GNOSIS: an OH suppression unit for near-infrared spectrographs

S. C. Ellis[a], J. Bland-Hawthorn[b], J. S. Lawrence[c,d], J. Bryant[a], R. Haynes[e], A. Horton[c], S. Lee[c], S. Leon-Saval[b], Hans-Gerd Löhmannsröben[e] , J. Mladenoff[c], J. O'Byrne[a], W. Rambold[e], M. Roth[e], C. Trinh[a]

[a]Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia;
[b]Institute of Photonics and Optical Science, School of Physics, University of Sydney, NSW 2006, Australia;
[c]Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia;
[d]Department of Physics and Astronomy, Macquarie University, NSW, 2109, Australia;
[e]innoFSPEC - Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

ABSTRACT

GNOSIS is an OH suppression unit to be used in conjunction with existing spectrographs. The OH suppression is achieved using fibre Bragg gratings (FBGs), and will deliver the darkest near-infrared background of any ground-based instrument. Laboratory and on-sky tests demonstrate that FBGs can suppress OH lines by 30dB whilst maintaing $> 90\%$ throughput between the lines, resulting in a ≈ 4 mag decrease in the background.

In the first implementation GNOSIS will feed IRIS2 on the AAT. It will consist of a seven element lenslet array, covering ≈ 1.4" on the sky, and will suppress the 103 brightest OH lines between 1.47 and 1.70 μm. Future upgrades will include J-band suppression and implementation on an 8m telescope.

Keywords: near-infrared, spectroscopy, OH suppression, photonics, fibre Bragg gratings

1. INTRODUCTION

Near-infrared spectroscopy is made difficult by the extremely bright and variable background. The night sky surface brightness is more than a thousand times brighter at 1.6μm than at 0.4μm (see e.g. ref. 1 and ch.7 in ref. 2). Furthermore the brightness of the sky changes by factors of $\approx \pm 0.1$ on time-scales of minutes.[3,4] Background-subtraction is therefore frustrated by high Poisson noise from the extreme brightness, and by systematic noise from the variability.

Between 1.0 and 1.8 μm almost all of this background results from the rotational and vibrational de-excitiation of hydroxyl molecules located at ≈ 90 km in the atmosphere.[5] The hydroxyl emission lines are intrinsically very bright, but very narrow ($\approx 5 \times 10^{-6}\mu$m). Between the OH lines the sky should be very dark; it is expected that the interline continuum is dominated by the zodiacal scattered light,[5] which has a surface brightness of 80 ph s^{-1} m^{-2} μm^{-1} $arcsec^{-2}$ on the ecliptic plane (see e.g. ref. 6). Therefore selectively filtering the OH lines would enable deep near-infrared observations.

Achieving this goal would enable many different science cases. Near-infrared spectroscopy is important for studies ranging from low mass stars and planets in the nearby Universe to studies of star-formation and galaxy assembly at high redshift. Indeed this goal is so desirable that NASA, the European Space Agency and the Canadian Space Agency are together planning on launching an infrared space telescope in 2014 (the James Webb Space Telescope) into an orbit 1.5 million km from Earth, at a cost of ≈\$4.5B, in order to circumvent the infrared background.[7]

Send correspondence to S.C.E.: simon.ellis@sydney.edu.au

Ground-based and Airborne Instrumentation for Astronomy III, edited by Ian S. McLean,
Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 7735, 773516 · © 2010
SPIE · CCC code: 0277-786X/10/\$18 · doi: 10.1117/12.856348

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

GNOSIS is an OH suppression unit designed to achieve this goal from the ground. This is made possible by a novel technology developed in a collaboration between the University of Sydney, the Anglo-Australian Observatory, the Astrophysikalisches Institut Potsdam and industrial partners. This technology is based on two recent advances in photonics: aperiodic fibre Bragg gratings, and photonic lanterns. The first makes it possible to construct extremely complex optical filters. The second allows very efficient conversion between multi-mode and single-mode fibre s. This technology is at the heart of GNOSIS and will be described in the next section. The interface between this technology and the telescope and instrument is described in section 3. The expected performance of GNOSIS is given in section 4, with reference to particular science goals.

