Grism Spectroscopy with FLITECAM

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ABSTRACT

FLITECAM, a near-infrared instrument being developed at the UCLA Infrared lab, will be the first light infrared instrument for NASA's SOFIA aircraft. In addition to its imaging capability, FLITECAM has been equipped with three direct-ruled KRS-5 grisms, allowing observations in 9 spectral bands, and giving nearly continuous spectral coverage from 1 to 5.5 microns. The design favors regions of the spectrum that are heavily attenuated except at high altitudes. The grisms are used with a dual-width long slit to yield a spectral resolution of R~1700 at high resolution and R~ 900 at low resolution. This resolution is better than that of the IRAS, ISO or KAO spectrometers, and covers a spectral regime left unsampled by the Spitzer Space Telescope. When used on the SOFIA, FLITECAM's spectroscopic mode will allow astronomical investigation of near-infrared features at a low water vapor overburden. The grism spectroscopic mode has been demonstrated on the Shane 120 inch telescope at Lick Observatory by observations of astronomical targets of interest, especially the PAH feature at 3.3 microns in HII regions and young planetary nebulae.

Keywords: airborne astronomy, instrumentation, grisms, infrared astronomy, FLITECAM, SOFIA, PAH, planetary nebula, spectroscopy, KRS-5

1. INTRODUCTION

FLITECAM, the First Light Test Experiment Camera for SOFIA is a 1-5 micron near-infrared instrument developed at the UCLA Infrared Lab by a team led by Professor Ian McLean. Although operating in the near-infrared, FLITECAM is designed to take advantage of the low (~10 micron) water vapor overpressure expected with SOFIA which opens up parts of the 2-5 micron regime relative to ground-based observations. The instrument has an 8′ x 8′ circular FOV inscribed on a 1024 x 1024 pixel InSb Aladdin III detector. FLITECAM has three modes of operation: a pupil-viewing mode used to evaluate the SOFIA primary; an imaging mode with a suite of broad and narrow-band filters; and a spectroscopic mode with fixed slits to provide moderate R~2000 resolution[3].

Although designed for deployment on SOFIA, FLITECAM has been used successfully 7 times at Lick Observatory on the Shane 3 meter telescope. The close focal length match between the Shane and SOFIA telescopes allows not only calibration and characterization of FLITECAM, but also scientific investigation with the instrument before completion of the SOFIA aircraft. The first four observing runs at Lick were dedicated exclusively to the imaging mode and resulted in two ApJ papers and a PhD dissertation [4,5]. A detailed description of FLITECAM's imaging capabilities can be found elsewhere in these proceedings.

FLITECAM's grism spectroscopy mode was installed in March 2004 and was commissioned at Lick in September 2004. Using a set of three direct-ruled, KRS-5 grisms and appropriate order-sorting filters, FLITECAM achieves R~1700 spectroscopy in nine bands with a 1″ wide slit. These bands offer nearly contiguous coverage of the 1-5.5 micron wavelength regime, neglecting only the 4.2 to 4.4 micron region, which is inaccessible except to space-based missions[3]. The grism spectroscopy mode is currently being used to perform a combined spectroscopic and narrow-band imaging study of PAH formation in planetary nebulae and their evolutionary precursors.

2. FLITECAM

FLITECAM was originally commissioned as the primary test instrument for the SOFIA telescope—it was to characterize the primary mirror, calibrate the observatory's water vapor monitor, and provide large- FOV multi-wavelength images in the near-IR[1]. In order to fulfill this test function, it was also designed to be mountable on the Shane 3 meter telescope at Lick observatory, where the instrument could be fully characterized prior to use aboard SOFIA. Although designed specifically for the thermal infrared and the expected image quality on SOFIA, FLITECAM is still a highly capable scientific instrument for ground-based observations. In particular, the large field of view makes FLITECAM an ideal survey instrument.

