1. Introduction

The primary science goal of NICI is to search for faint companions within the circumstellar halo of bright stars. Characterization of companions with NICI is currently limited to broad-band and narrow-band imaging. Methane-difference imaging will identify objects cooler than L but perhaps the best way to confirm and characterize companions is to obtain a spectrum. Spectral resolutions of R~100s are adequate to spectrally type objects earlier than ~M8, objects which are the primary targets of NICI. To achieve this we propose to equip NICI with a low-resolution (R=200-400) grism mode. Low resolution grisms are optimum for speed, sensitivity and wavelength coverage.

To characterize companions we propose to cover the wavelength range 1.0-3.6µm simultaneously - 1.0-1.9µm in the blue science channel, and 1.9-3.6µm in the red science channel. This requires an IJH grism plus order sorter in the blue channel filter wheel, a KL grism plus order sorter in the red channel filter wheel, a 1.9µm dichroic in the dichroic wheel, and a slit in the telescope focal plane mask wheel. Slit widths of 0.07 arcseconds (4 pixels) and 0.14 (8 pixels) give in spectral resolutions of R=400 and R=200 respectively.

NICI is optimized for coronagraphic science. The grism mode is simple to install and does not drive the instrument design.

NICI will also be used as a general purpose AO-assisted infrared imager for Gemini South with multiple science goals. Clearly, a low-resolution grism mode will add significantly to NICI's ability to address this science (e.g. spectral energy distributions
of YSOs and high red shift objects). However, for better sensitivity on emission lines, both to disperse the continuum and to separate telluric OH lines, grisms with spectral resolutions of R ≥ 2000 are required. These medium-resolution grisms can also be added to spare slots in the filter wheels without impacting the design. This mode not be discussed further here.

2. Grism Science

The purpose of the proposed grism mode is to confirm and characterize candidate companions found in the circumstellar halos of bright stars. Due the proximity of the primary star and the relative faintness of actual companions, the companions revealed by NICI are likely to be, in order of decreasing effective temperature, late M dwarfs, L dwarfs, T dwarfs and Jupiter-like planets.

The definitive way to confirm companionship is with proper motion astrometry, a process which can take months. With methane-difference imaging NICI will be able to detect ultra-cool (T_{eff} < 1200K) objects and thereby conclude probable companionship, but further characterization is limited. A low resolution spectrum can measure the spectral energy distribution of an object and immediately determine spectral type and therefore temperature. In practical terms, no one will be confident of identifying an ultra-cool object until a confirming spectrum is obtained.

The 1-4 µm region contains many spectral temperature indicators of cool dwarfs. Figures 2.1 and 2.2 show a spectral sequence of M, L and T dwarfs obtained with SpeX on IRTF. These spectra have been smoothed down to resolutions of R=400 and R=100 respectively, resolutions in the range proposed for the NICI grism mode.

