the Galaxy. We are attempting to extend the exploration of Be in the early universe by observing Be in extremely metal-poor halo dwarfs with HIRES. A team consisting of A. Boesgaard, C. Deliyannis, J. King, S. Ryan, T. Beers, S. Vogt, and M. Keane are collaborating on this effort. High spectral resolution and high signal-to-noise on these faint stars are essential for this project, data which can only be obtained at the Keck Observatory with HIRES. In fact, this project was one of the key science drivers in the design and optimization of the HIRES instrument concept. The ability to make observations at the extremely difficult ultraviolet wavelength of the Be II $\lambda\lambda$ 3130,3131 doublet largely determined the HIRES camera design, and mirror reflectance optimizations.

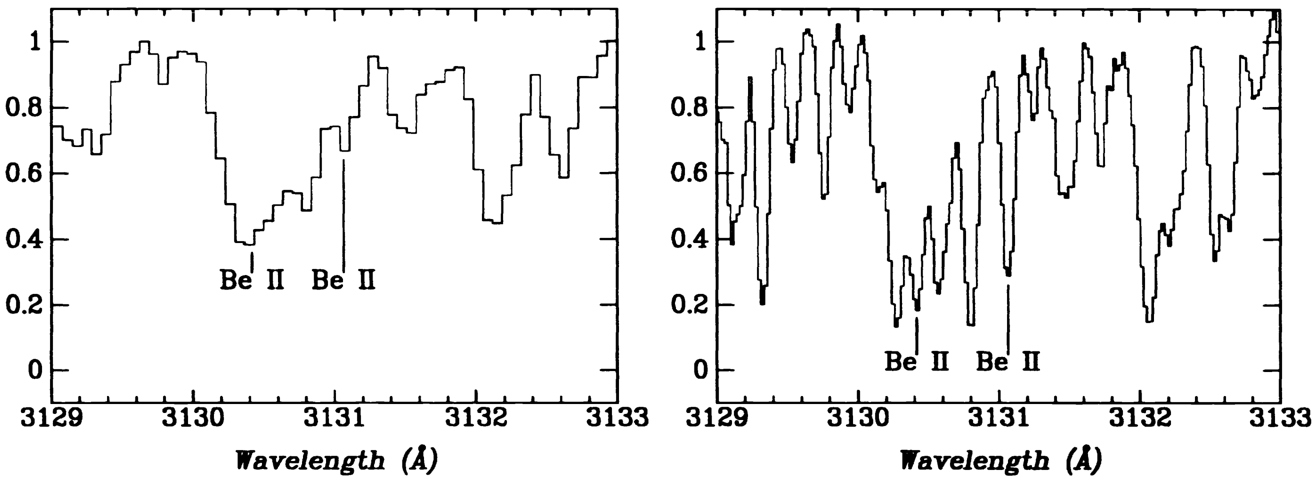

Figure 8: Spectra of the Be II region of HD 184499. The spectrum at the left represents the best previously available data obtained with a 4-m class telescope. The spectrum at right was taken with HIRES/Keck in October, 1993. The Be II features are marked, and stand out clearly separated from the blends in the HIRES spectrum.

Preliminary beryllium observations were obtained on October 5, 1993 as part of HIRES commissioning. Figure 8 shows a comparison of beryllium spectra obtained at the CFHT against a HIRES spectrum of the same star. The HIRES observation was 10 minutes at a resolution of about 45,000. These data and others confirmed our expectations and demonstrated that speed gains of at least 50 to 100 have been achieved with HIRES over the best previous results.

4.3 Lithium in Brown-Dwarf Candidates

As an example of the capability of HIRES at the faint end ($V \approx 21$) for stellar spectroscopy, we show a search for lithium in Pleiades brown dwarf candidates done by G. Marcy, G. Basri, and J. Graham of UC Berkeley. Basically, the presence of lithium in the atmosphere of any but the most youthful of M dwarfs is a spectroscopic signature for a brown dwarf. Several of the lowest luminosity Pleiades stars are brown-dwarf candidates, with estimated masses of 0.055–0.059 $M_{\odot}$. If their masses are this low, stellar interior models predict that they should not have burned any lithium, and should thus show strong lithium in their spectra.