Calibration of the SOFIA water vapor monitor required the addition of a grism spectroscopy mode to FLITECAM. In order to calibrate the monitor, FLITECAM needed to resolve the 2.5 micron atmospheric water lines—requiring a resolution of R~1000 or better[2]. By careful selection of grism characteristics we are able to cover the entire 1-5.5 micron band with R~ 1700, thereby fulfilling FLITECAM's test function for SOFIA, while simultaneously expanding its ground-based and airborne science capabilities.

3. GRISM SPECTROSCOPY

Grisms offer a relatively low-cost method of adding moderate resolution spectroscopic capabilities without modification of an instrument's optical path. A grism is essentially a prism with a transmission grating either etched into or adhered to its surface. The transmission grating disperses light away from the optical axis, so the prism geometry is chosen so as to bend the dispersed light back into the optical path by exploiting Snell's Law. Figure 1 shows the basic geometry for a grism.

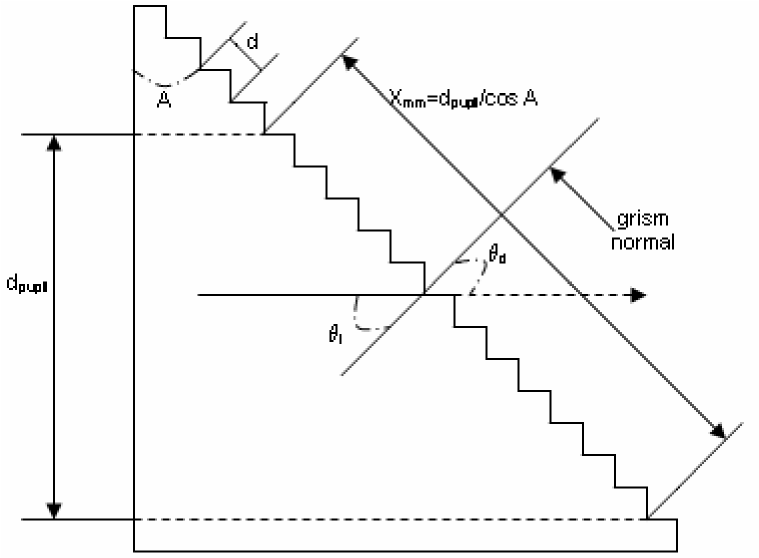

Figure 1. Grism geometry

In grism spectroscopy the blaze angle of the grating is equal to the apex angle of the prism—we have assumed a right-angled prism shape to simplify mounting and to ensure the incident light beam is perpendicular to the grism surface. The basic grism dispersion relation is given by [3]:

$$T\, m\, \lambda_c = (n - 1) \sin A$$

In this expression, T is the groove spacing in lines/mm and m is the order number. We can relate the resolution to the grism angle, A by placing the grism at the pupil and assuming we are seeing-limited (which is valid for both the Shane 3 meter telescope and the SOFIA telescope for FLITECAM's wavelength range). This gives[6]

$$R = 206265\, (n - 1)\, d_{pupil} \tan A / D_{tel}\, s_{arc}\, ,$$

where s_{arc} is the entrance slit size in arcseconds. The smallest Nyquist-sampled slit size for FLITECAM is 1″, which is also well-matched to the seeing at Lick Observatory. FLITECAM's grisms were made of KRS-5 (n~2.4) for reasons discussed below and the pupil size is 26mm. This leaves the grism angle A as the adjustable parameter. To achieve R~2000, the FLITECAM grisms need a prism angle, A, of about 30 degrees.

The final equation gives the range of the grism's dispersion incident on the detector[6].

$$(max/min\ wavelength) = \lambda_c +/- \ [(n-1)\, d_{pix} \cos A / F_{cam}\, m\, T] * N_{pix}/2,$$

where N_{pix} is the number of pixels on the detector in the direction of dispersion, F_{cam} is the F/# of the re-imaging optics and d_{pix} is the linear size of a detector pixel. Grisms are blazed to the first order, so only the first four orders will have high enough throughput to be useful. While the slit width controls the resolution (to the first order), the line spacing controls the central wavelength of each grism order. Assuming three useful orders for each grism, we can cover the entire 1-5.5 micron range with three grisms.