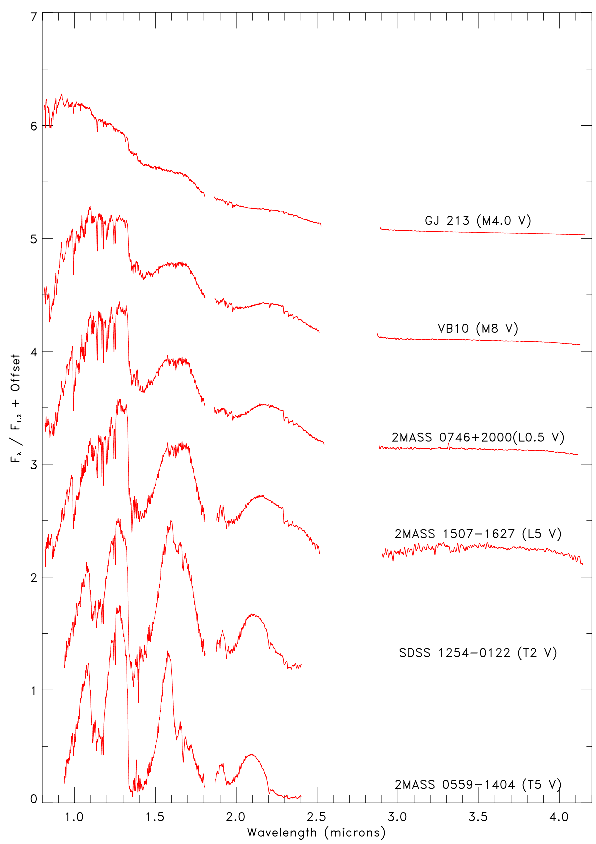

Figure 2.1 Temperature sequence of cool dwarfs at 1-4 µm, R=400

As dwarfs cool from mid-M (T_{eff} = 3500K) to late-M (T_{eff} = 2200K), water vapor absorption bands at 1.4µm and 1.9µm deepen together with alkali metal and metal hydride features in the 1.0-1.3µm range. L dwarfs are characterized by dusty photospheres with temperatures in the range T_{eff} = 2200-1200K. Spectrally, L dwarfs show deepening water vapor and carbon monoxide bands (bandhead at 2.3 µm), and strong alkali metal and metal hydride features. Flux shortward of about 1.0 µm is strongly absorbed by potassium and sodium, making L dwarfs primarily infrared objects. As L dwarfs cool below about 1400K an important chemical change occurs as methane attains a large abundance at the expense of carbon monoxide. The appearance of methane is first seen in the Q-branch of the ν_3 band centered at 3.3µm.

In the sequence shown here this feature first appears in the L5 dwarf. It increases in depth with decreasing temperature and is very strong in T dwarfs (which are not shown here at 3-4 µm). Strong overtone methane bands at 1.15µm, 1.6µm and 2.2µm are the defining characteristic of T dwarfs and first appear at T_{eff} = 1200K. Broad water vapor absorption at 1.4µm and 1.9µm is also very strong in T dwarfs. Late L dwarfs and all T dwarfs are brown dwarfs (sub-stellar objects). Further dramatic changes in the 1-4µm spectra of sub-stellar objects are not expected to occur again until water vapor begins to condense at temperatures of about 400K.

As explained above, the 1-4µm range covers many of the diagnostic spectral features associated with cool dwarf stars and sub-stellar of objects. Acquiring this range simultaneously can be done at spectral resolutions of R=400-200 with NICI. As shown in Figures 2.1 and 2.2 this resolution is well suited to the task of identifying and characterizing the types of companions in this temperature range, companions we expect to detect with NICI. Low resolution grism spectra are also optimum for speed and sensitivity. Additionally, obtaining the 1-4µm in one observation avoids the problem of joining together spectral regions obtained at different times. In implementation the KL grism has a long wavelength limit of 3.6µm in order to maintain a spectral resolution of R=400. This is adequate to cover the broad methane feature at 3.3µm.