2. OH SUPPRESSION

The OH suppression in GNOSIS is achieved using aperiodic fibre Bragg gratings. These are optical fibres with a varying refractive index in the core of the fibre. By carefully controlling the variation in refractive index it is possible to build up strong reflections at particular wavelengths. These devices are very attractive as OH suppression filters, because very strong reflections (transmission < -30 dB) can be achieved over very narrow wavelengths (width < 200 pm), whilst maintaining high throughput elsewhere (losses < 0.5 dB). Bland-Hawthorn et al.[8] showed that it is possible to write many such notches within a single device, and that the wavelengths of the notches can be controlled very accurately.

Figure 1 shows the measured response of a grating with 63 notches covering a bandwidth of 160 nm (middle panel). Comparison with the sky spectrum (top panel) shows that the wavelength of the notches are very accurate. This device was used in an on-sky demonstration of the technology at the AAT in Dec. 2008.[9] The resulting spectrum is shown in the bottom panel, along with the results from a control fibre, with no Bragg grating. All the OH sky-lines are suppressed within the region covered by the FBG filters.

GNOSIS will use two FBGs in series to suppress the 103 brightest OH doublets between $1.4665 - 1.6955\mu$m. The performance of the GNOSIS gratings is highly satisfactory. The notch profiles are extremely square and can be well fit with an $n = 7$ Butterworth profile (Fig. 2, panel a). The square profile makes the filtering very efficient since it maximises the amount of inter-line light able to get through to the spectrograph, without any leakage of OH light in the profile wings (e.g. as for the Lorentzian profile of an interference filter). The wavelengths of the notches are very accurate with an RMS error of 11 pm (Fig. 2, panel b). The interline throughput is good < 0.3 dB. The suppression factor is high, with the brightest lines being suppressed by factors of up to 50 dB.

These properties of FBGs, which make them so useful as OH line filters, are dependent on using single-mode fibres (SMFs). This presents a problem for astronomical applications; coupling light into single-mode fibres is highly inefficient for the distorted wavefronts of light passing through the atmosphere. Therefore we require a method to convert between the large diameter multi-mode fibres (MMFs) necessary to accept the light from a ground based telescope, and the single-mode fibre Bragg gratings.

This problem was solved by Leon-Saval et al.,[10] using fibre tapers to convert between a multi-mode fibre and a parallel array of single-mode fibres and back again. Bragg gratings can then be connected to the single-mode fibres. These devices, called photonic lanterns, are the key to unlocking the potential of many photonic technologies which require single-mode fibres for astronomical applications. Noordegraaf et al.[11] have shown that it is possible to make efficient photonic lanterns by matching the number of modes in the MMF to the number of SMFs. The losses in the MMF-SMF-MMF conversion, including splicing are < 1dB.

3. GNOSIS

GNOSIS is an OH suppression unit designed to exploit the technology described above. The primary requirement of GNOSIS is to demonstrate the potential of FBG OH suppression. This will be done by measuring the interline background and through the demonstration of OH suppressed observations of astronomical targets.

GNOSIS is fully funded by an Australian Research Council Linkage Infrastructure, Equipment and Facilities grant led by the University of Sydney, with further contributions from the Astrophysikalisches Insitut Potsdam. GNOSIS will be built by the Anglo-Australian Observatory. The project is currently in the preliminary design phase, and is expected to see first light by early 2011. In its first implementation GNOSIS will feed IRIS2 on the

