Performance and results with the NIRSPEC echelle spectrograph on the Keck II Telescope

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ABSTRACT

This paper describes the performance of NIRSPEC, the cryogenic cross-dispersed infrared echelle spectrograph for the Keck II telescope on Mauna Kea. NIRSPEC employs a 1024 x 1024 InSb array, diamond-machined metal optics and closed-cycle refrigeration to achieve high throughput and low backgrounds. The instrument operates directly at the f/15 Nasmyth focus, but can also be used in conjunction with the Keck adaptive optics system. First Light was obtained on April 25, 1999. As expected, the performance is detector-limited at short wavelengths and background-limited at longer wavelengths. All of the design goals have been met and results illustrating the optical performance and sensitivity are reported.

Keywords: infrared instruments, infrared detectors, infrared optics

1. INTRODUCTION

NIRSPEC, the near-infrared spectrometer, is a facility instrument for the right Nasmyth focus of the Keck II 10-meter telescope on Mauna Kea, Hawaii. Following a successful conceptual design review in April 1994, the project was funded by CARA (the California Association for Research in Astronomy) in October 1994 with a budget of \$3.49M and a delivery date of November 1998. NIRSPEC was actually delivered to Mauna Kea in March 1999 and achieved "first light" on the Keck II telescope on April 25, 1999, only four months late on a schedule set five years earlier. The cost over-run was only \$150,000. Initial design concepts and design goals for NIRSPEC were presented at an SPIE meeting in 1995[1]. The final design was presented at the SPIE meeting in Kona in 1998[2,3]. No significant changes in design, or reductions in scope were required.

From the outset, NIRSPEC was designed as a high-resolution spectrograph to take full advantage of the very large aperture of the Keck telescope. Briefly, the design goals were as follows: wavelength coverage from 0.95-5.5 μm, high optical throughput, resolving power ($R=\lambda/\Delta\lambda$) of 25,000 for a slit width of ~0.43″ (3 pixels) consistent with median infrared seeing on Mauna Kea, cross-dispersion to maximize the use of the large-format square array, use of closed-cycle refrigerators for cooling, and matched to the f/15 Nasmyth focus but moveable on rails. These goals were met with an all-reflective optical design based on silver-coated, diamond-machined aluminum mirrors, custom gratings and the ALADDIN 1024 x 1024 InSb array from Raytheon IR Center of Excellence (IRCOE). A separate Low-Resolution mode with R=2,500 (2 pixels) was also achieved. An infrared slit-viewing camera (SCAM) for ease of setup, a cryogenic image rotator, and a CCD guider were also included. NIRSPEC has three different detectors: a standard CCD camera for acquisition and offset guiding, a 1-2.5 μm near-infrared "slit-viewing" camera - the SCAM, and the primary 1024 x 1024 InSb array for the spectrograph. The instrument is controlled from a Graphical User Interface which includes a powerful Echelle Format Simulator (EFS). This paper describes the basic principles of operation of NIRSPEC and also summarizes its performance.