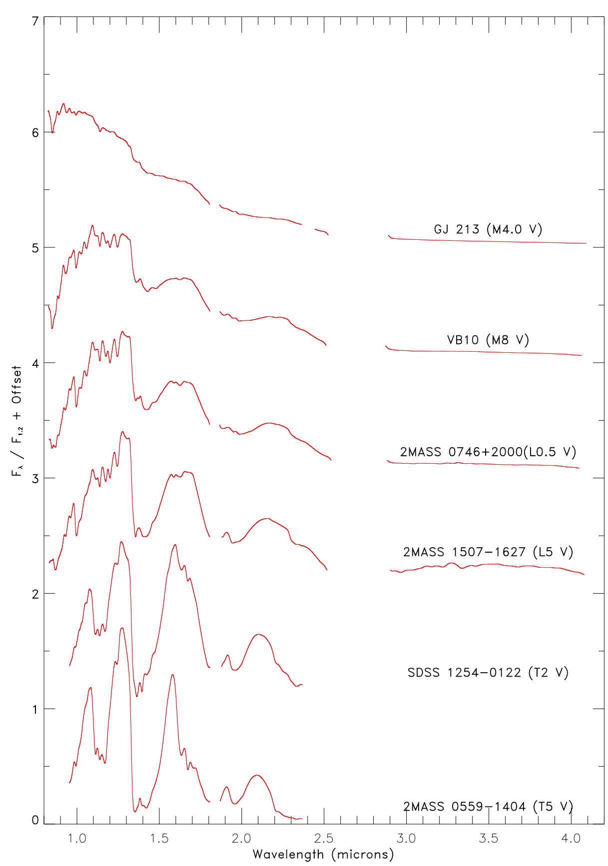

Figure 2.1 Temperature sequence of cool dwarfs at 1-4 µm, R=100

3. Optical Design

A variety of grism options have been investigated with the aim of optimizing spectral resolution and wavelength coverage. Attempts were made to cover the JHK region simultaneously in one channel and the L-band in the other channel. The limitation is keeping side-lobe orders (second and zeroth order in the case of first order) from overlapping with the primary spectrum. In the case of the JHK grism the widest uncontaminated coverage that could be achieved was 1.20-2.35µm with R=350 matched to a four-pixel (0.07 arcsecond) slit. This is not acceptable because it doesn't cover 1.0-1.2µm which contains many interesting features in the spectra of cool dwarfs. Ultimately, it was found that the best way to cover 1-4µm simultaneously was to put 1.0-1.9µm in one channel and 1.9-3.6µm in the other, with a spectral resolution of R=400 matched to a four-pixel (0.07 arcsecond) slit.

To achieve the highest possible optical efficiency, the proposed grisms are used in first order and are direct-ruled on KRS-5 substrates. Solid grisms are essential for the KL mode to avoid absorptions in the resin, however the IJH grism could possibly use a replica if thickness limitations permit (see section 3.1).

3.1. IJH Grism

The IJH Grism is mounted in the blue channel filter wheel following beam division at the dichroic. Since there is only one filter wheel in each channel, the order sorting filter must be sandwiched together with the grism in the same mount. The optical layout of the IJH grism mode is shown in Figure 3.1

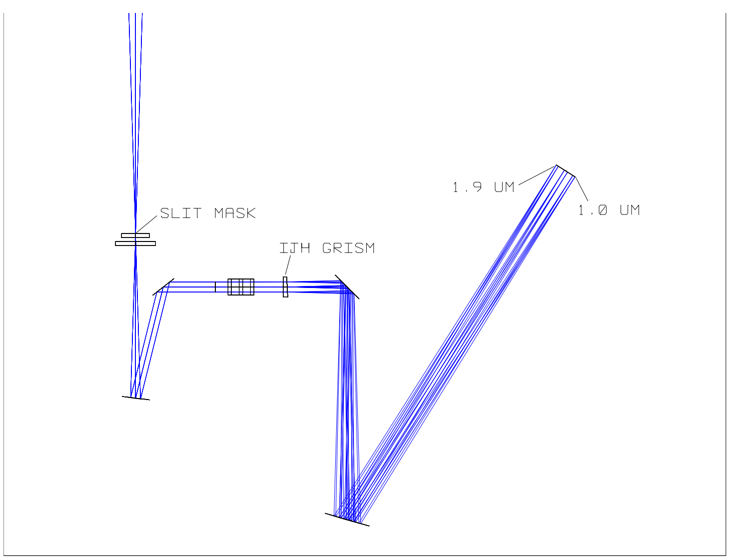

Figure 3.1 Layout of IJH Grism mode

The side-lobes associated with the first order 1.0-1.9µm spectrum are shown in Figure 3.2. In theory the side-lobes should be heavily suppressed by the ruling blaze angle but in practice significant amounts of flux appear in these orders and so careful order sorting is required as shown.

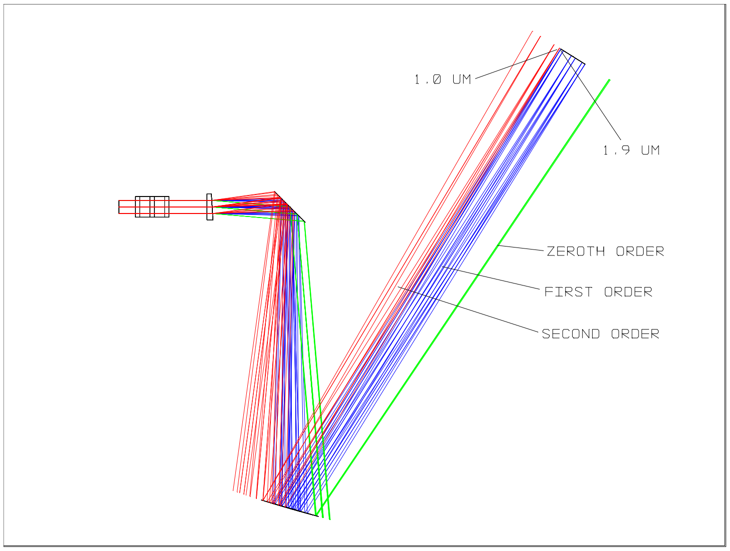

Figure 3.2 IJH Grism first order spectrum and side-lobes

3.2. KL Grism

The KL Grism is mounted in the red channel filter wheel following beam division at the dichroic. In all other respects the layout is identical to the IJH grism mode.