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

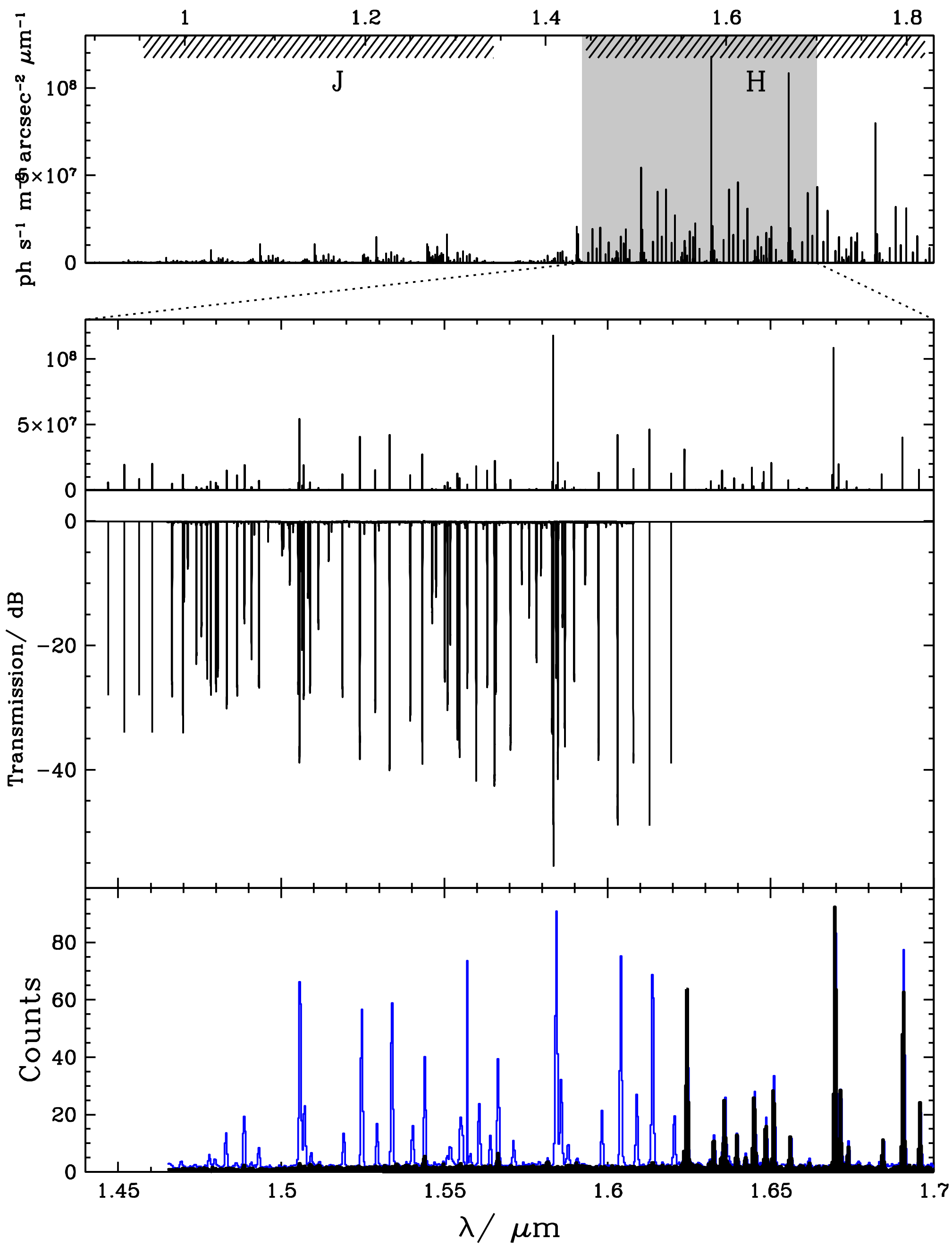
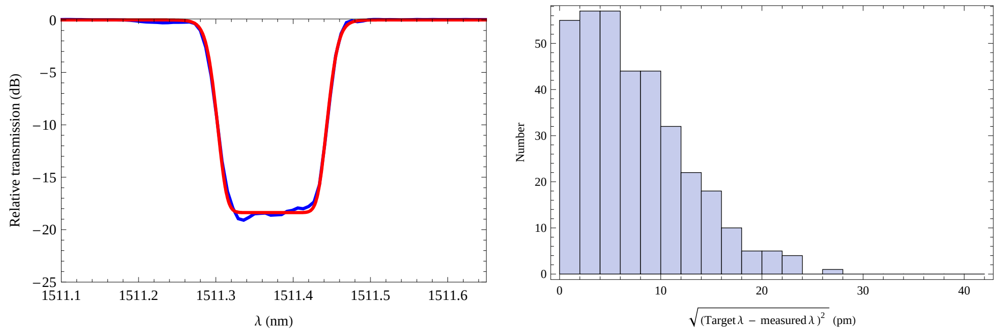


Figure 1. The results of our OH suppression technology. The top panel shows a model of the night-sky spectrum at near-infrared wavelengths, illustrating the strong OH emission lines. The J and H passbands are shown by the hatched regions. The second panel shows a zoom of the model sky spectrum between 1.44 and 1.7 μm, this is the shaded region in the top figure. Underneath this is a plot of the measured transmission of a fibre Bragg grating. 63 OH lines are suppressed from 1.44 to 1.63 μm, and the match to the model sky spectrum is excellent. The bottom panel shows the results of our on-sky demonstration. The blue spectrum shows the night sky spectrum as measured by our control fibre. The black spectrum shows the sky spectrum after suppression by the FBG. All of the sky lines corresponding to the FBG notches are suppressed.