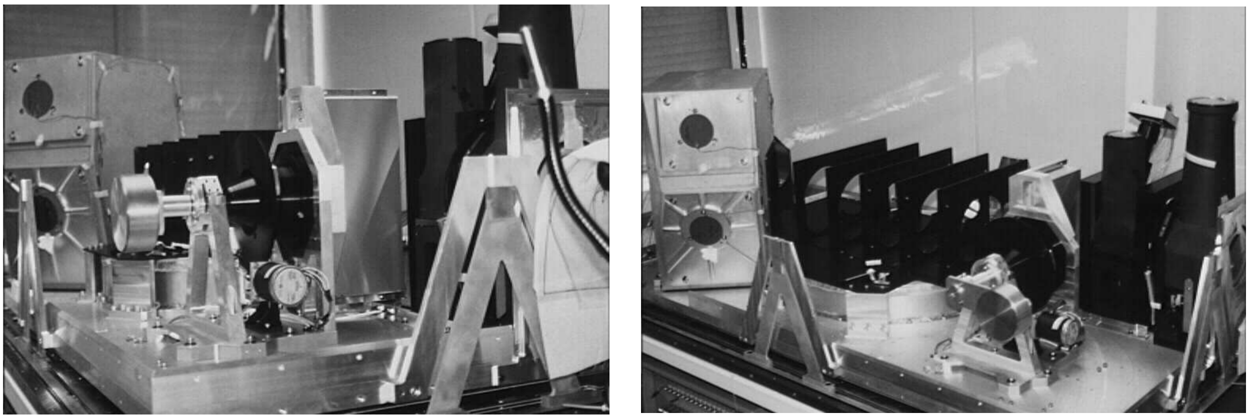

Figure 1. Two views showing the layout of the internal optics of NIRSPEC. On the left, the gold-coated 22 l/mm echelle grating is seen in the foreground. In the position shown, the flat mirror on the rear side is in place for the low-resolution mode. The image on the right shows the distribution of components on the cryogenic optical bench. The large gold unit to the rear is the three mirror anastigmat (TMA). The tower-like tube at the extreme right is the K-mirror collimator and image rotator.

2. DESIGN AND BASIC PRINCIPLES

Optically, NIRSPEC consists of a “front end” which collimates the diverging f/15 beam from the telescope to produce a pupil image approximately 26 mm in diameter and provide a convenient location for a cold stop and filters. The collimator is the second element of a reflective K-mirror arrangement which folds the beam. This section is followed by re-imaging optics, again in the form of a K-mirror, which convert the beam from f/15 (1.38"/mm) to f/10 (2.06"/mm) at the slit plane. Following the slit, the emergent f/10 beam is collimated with a 1.2 m focal length off-axis parabolic mirror to produce a 120 mm diameter pupil on the echelle grating. A system of baffles keeps the beams apart and reduces scattered light to negligible levels (the baffles can be seen in Figure 1). Diffracted light from the echelle is then cross-dispersed by another grating at right angles to the first, and the beam is collected by a special f/3 camera in the “back end” and then focused onto the large-format infrared array detector. Each mirror is diamond-machined and post-polished on nickel-aluminum substrates. Both gratings also use aluminum substrates. All mirrors are silver-coated, whereas the gratings and slit substrates are gold-coated.

The NIRSPEC spectrograph employs a single echelle grating in Quasi-Littrow (QLM) mode with the out-of-plane angle, γ=5°. This approach provides higher efficiency than the Near Littrow mode with the same opening angle, with the minor penalty of slit images which are slightly tilted. With $\tan\theta_B = 2$, where $\theta_B = 63.5°$ is the blaze angle, and a (cryogenic) groove density of T=1/d=23.29 lines/mm, the product of central wavelength and order number is

$$m\lambda_B = d\,(\sin\theta_i + \sin\theta_o)\cos\gamma = 2d\sin\theta_B\cos\gamma = 76.56\ \mu m. \tag{1}$$

At short wavelengths, a central wavelength of λ = 0.957 µm occurs in order m = 80, but near the detector response cut-off , the central wavelength of λ = 5.47 µm occurs in order m = 14.

The free spectral range (FSR) in each order is λ/m and to fit one FSR onto a detector with N pixels, at 3 pixels per resolution element, requires $m_{fsr} = 3R/N$. For R=25,000 and an array with 1024 pixels this implies $m_{fsr} = 73$ and the corresponding central wavelength is 1.045 µm; the FSR is therefore 0.014 µm or 140 Å and the dispersion *at this wavelength* is 0.139 Å/pixel. At longer wavelengths the FSR is larger than the detector array and therefore *multiple* grating settings are needed for complete coverage of a given band. Since the “extent” of a free spectral range in microns scales with the wavelength squared, but the resolving power is constant and therefore the “size” of a resolution element ($\Delta\lambda$) in microns scales with wavelength, then the number of grating “settings” needed to cover the width of the echellogram scales only as λ. For example, at λ= 5.225 µm (5 x 1.045 µm), the number of non-overlapping settings would be $5^2/5 = 5$.

For *cross-dispersion*, the grating used has a smaller blaze angle, a higher groove density and zero out-of-plane angle. Since the geometry of NIRSPEC's optical layout requires a difference of 50° between the input and output beams, and the condition for maximum efficiency is met when $|\theta_i - \theta_B| = |\theta_o - \theta_B|$, then we find that $\theta_i \sim 35°$, $\theta_o \sim -15°$, and $\theta_B \sim 10°$. NIRSPEC's cross-disperser grating (or CDG) has a groove density of 75.75 lines/mm (at the operating temperature). Using these values in the grating equation yields

$$m_c \lambda_{cen} = 4.155\ \mu m. \tag{2}$$

The CDG is used in low order (m_c = 1 - 4) together with custom *order-sorting* filters located in a filter wheel near the pupil image formed by the front-end optics. Separation of orders in pixels is $14.25\lambda_B{}^2 m_c$ which gives 62 pixels at 1.045 µm in 4th order, or about 11.8″. Two slit lengths are provided in NIRSPEC as described below.