HHJ 3 and HHJ 14, two of the lowest mass objects known in the Pleiades (or in any open cluster) were observed with HIRES on 11 November, 1993 at a resolution of $R = 31,000$. These objects have R magnitudes

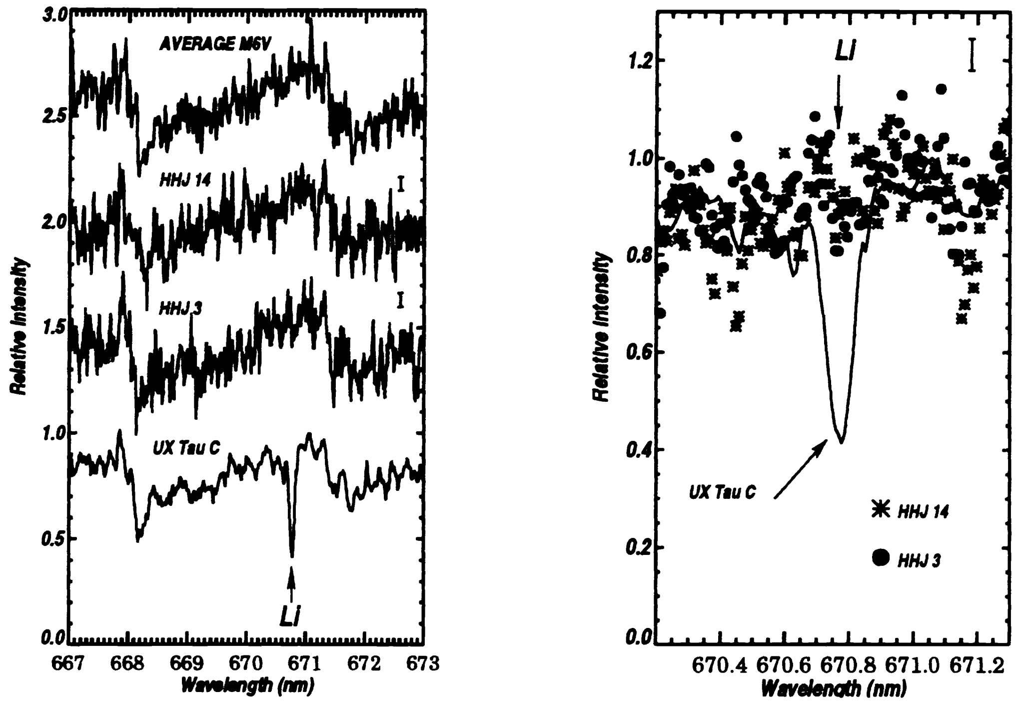

Figure 9: *Left:* spectra of program stars near Li 670.8 nm. The upper spectrum is the average of four field M6 dwarfs showing no lithium. The middle two spectra are HHJ 14 and HHJ 3, the two Pleiades brown-dwarf candidates, neither showing the Li line. The bottom spectrum is of the T Tauri star UX Tau C, which shows strong Li due to its extreme youth. ***Right:*** A detailed plot of the Li line for both the Pleiades brown-dwarf candidates, HHJ 3 and 14, and for the T Tauri star, UX Tau C. The brown dwarf candidates show no Li, demonstrating severe depletion.

of 19.6 and 18.9 respectively. They were observed for 3.0 and 1.63 hours respectively, for a resultant S/N of 15 and 20 respectively. Figure 9 shows the spectral data along with that of some field dwarfs and T Tauri stars for comparison. No evidence of lithium was found, indicating a high degree of lithium depletion, and suggesting strongly that these objects have masses of $M > 0.09 M_{\odot}$. Thus, they do not seem to be brown dwarfs.[17]

4.4 Asteroseismology

HIRES has an iodine absorption cell for obtaining extremely high precision radial velocities of cool stars. This capability will be used to search for planetary companions around bright stars, and to study global acoustic oscillations on solar-type stars (asteroseismology). Detection of analogs to the solar 5-minute oscillations in other stars would provide a powerful technique for studying details of internal structure that has heretofore been restricted to the Sun.