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms



(a) Notch profile of the GNOSIS FBGs (b) RMS error in wavelength position

Figure 2. The properties of the GNOSIS FBGs. The notch profiles (a) are very square, narrow and deep, allowing efficient filtering of the OH lines. The blue lines shows a measured profile and the red line shows the best fitting Butterworth function. The notch wavelengths measured from 8 different FBGs are accurate to an RMS error of 11 pm. The accuracy of all notches to within < 30 pm will ensure that the OH lines are suppressed by the 200 pm wide notch.

AAT with OH suppressed light over two-thirds of the H band. A J band suppression unit is a proposed upgrade. Thereafter it is planned to redeploy elements of GNOSIS to feed the GNIRS spectrograph on Gemini.

The rapid time frame for the design and build of GNOSIS is possible because GNOSIS will feed existing spectrographs. Therefore GNOSIS will consist of interfaces between the telescope, the OH suppressing photonic lanterns, and the spectrograph. The preliminary design is as follows.

3.1. Fore-optics

GNOSIS will be mounted at the f/8 Cassegrain focus of the AAT. A fore-optics unit will take light from the telescope and feed it to an integral field unit. A beam splitter will divert some fraction of the incoming light to the acquisition and guide-camera. A deployable mirror will allow a Xe arc lamp to illuminate IRIS2 for wavelength calibration. A schematic drawing of the fore-optics is shown in Figure 3.

GNOSIS is required to permit spectroscopy of a single source at a time. This will be achieved with a seven element hexagonally packed lenslet array. Each lenslet will feed a 50–65μm core diameter fibre. This fibre diameter is chosen to match the number of modes to a 1×19 photonic lantern; larger fibres would require larger lanterns, which would be more expensive to produce. Therefore in order to increase the field of view to accommodate the seeing an IFU is adopted.

The median seeing at Siding Spring is 1.2” at 1.6μm. The field of view of GNOSIS will be 1.4” which minimises aperture losses and losses due to focal ratio degradation when feeding the lanterns. The IFU lenslets will be 2 mm wide requiring a magnification of ≈ 33.4 from the fore-optics.

3.2. Grating unit

Each fibre from the IFU will be fusion spliced to a 1×19 photonic lantern. The SMFs in the lantern will be fusion spliced to the two FBGs in series. This will be followed by the reverse transition back to MMFs. Thus GNOSIS will contain 14 photonic lanterns (an input and output for each of the seven IFU channels) and 133×2 FBGs (i.e. two gratings in series for each SMF). These will be housed together in box in the Cassegrain cage. The FBGs are provided in a temperature compensating tube, which maintains the grating performance from -10 to +25 degrees Celsius. Thus there is no need to temperature control the grating box unit.

3.3. Relay optics

GNOSIS will feed IRIS2.[12] The output fibres from the grating unit will be arranged into a slit block. A pair of relay lenses and a fold mirror reimages the fibre array onto the entrance slit of IRIS2, and provides the necessary magnification to reimage the fibre cores to the appropriate slit size. A sketch of the relay optics is shown in Figure 4.

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

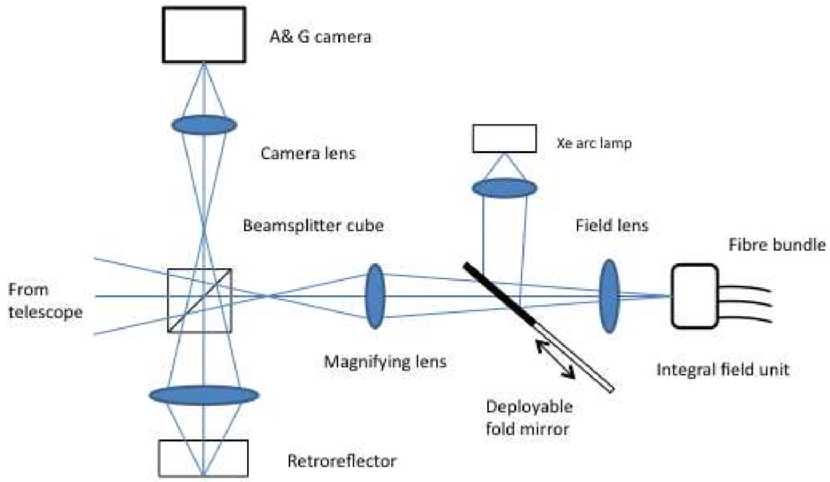


Figure 3. Schematic diagram of the GNOSIS fore-optics.