The only penalty of the Quasi-Littrow mode is that the image of the slit is tilted with respect to the grating grooves by an angle χ given by[4]

$$\tan \chi = 2 \tan\theta_B \tan\gamma = 4 \tan\gamma. \tag{3}$$

For our adopted value of $\gamma = 5°$, $\chi = 19.3°$. The array can be rotated so that the image of the slit runs along columns and the slits can be rotated so that the dispersion is along the rows. The only remaining effect is a small differential change in tilt across an echelle order of about 1% of a pixel per resolution element.

Mounted back-to-back with the echelle grating is a flat mirror. When the flat mirror replaces the echelle grating a convenient Low-Resolution ("low-res") mode is formed with the CDG alone yielding R = 2,500 (120 km/s) for a two pixel wide slit. The dispersion is approximately 2 Å/pixel at 1 µm and scales with λ, and the free spectral range always exceeds the bandwidth of the order-sorting filters. For the NIRSPEC-3 filter, the central wavelength is 1.245 μm and the range falling on the array is 1.13 - 1.36 μm yielding 2.246 Å/pixel and a 2-pixel resolution of R = 2771 (4.5 Å).

Seven custom-designed filters, referred to as NIRSPEC-1 through NIRSPEC-7, give over-lapping wavelength coverage from 0.95 - 2.6 µm, and there is a KL, L, M and Mwide for 3.0 - 5.5 µm. The NIRSPEC-3 and NIRSPEC-5 correspond very roughly to the J and H bands. NIRSPEC-6 is a broad H+K filter centered at 1.925 µm with a bandwidth of 0.75 µm. Standard K and K′ filters are also included. The broad KL filter allows the SCAM (which has a detector which is only sensitive out to 2.5 µm) to be used for guiding or imaging in the K band while performing spectroscopy in the L band; this filter reaches the Brackett alpha line at 4.05 µm. There are several 1% wide "narrow-band" filters, such as Brγ at 2.165 µm and the H_2 S1 line at 2.122µm. Plots of the spectral transmission curves of all these filters are available on the NIRSPEC web pages at the Keck and from within the Echelle Format Simulator (EFS).

A selection of polished, laser-cut, air-spaced slits are mounted in a wheel in the re-imaged focal plane. Each slit is tilted by about 12° to enable reflected light to reach the infrared slit-viewing camera. Slits of 1, 2, 3, 4 and 5 pixels are available with 12" length, and widths of 2, 3, 4 and 5 pixels are provided at 24" length. Shorter slits are needed to avoid order overlap at the very shortest wavelengths. Order overlap can be inspected with the EFS. About 10 orders are captured at 1 µm but only about three at 4 µm due to the larger order separation at longer wavelengths. In the Low-Res mode the available slit widths are 2, 3 and 4 pixels and all of the low-res slits are 42" long. There is no imaging mode which does *not* have a slit, but a "box-9" dithered imaging pattern using the short, narrow slit (1 x 60 pixels) is extremely effective in removing the presence of the slit from deep images. Each slit is rotated relative to the rows and columns of the SCAM, but the angles are known to the software for "nod" commands. In the echelle mode, the built-in slit rotation angles and a built-in rotation of the InSb detector, enable the echelle orders and slit images to be aligned along the rows and columns of the spectrometer detector.

The Three-Mirror Anastigmat (TMA) camera in the back-end of the spectrograph has *different* focal lengths along the normal spectral dispersion and spatial (slit height) directions. In the Echelle mode, this circumstance yields an image scale of 0.144"/pixel in the dispersion direction and 0.193"/pixel along the spatial direction on the array. In the Low-Res mode these scales are *reversed*. Three pixels in echelle mode is 0.432" whereas 2 pixels in low-res mode gives 0.386".