4. SPECTROSCOPY MODE DESIGN

4.1 Entrance Slit

The FLITECAM entrance slit is a 16.5mm long slot cut into an aluminum plate (2′ long as seen by the detector). For half the length it is 675μm wide, and for the other half it is 450μm wide (2″wide and 1″ wide respectively on the detector). A computer-controlled slide mechanism moves the slit plate in and out of the beam. When in the beam, the slit is positioned at the telescope focus, just inside the FLITECAM dewar window, with the long axis of the slit positioned slightly below the central row of the detector, and the center of the slit (where the two widths meet) placed roughly at the center of the detector. On the detector, the long axis position is repeatable to within 2 pixels in laboratory tests. Current control and data reduction software are able calibrate the exact slit position for data reduction and object positioning. Figure 2 shows the slit as positioned in the beam.

Figure 2. FLITECAM's entrance slit. The left side of the slit is 2″ wide, while the right side is 1″ wide.

4.2 Grism Selection

There are two ways to fabricate a grism. The most common technique is to use a prism and simply adhere a transmission diffraction grating to the prism's hypotenuse surface using a resin. Another, more technically demanding approach, is to rule grooves directly into the face of the prism. While using a resin grating is often less expensive and less time-consuming than direct-ruling, the resin has several drawbacks; adhering a transmission grating to the prism adds another surface to the system; trapped air beneath the surface of the transmission grating can cause multiple reflections and 'ghosted' spectral features; and the adhesive itself has an absorption feature at 3.4 microns resulting from C-H stretching—the same organic feature we hope to investigate in the interstellar medium[3].

In order to fully bend the diffracted light back onto the optical path infrared grisms are made with high index of refraction material, such as ZnSe (n~2.4) or KRS-5 (n~2.4). ZnSe prisms are relatively common and inexpensive, but the material is highly brittle, which leads to pitting and cracking when the grooves are machined. As with any grating, the efficiency and throughput is directly related to the quality of the groove spacing, making ZnSe unattractive for directly ruled grisms. KRS-5 is a softer material, making precision ruling possible.[7]

Zeiss Jena can make high quality directly ruled grisms of KRS-5 with grism angles of up to 40 degrees, but require the line spacings of 651/n, where n is an integer. The only restraint on the FLITECAM spectroscopy mode set by SOFIA requirements is for FLITECAM to resolve the atmospheric water line at 2.5 microns in order to calibrate the SOFIA water vapor monitor, which requires a resolution of R~ 1000. A grism with an apex angle, A of 34.4° and line spacing T of 162.75 ln/mm places the 2.5 micron feature at the center of the second order (m=2) with an approximate resolution of R~2000. For simplicity we used A=34.4° for all three grisms, but chose the line spacings for the remaining two grisms such that the set of three grisms would cover the entire 1-5 micron band. The 2.5 micron water feature is resolved by the 'B' grism. The specifications for all three grisms are found in Table 1.

Table 1: Grism specifications

Grism	T	Order	OSF	λi (μm)	λc (μm)	λf (μm)
A	162.75	1	L&M	4.395	4.96	5.533
A	162.75	2	Klong	2.216	2.5	2.784
A	162.75	3	Hwide	1.497	1.69	1.877
B	217	1	L&M	3.307	3.73	4.16
B	217	2	Hwide	1.649	1.86	2.076
B	217	3	J	1.14	1.28	1.424
C	130.2	2	L&M	2.756	3.11	3.467
C	130.2	3	Kwide	1.872	2.11	2.346
C	130.2	4	Hwide	1.445	1.62	1.801

4.3 Order Sorting Filters

Grisms result in overlapping orders of diffraction. To separate these orders, the grism must either be cross-dispersed or be used with an order-sorting filter. FLITECAM uses 6 order sorting filters, 4 of which are customized specifically for spectroscopy and 2 of which are common broadband filters. All are located in the first of two filter wheels. These filters were manufactured by Barr Associates. The three KRS-5 grisms are located in the second filter wheel. Figure 3 shows the optical layout of FLITECAM in spectroscopic mode.