The interface assembly also provides a light source to back illuminate the slit block, via a deployable fold mirror, to allow acquisition.

4. EXPECTED PERFORMANCE

The major contributions to the GNOSIS background are the OH lines, the telescope and instrument thermal background and the zodiacal scattered light. These are shown in the top panel of Figure 5. The OH emission is by far the dominant component. The estimated throughput of the different system components is shown in the middle panel of Figure 5, giving rise to the final background spectrum at the detector as shown by the bottom panel.

The GNOSIS background shown in Figure 5 has been used to estimate the 5σ limiting sensitivities in 1 hr. These are shown in Figure 6.

We further illustrate the performance of GNOSIS with some simulated observations. These follow the simulations developed by Ellis & Bland-Hawthorn,[5] which include systematic variation in the OH lines as a function of time, and systematic errors in wavelength calibration, both of which lead to a realistic simulation of sky-subtraction errors.

Figure 7 shows a simulated 6hr exposure of a $z = 1.4$ H=20 mag emission line galaxy. The galaxy spectrum was taken from the SDSS spectral templates, then scaled according to the redshift and magnitude. The simulation shows the detection of the Hα emission line at $\lambda = 1.575$ μm. Such observations are highly desirable; measuring Hα emission line strengths in redshifted galaxies allows a direct comparison of the instantaneous star-formation rate with that of nearby galaxies. Measuring the star-formation rate in redshifted galaxies currently requries

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

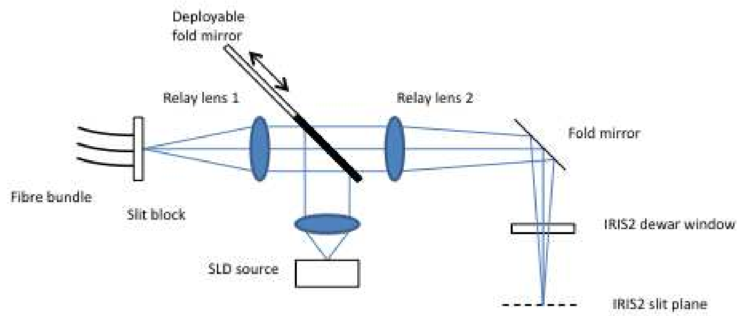


Figure 4. Schematic diagram of the GNOSIS relay optics.

comparison of different signatures making calibrations between the different signatures necessary. Furthermore GNOSIS will be able to measure Hα over the redshift range $1.2 \leq z \leq 1.6$, sampling the cosmologically important epoch at which galaxy assembly and star-formation are thought to be at a maximum.

Measuring the number density of low-mass stars as a function of mass is essential for a full understanding of star-formation. To achieve this it is necessary to determine the temperatures, surface gravities and atmospheric composition of low mass stars. These observations require NIR spectroscopy, such as the simulation shown in Figure 8 of a T5 dwarf with J=20 mag. The methane and water absorption features are easily identifiable, allowing accurate spectral typing of the star. Thus GNOSIS will allow spectroscopy of very faint low mass stars, increasing the search volume and number of objects able to be properly characterised.

REFERENCES

1. K. Krisciunas, "Optical Night-Sky Brightness at Mauna Kea over the Course of a Complete Sunspot Cycle," *PASP* **109**, p. 1181, Oct. 1997.
2. A. N. Cox, *Allen's astrophysical quantities*, Allen's astrophysical quantities, 4th ed. Publisher: New York: AIP Press; Springer, 2000. Editedy by Arthur N. Cox. ISBN: 0387987460, 2000.
3. S. K. Ramsay, C. M. Mountain, and T. R. Geballe, "Non-thermal emission in the atmosphere above Mauna Kea," *MNRAS* **259**, p. 751, Dec. 1992.
4. H. U. Frey, S. B. Mende, J. F. Arens, P. R. McCullough, and G. R. Swenson, "Atmospheric gravity wave signatures in the infrared hydroxyl OH airglow," *Geophysical Research Letters* **27**, p. 41, 2000.
5. S. C. Ellis and J. Bland-Hawthorn, "The case for OH suppression at near-infrared wavelengths," *MNRAS* **386**, p. 47, 2008.