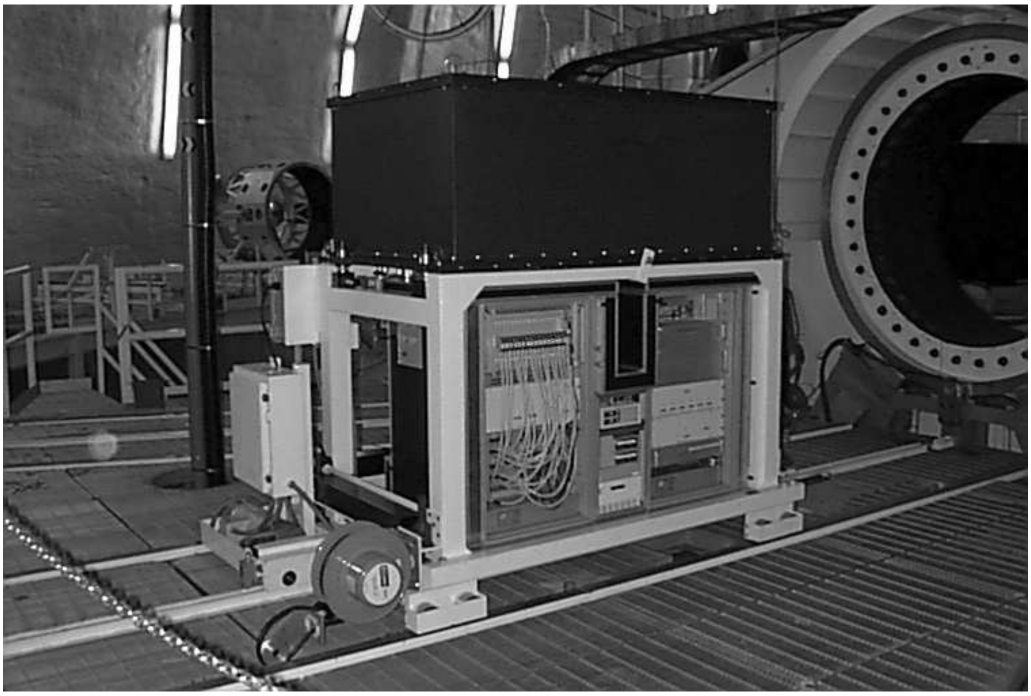

Figure 2. A view of NIRSPEC being moved into position on the right Nasmyth platform of Keck II. The optical axis is horizontal at about 1.5 m above the floor. The entire instrument weighs about 1 ton.

Arbitrary position angles can be obtained by rotating the sky field of view relative to the slits, since the slits must remain at fixed angles relative to the detector rows and columns. This action is achieved by motorizing the first K-mirror system in the front end optics. Field rotation from the alt-azimuth telescope mount can also be eliminated by applying suitable tracking rates to this image rotator. This is the most difficult mechanism in the instrument because it is large, massive, stiff, awkwardly-located and continuously moving.

Acquisition and guiding can be performed either with the infrared SCAM or with a standard (PXL) CCD camera which views an annular field around that of the SCAM. The image scale on the SCAM is 0.183"/pixel and on the CCD camera it is 0.21" per pixel. The outer diameter of the annular field on the CCD camera is about 3.5 minutes of arc. A fixed R-band filter is used and guiding is possible on stars as faint as R = 20. If the SCAM is used for guiding, then it is no longer available for imaging during long spectroscopic exposures. However, infrared guiding on slit-spillage light is possible and effective, especially during twilight, for sources that are bright enough.

NIRSPEC has a built-in Calibration Unit containing a white light source and four noble-gas arc lamps. In this unit, the output of an integrating sphere is re-imaged at f/15 into the instrument to provide a close match to the illumination from the telescope optics. For convenience, calibration arcs and flat fields can be pre-programmed using the Echelle Format Simulator to follow any spectroscopic exposure. Since the grating settings do not repeat to better than 1-2 pixels for large moves (*e.g.* from low- to high-resolution settings) frequent arc lamps are important; OH sky lines can also be used.

NIRSPEC (shown in Figure 2 above) is operated remotely using a suite of graphical user interfaces(GUIs). There is a Status and Instrument Control Panel with an active “cartoon” display of the instrument. Each mechanism can be accessed and controlled manually from this screen. Usually this is not necessary however, unless an extra calibration procedure is desired. There is a pair of similar-looking exposure-control panels, one for each infrared detector, and a pair of re-sizeable IDL Widget-based displays for the Quick Look software. The image rotator has its own graphical user interface and status display. Finally, there is the echelle Format Simulator (EFS).