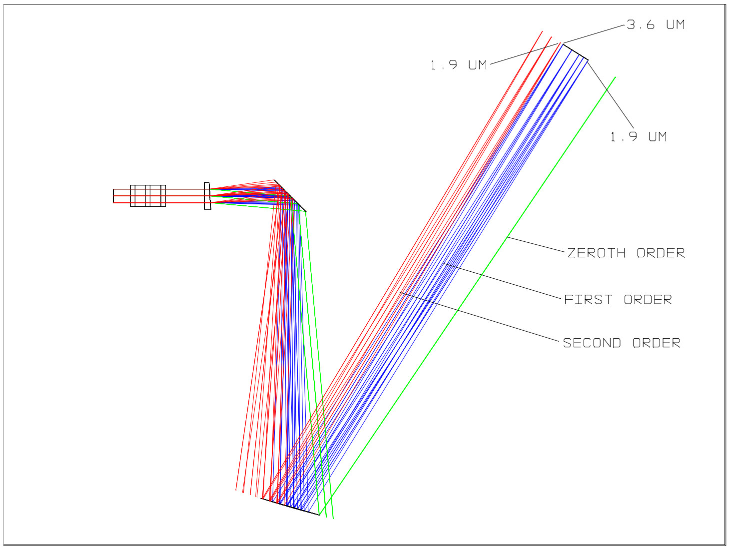

Figure 3.2 KL Grism first order spectrum and side-lobes

3.3. Design and Use Issues

Slits are mounted in the telescope focal plane mask wheel and are therefore warm. Potentially this presents thermal background problems at wavelengths longer than about 2 μm. The thermal background from the slit mask can be effectively eliminated by making the rear of the slit reflective and by making it view the cold interior of the cryostat, just as is done for the warm coronagraphic masks. This is helped considerably by having the mask wheel positioned immediately above the cryostat window but the baffling in this area will have to be examined carefully.

To obtain spectra of candidate companions discovered in coronagraphic mode the coronagraphic mask will have to be removed for the object to be positioned in the slit. Consequently some of the stray light rejection capability of the instrument will be lost. Nevertheless, the high Strehl images delivered through use of the 85-element AO system coupled with the low-scatter optics, will still make NICI an ideal instrument with which to do this type of grism spectroscopy.

When moving from coronagraph to grism mode by replacing a coronagraphic mask with a slit mask, AO lock will not be lost since the warm beamsplitter is located above the focal plane mask wheel. Once the slit is in place a precise telescope offset will place the object in the slit.

The design slit widths of 0.07 arcsecond (4 pixels, R=400) and 0.14 arcsecond (8 pixels, R=200) are well matched to the expected AO-delivered (i.e. diffraction limited) PSFs in the 1.0-1.9 μm and 1.9-3.6 μm grism ranges respectively. The IJH and KL grisms have diffraction limits (the number of grating lines illuminated by the beam) of R=800 and R=420 respectively. Consequently, higher resolution can be obtained with the IJH grism using a two-pixel (0.036 arcsecond) slit if the additional light loss is acceptable. For optimum throughput the slits will need to be rotated to the parallactic angle because of atmospheric dispersion.

4. Work Breakdown and Cost

Preliminary estimates of the hardware costs are as follows:

IJH solid KRS-5 grism	$25k
IJH order sorting filter	$5k
KL solid KRS-5 grism	$25k
KL order sorting filter	$5k
Slit mask	$10k
1.9 μm dichroic	provided
Total hardware	**$70k**

To implement the grism mode as proposed we estimate about 160 hours of optical design, 40 hours of mechanical design, 40 hours of mechanical fabrication, 40 hours of lab assembly and testing, and160 hours of documentation and software specification. Additionally, we estimate about 320 hours to model stray light effects on grism sensitivity, if required by Gemini.