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

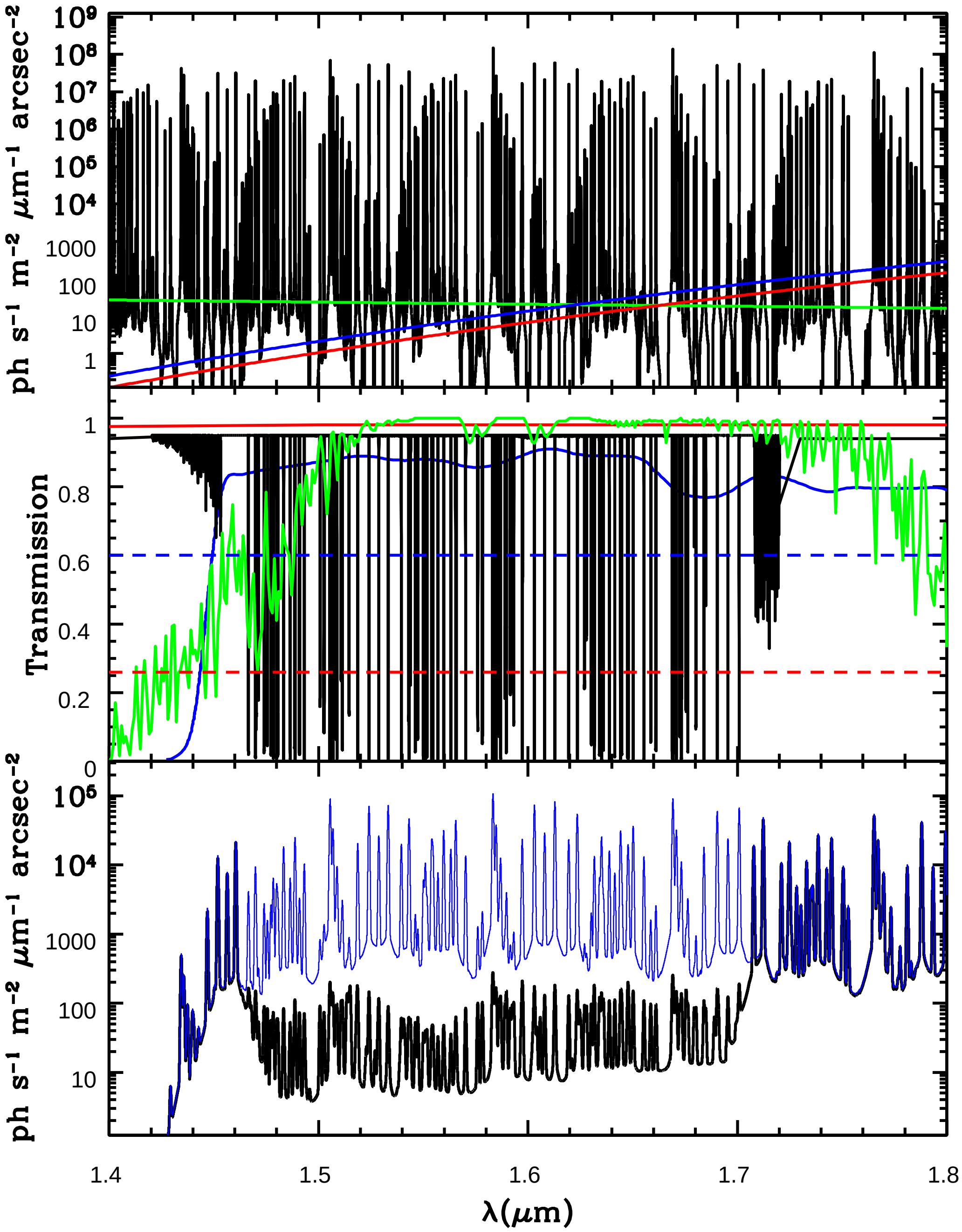


Figure 5. The GNOSIS background. The top panel shows a model of the OH emission line spectrum (black), the telescope thermal background (red) and the instrument thermal background (blue). The middle panel shows the system throughput, including the FBGs (black), atmosphere (green), the telescope reflectivity(red), the GNOSIS optics (dashed blue), the IRIS2 throughput (dashed red) and the Hs filter response (blue). The bottom panel shows the resulting background spectrum, at the resolution of IRIS2 (R = 2400) incident on the detector (black), and for comparison the spectrum of an identical system without FBGs.