The EFS is a powerful means of generating scripts and controlling entire instrument set-up procedures and spectral exposures.

The program draws a cartoon of the expected echellogram given the current grating angles, order-sorting filter and slit selection. A frame superimposed on the echellogram shows how much of the spectrum falls within the detector edges. Dragging this frame to a new location determines new grating angles. Clicking the “go” button then configures the instrument to this new setting. There are options to follow the set-up with a complete set of object and calibration exposures.

3. PERFORMANCE

NIRSPEC acheived “first light” on Keck II on April 25, 1999, with a near flawless integration, including alignment on the kinematic mounts and the first serious use of the closed-cycle refrigerator lines plumbed into the telescope. The InSb detector used during commissioning and for the first year of operation was obtained through an agreement with the International Gemini Telescopes organization. This ALADDIN II chip has higher noise and higher dark current than desirable for a high-resolution spectrograph. A planned “down-time” in Fall 2000 will be used to replace the detector and service problematic cryogenic mechanisms after their first year of use. Nevertheless, the overall system performance of NIRSPEC has been outstanding. Detailed scientific results are given elsewhere[5] in these proceedings and in a set of six “first light” papers in volume 533 of the Astrophysical Journal Letters.

3.1 Optical

NIRSPEC’s optical performance is just as expected. Laboratory tests with a pinhole target, illuminated such as to properly fill the pupil, demonstrate that 80% of the light falls within one pixel in the spectrograph. Illuminating the narrowest one-pixel wide entrance slit from the Arc Lamp Calibration source, which feeds the instrument with an f/15 beam, reveals slit images only slightly broadened. Scanning the echelle grating allows hundreds of lines in all parts of the focal plane to be measured. Only a small (few percent) expected degradation in image quality occurs near the edge of the field spanned by the 1024 x 1024 array.

Witness samples for the silver-coated optics imply 99% reflectance. Direct measurements of the efficiency of the diffraction gratings gave 72% for the echelle and 86% for the cross-dispersion grating. Together with the high transmissions of our custom filters (typically 85%), these peak values suggest a very high internal optical throughput of about ~44%. Taking into account the detector quantum efficiency (QE) reduces this to about 35%, still better than the original goal of 30%. Typical values for atmospheric transmission and telescope optics reduce the end-to-end efficiency to about 25-27% prior to slit loses. Using a 3-pixel wide slit under average seeing conditions would result in a 50% light-loss at the slit. During commissioning, observations of known standard stars gave a figure of 11%, confirming the throughput estimates and optical measurements. Replacing the echelle with the plane mirror for the low-resolution mode improves the total end-to-end throughput to about 15% for similar conditions.

The optical performance of the slit-viewing camera (SCAM) was tested in the lab with a pinhole target to demonstrate that it meets the specification. Throughput for the SCAM is determined largely by the reflectance of the gold-coated slit substrates, which is less efficient at short wavelengths, as well as by transmission through the re-imaging optics. The expected optical transmission is 55%. Since the HgCdTe detector in the SCAM has no active temperature control, it attains the mean temperature of the optical base plate, which is about 57 K. This is really too cold for this type of array detector and there is a noticeable loss of QE at short wavelengths (down to ~25%) resulting in a lower end-to-end efficiency in the J-band. Fortunately, the PICNIC detector has very low readout noise and it is easy to become background-limited and therefore sensitivity is still good (see below). The derived transmissions are 10% at J, 15.5% at H and 20.7% at K.

3.2 Detectors

As already stated, NIRSPEC has three detectors. The spectrograph detector is a Raytheon/SBRC 1024 x 1024 (ALADDIN) array of indium antimonide (InSb) with 27 µm pixels. The particular device used for first-light observations has a median dark current of ~0.4 electrons/s/ pixel, but unfortunately there is a large spattering of “hot” and unstable pixels with much higher dark current. Operating the device colder than the normal 30 K helps to reduce these hot pixels, but makes charge persistence worse. The conversion gain is 5 electrons/data number (DN) and the “safe” limit on well-depth (with a 300 mV reverse bias) to maintain good linearity is 100,000 electrons or about 20,000 DN. Three sampling modes are available: single sampling, correlated double sampling (CDS) and multiple correlated double sampling (MCDS) - also known as Fowler sampling. The shortest exposure time is 0.25 seconds. In normal operation with exposures longer than about 5 seconds, the default mode is 16 multiple reads (Fowler 16) which yields a read noise of about 25 electrons rms with the currently available array.