Each of the grisms yields 3 spectroscopic orders in the 1- 5.5 micron regime, leading to 9 total spectroscopic bands for the instrument itself. The bands are displayed graphically in Figure 3. The spectroscopic flat for the CKw band is shown in Figure 4.

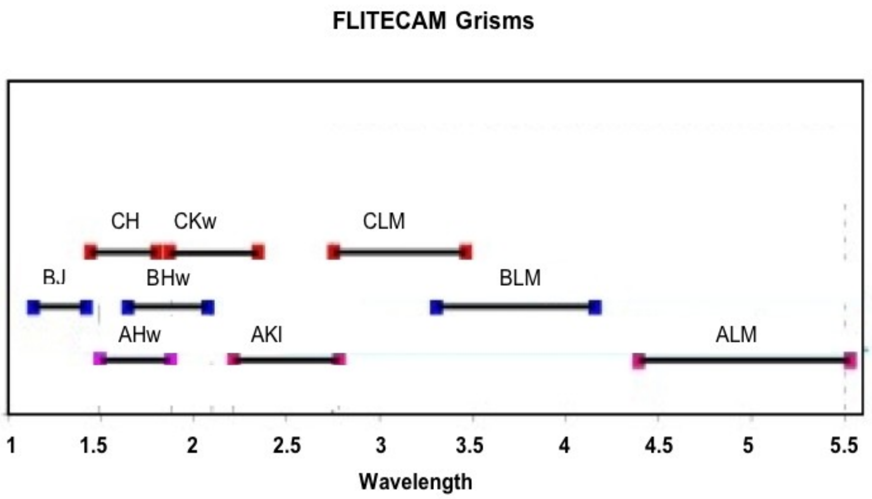

Figure 3: Wavelength coverage of FLITECAM's grism spectroscopy mode

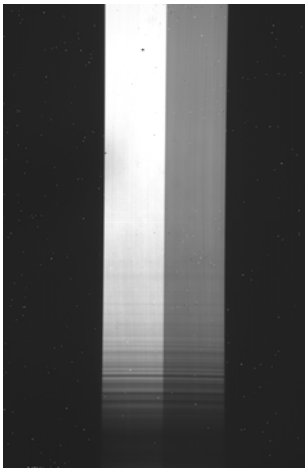

Figure 4. White light flat for the CKw band. Wavelength increases in the down direction.

4.4 Installation & Testing

After grism fabrication, the most challenging aspect of the FLITECAM spectroscopy mode was mounting the KRS-5 grisms. It has been reported that KRS-5 can become opaque when subjected to high stresses[7]. All the optics inside the FLITECAM dewar are cooled to roughly liquid nitrogen temperatures (~80K), so expansion characteristics are non-negligible. The grism must also be kept stationary in the beam, no matter the orientation of the filter wheel. The final grism mounts are fully reversible, and constrain the grism position with copper springs on the base and lid of the mount. The KRS-5 grism is installed in the mount first, so the mount can then be loaded into one of three square holes in the second filter wheel. Figure 5 shows the KRS-5 grism in its mount and in the filter wheel. It should be mentioned that there is one major concern when working with KRS-5. KRS-5 is made of Thallium Bromoiodide, a heavy metal that can be absorbed through the skin[7]. Therefore, as with all optics, the grisms should be handled only with gloves. The grism holders were designed to hold the grisms for the lifetime of the instrument. Since their assembly and installation, the grisms have not been disturbed except for visual inspection.