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

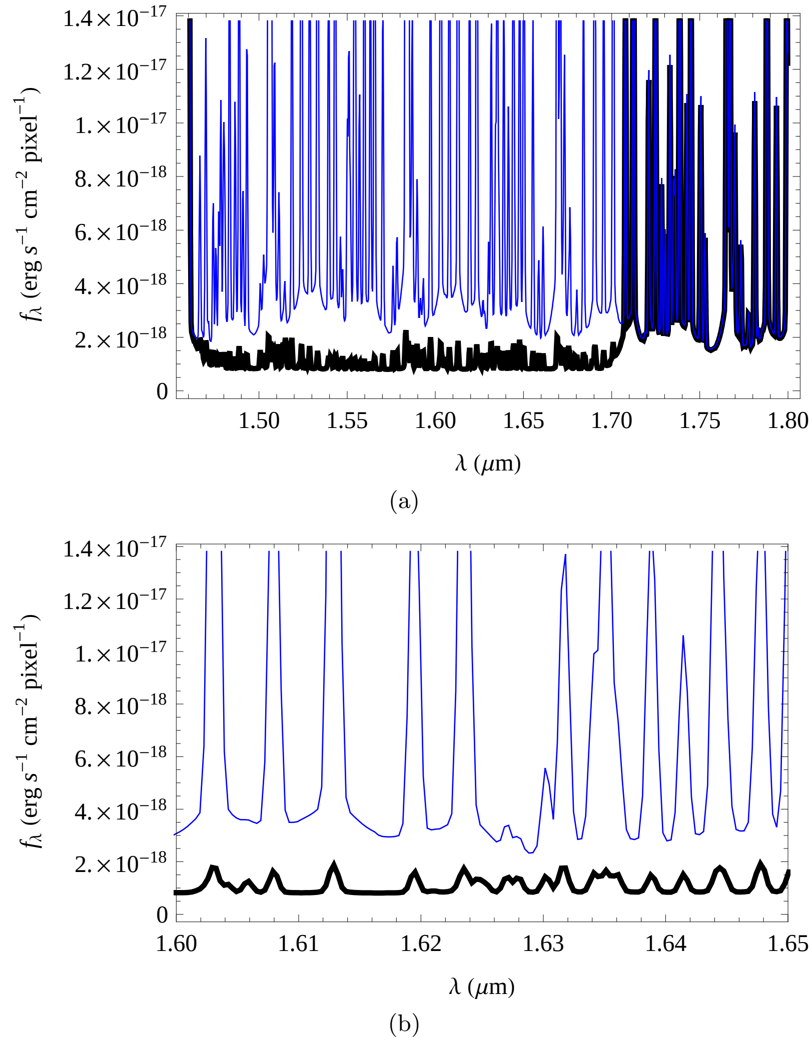


Figure 6. The 5σ limiting sensitivities in 1hr for GNOSIS (black) and for and identical system without FBGs (blue). Panel (b) shows a close up of the region between 1.60 and 1.65μm. There is a small decrease in sensitivity at the location of residual OH emission lines.

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

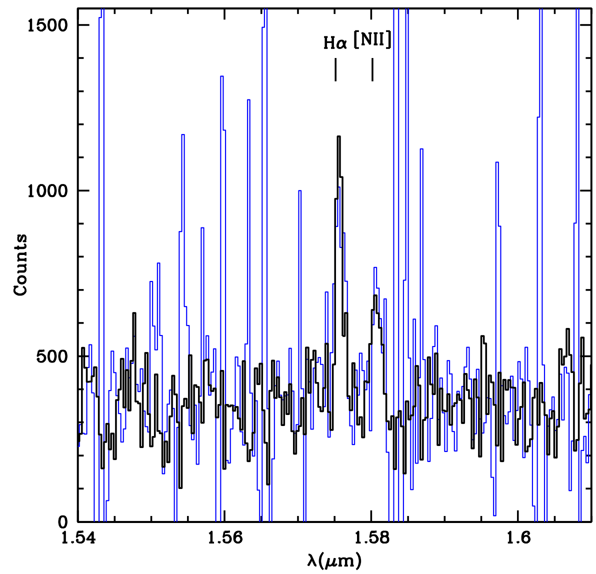


Figure 7. A simulated 6hr GNOSIS observation of an H=20 mag emission line galaxy at $z = 1.4$ (black) shows that Hα is detectable. Also clearly visible is [NII]6584Å. The blue spectrum shows simulations for an identical system without FBGs, in which the Hα line is lost in the residual sky lines.