In the SCAM, a low-noise Rockwell 256 x 256 (PICNIC) array of HgCdTe detectors with a cut-off wavelength of 2.5 microns provides a field of view of about 46" x 46" and a scale of 0.183"/ pixel. At ~60 K, dark current in this detector is negligible but the quantum efficiency is much less than the InSb detector. Images with full width half maximum (FWHM) values of 2-3 pixels (0.37" - 0.55") were seen routinely during commissioning. Using a conversion gain of 4 electrons/DN with the HgCdTe array, the safe limit for good linearity is 120,000 electrons or about 30,000 DN. The shortest exposure time is 0.10 seconds. Readout noise is typically about 10 electrons (CDS) and therefore this camera is readily background-limited.

The CCD in the PXL camera is a 1024 x 1024 SITe chip. This camera can be operated with or without a shutter. Images from the PXL camera can be saved if required.

3.3 Sensitivity

The high-resolution echelle mode is source-flux-limited until about H = 16. For fainter sources, the signal-to-noise ratio is dominated by read-noise with the current InSb detector for any practical exposure times at all wavelengths less than 2.2 µm. A signal-to-noise ratio of 10 is obtained in 1 hour at J = 14, H = 13.5, K = 13 and L = 11 for R ≈ 25,000 under good (2 pixel) seeing conditions. In the low-res mode, a signal-to-noise ratio of 10 (read-noise limited) can be obtained with an integration time of 1 hour at R = 1400 in 2 pixel seeing for H = 18.1 (similar for J). The limit is 17.3 at K. Line detection fluxes (10 sigma, 1 hour) in this low-res mode are ~1.2 x 10^{-16} ergs/s/cm^2 in both the H and K bands. The mean background between the OH lines is less than 0.3 e/s/pixel or about 0.1 photons/s/Å. In the thermal IR, both spectroscopic modes are background-limited.

For the SCAM, since the zeropoint for 1 DN/s is about 24.7 magnitudes in the J band and the background is typically about 15.4 magnitudes per square arc second, or about 158 DN/s, this camera is always background-limited. The 3 sigma, 1 minute detection limit is J = 21.4 and K = 19.2. The sky background in the K filter is about 13.4 magnitudes per square arc second, and about 0.2 magnitudes better at K′.

4. RESULTS

The official “first light” target for NIRSPEC on April 25, 1999 was the starburst galaxy M82. The SCAM image (Figure 3 , left) shows the core of M82 captured with the KL filter which enables the HgCdTe slit-viewing camera to image in the K-band while the InSb array obtains a spectrum in the L-band. In the central image, an L-band echellogram containing the Brackett-α emission line at 4.05 µm is shown. For comparison, a K-band echellogram is also reproduced (Figure 3, right) in which the Brackett-γ line at 2.167 µm is the bright feature at the far left of the 4th order from the bottom. The slit is 24" long and 0.576" wide. The resolving power is about 18,250 (16.4 km/s).

In each echellogram, wavelengths increase from left to right and from bottom left to top right; one pixel represent about 4 km/s. These images are completely raw; the only processing applied is a sky subtraction. Remarkable velocity structure is visible at a glance. The left (lower) part of the slit in the SCAM image corresponds to the upper part of each spectral order. Since the observed lines are blue-shifted in the upper part of each order, then the left side of the galaxy as seen in the SCAM image is approaching the Earth. In the 2-micron image, the faint emission feature in the third order from the bottom is the 2.122 µm S(1) 1-0 line of H_2 and the stronger line near the center of the order below is He I at 2.085 µm.

Note also, the strong series of dark lines shortward of 2 microns due to water absorption in the Earth’s atmosphere, and the broad stellar CO absorption features, starting at 2.295 µm near the right edge of the 6th order from the bottom, which also clearly show the galaxy rotation. It is relatively straightforward to extract and linearize each order.

Regions of high dark current due to “hot” pixels can be seen, together with three blemishes near the top right of the frame.