In a collaboration with G Marcy, P. Butler and T. Brown, the K1 V star 107 Psc ($V = 5.2$) was observed continuously for 6 hours with Keck/HIRES. Every 75 seconds, a spectrum covering 4800–6000Å at a spectral resolution of 60,000 was acquired using the iodine absorption cell for wavelength reference. These individual spectra have $S/N \approx 700$. Analysis of this data set is in progress. The expected radial velocity accuracy of this dataset, set by photon statistics, is 3–4 $\mathrm{cm\,s^{-1}}$ which should be sufficient to permit detection of low-degree disk-integrated solar oscillations if they are present on this star.

5 ACKNOWLEDGMENTS

We would like to thank the Keck Observatory Science Steering Committee and the CARA board for funding the construction of HIRES. We would also like to thank the many talented members of the W.M. Keck Observatory staff who helped in the interfacing, installation, and commissioning of HIRES on the Keck telescope. These individuals include Tom Bida, Teresa Chelminiak, Jon Chock, Peter Gillingham, Chris Hunt, Kyle Kinoshita, Hilton Lewis, William Lupton, Bill Mason, Bob Moskitis, Jerry Nelson, Maurice 'Mo' Noe, Ed Romana, Barbara Schaefer, Julia Simmons, Mark Sirota, Gerald Smith, Terry 'Stick' Stickel, Sheila Sumaylo, and Peter Wizinowich. Special thanks are also due to Ian Thomas, Gary Edwards and the coating group at the Lawrence Livermore National Labs for providing the Sol-Gel anti-reflection coatings for the camera lenses, to John Hoos, Tom Blaziak and associates at Milton Roy Co. for the large custom-ruled echelles and cross-dispersers, and to Rich Wortley and associates at Hextek for the lightweighted camera mirror blanks.

6 REFERENCES

1. Vogt, S.S. 1992, in *High Resolution Spectroscopy With The VLT ; ESO Conference and Workshop Proceedings No.40*, ed. M.-H. Ulrich (Garching: European Southern Observatory), p. 223.

2. Vogt, S.S. 1988, *HIRES Phase B Proposal*, UCO/Lick Observatory.

3. Nelson, J.E., Mast, T.S. & Faber, S.M. 1985, *Keck Observatory Report No. 90*, (Berkeley: U. of California Lawrence Berkeley Laboratory).

4. Vogt, S.S. 1983, *Keck Observatory Report No. 101*, (Berkeley; U. of California Lawrence Berkeley Laboratory).

5. Vogt, S.S. & Penrod, G.W. 1987, in *Instrumentation For Ground-Based Optical Astronomy: Present and Future*, ed. L.B. Robinson (New York: Springer-Verlag), p. 68.

6. Osborne, J. & Bigelow, B. 1993, *The Mechanical Design of HIRES*, UCO/Lick Observatory Technical Report No. 64.

7. Vogt, S.S., *HIRES User's Manual*, UCO/Lick Observatory Technical Report No. 67.

8. Marcy, G. W. & Butler, R.P. 1992, *Publ. Astron. Soc. Pacific.*, **104**, 270.

9. Allen, S.L., *Keck HIRES Echelle Simulator*, UCO/Lick Observatory Technical Report No. 68.

10. Epps H.W. & Vogt, S.S. 1993, *Applied Optics*, **32**, 6270.

11. Osborne, J. & Bigelow, B. 1989, *Keck Telescope High Resolution Spectrograph Thermal Models*, UCO/Lick Observatory Technical Report No. 51.

12. Kibrick, R.I., Stover, R.J., and Conrad, A.R., *Astron. Soc. Pacific Conf. Series*, **52**, 277.

13. Leach, R. 1988, *Publ. Astron. Soc. Pacific.*, **100**, 1287.

14. Conrad, A., Cromer, J. & Kibrick, R. 1994, these proceedings.

15. Meyer, D.M. & Roth, K.C. 1990, *Ap.J.*, **363**, 57.

16. Pettini, M., Boksenberg, A. & Hunstead, R.W. 1990, *Ap.J.*, **348**, 48.

17. Marcy, G.W., Basri, G. & Graham, J. 1994, *Ap.J.Lett.*, submitted.