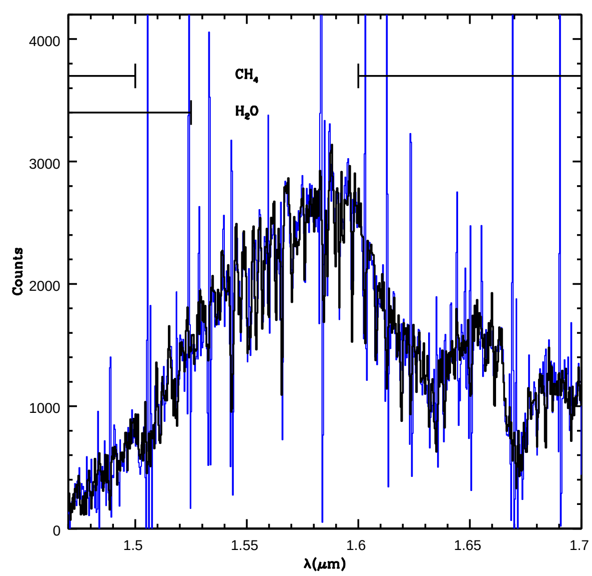


Figure 8. A simulated 6hr GNOSIS observation of an J=20 mag T5 dwarf star (black). The blue spectrum shows simulations for an identical system without FBGs.

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms

6. T. Kelsall, J. L. Weiland, B. A. Franz, W. T. Reach, R. G. Arendt, E. Dwek, H. T. Freudenreich, M. G. Hauser, S. H. Moseley, N. P. Odegard, R. F. Silverberg, and E. L. Wright, "The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. II. Model of the Interplanetary Dust Cloud," *ApJ* **508**, p. 44, Nov. 1998.
7. J. P. Gardner, J. C. Mather, M. Clampin, R. Doyon, M. A. Greenhouse, H. B. Hammel, J. B. Hutchings, P. Jakobsen, S. J. Lilly, K. S. Long, J. I. Lunine, M. J. McCaughrean, M. Mountain, J. Nella, G. H. Rieke, M. J. Rieke, H.-W. Rix, E. P. Smith, G. Sonneborn, M. Stiavelli, H. S. Stockman, R. A. Windhorst, and G. S. Wright, "The James Webb Space Telescope," *Space Science Reviews* **123**, p. 485, Apr. 2006.
8. J. Bland-Hawthorn, M. Englund, and G. Edvell, "New approach to atmospheric OH suppression using an aperiodic fibre bragg grating," *Optics Express* **12**, p. 5902, 2004.
9. J. Bland-Hawthorn, S. Ellis, R. Haynes, and A. Horton, "Photonic OH suppression of the infrared night sky: first on-sky results," *Anglo-Australian Observatory Newsletter* **115**, p. 15, Feb. 2009.
10. S. Leon-Saval, T. Birks, J. Bland-Hawthorn, and M. Englund, "Multimode fiber devices with single-mode performance," *Optics Letters* **30**, p. 19, 2005.
11. D. Noordegraaf, P. M. W. Skovgaard, M. D. Nielsen, and J. Bland-Hawthorn, "Efficient multi-mode to single-mode coupling in a photonic lantern," *Optics Express* **17**, p. 1988, 2009.
12. C. G. Tinney, S. D. Ryder, S. C. Ellis, V. Churilov, J. Dawson, G. A. Smith, L. Waller, J. D. Whittard, R. Haynes, A. Lankshear, J. R. Barton, C. J. Evans, K. Shortridge, T. Farrell, and J. Bailey, "IRIS2: a working infrared multi-object spectrograph and camera," *Proc. SPIE* **5492**, p. 998, 2004.

Downloaded from SPIE Digital Library on 13 Dec 2011 to 137.111.13.200. Terms of Use: http://spiedl.org/terms