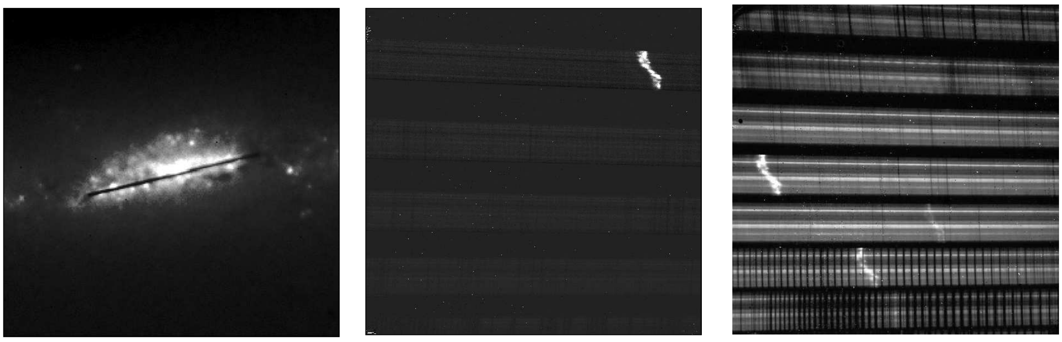

Figure 3. The official “first light” NIRSPEC target - M82. The left hand image is a 20s exposure in the KL filter with the slit-viewing camera. The central and right images show respectively, an L-band and a K-band echellogram. The slit is 24" long.

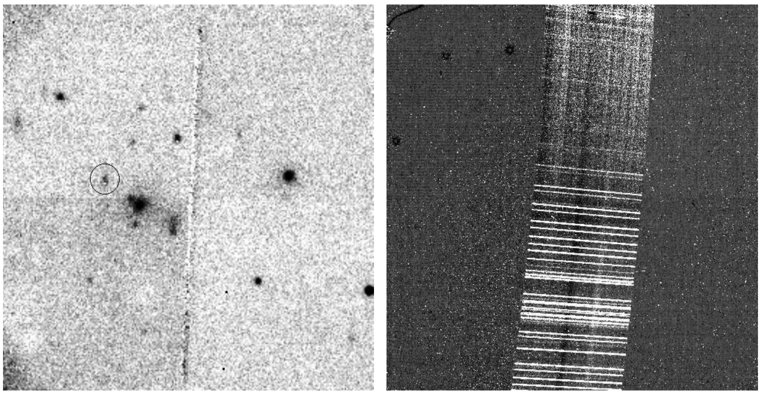

Figure 4. A K-band image of the field around MS 1512-cB58 identifying a gravitationally-lensed galaxy at a redshift of z = 2.7. The long 42" slit can be seen faintly in this dithered image. On the right is a display of the difference of two low-res spectra.

Our first target for the low-resolution mode was the unusually bright (K ≈ 17.5) high-redshift galaxy MS 1512-cB58 which is gravitationally-lensed by a foreground galaxy cluster. In the low-res mode (R≈ 2500), the dispersion is up and down the chip (the cross-dispersion direction of the echelle mode) and the slit is always 42" long (292 pixels on the InSb detector). Figure 4 shows the SCAM view of the field using a 9-point dither pattern (performed and reduced automatically with IDL) as well as the *difference* of two 600 s spectral exposures in the K-band. The lensed object, prior to being placed on the slit, is shown circled. The continuum can be seen in both the positive and negative images, and close inspection reveals that Hα (rest wavelength 6563 Å) appears at ~2.43 µm, corresponding to z = 2.7, near the very top edge of the spectrum. Bright horizontal lines in the lower part of the spectrum are residual OH lines in the difference. Thermal background dominates the upper end of the spectrum. The wavelength span is approximately 2.0 - 2.4 µm and the flux in Hα is about 12.6 x 10^{-16} ergs/s/cm^2.

5. CONCLUSIONS

When first conceived in 1993, NIRSPEC was a challenging and relatively expensive instrument. To achieve the goals of high operational efficiency, high throughput, high spectral resolution and good sensitivity required several design innovations, including the difficult three-mirror anastigmat (TMA) optics and the very low-background, low-temperature cryogenic design. In addition, the ultimate performance depended on achieving low noise and low dark current in the proposed InSb ALADDIN array detectors. As illustrated in this report, most of our ambitious goals have been achieved, with an almost on-time, on-budget delivery. Many research papers have now appeared in the refereed literature, and the power of infrared spectroscopy with a new generation of detectors is beginning to be felt.

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