The KRS-5 grisms, order sorting filters and entrance slit became available in May – December 2003, and were installed in early 2004. Before commissioning on the Shane telescope, the spectroscopy mode was tested extensively in the laboratory using arclamps, diffuse light sources, and sunlight. Eight of the nine bands have been lab-tested (the longest band saturates even at the shortest exposure times, and will need to be calibrated aboard SOFIA). Wavelength solutions were found with neon, hydrogen and argon arc lamps. Laboratory tests show the lower resolution slit to have R~900, and the higher resolution slit to have R~1700. Table 2 gives the laboratory characteristics of the spectroscopy mode.

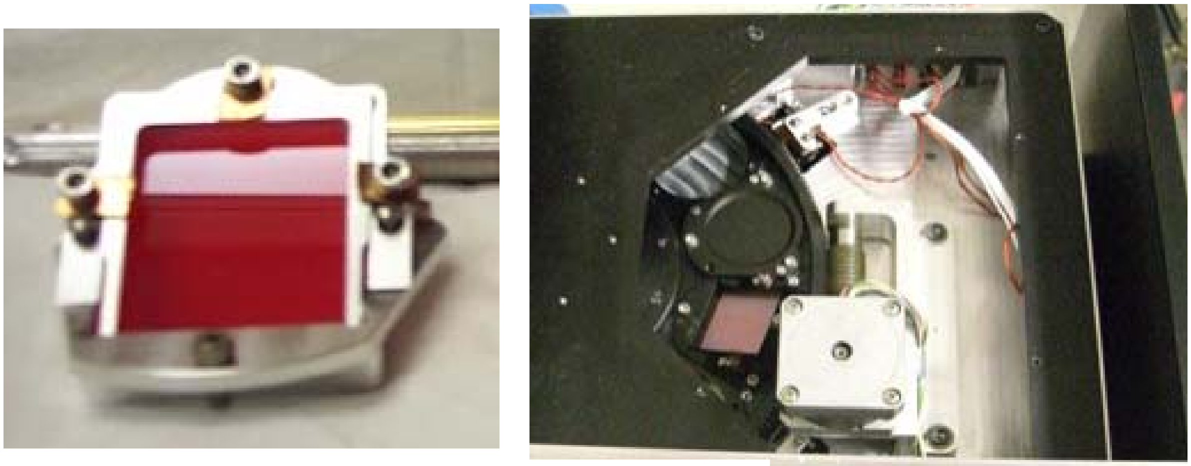

Figure 5. KRS-5 grism in mount (left), and in the filter wheel (right)

Table 2. Grism resolution and dispersion

Grism	Order	OSF	R(FWHM)	Dispersion (μm/pixel)
A	1	L&M	N/A	0.001111
A	2	Klong	1690	0.000556
A	3	Hwide	1710	0.00037
B	1	L&M	1780	0.000833
B	2	Hwide	1750	0.000417
B	3	J	1720	0.000278
C	2	L&M	1670	0.000694
C	3	Kwide	1650	0.000463
C	4	H	1640	0.000347

5. COMMISSIONING

5.1 Telescope Commissioning

The KRS-5 spectroscopy mode was commissioned on the Shane 3 meter telescope in May 2004. All the bands were tested on a series of red giant and A0 stars. K-band and 3-micron emission line spectra of several planetary nebulae were also obtained at the telescope, as part of an ongoing survey of PAH features in evolved stars. The spectroscopy mode has been used subsequently on 4 more observing runs at Lick observatory, with the primary focus on obtaining K and 3μm spectra of planetary nebulae. Several improvements to the spectroscopic system have been added in the course of these runs, including automated guiding via a special interface to the Lick Guider system, ABBA nodding, and a special mechanism control to apply small positional tweaks to each grism to straighten the spectral traces of objects at high airmass. Only the longest wavelength mode, which extends past 5 microns has not been used at the telescope. Figure 6 shows the 3 micron spectrum of NGC 7027 as an illustration.

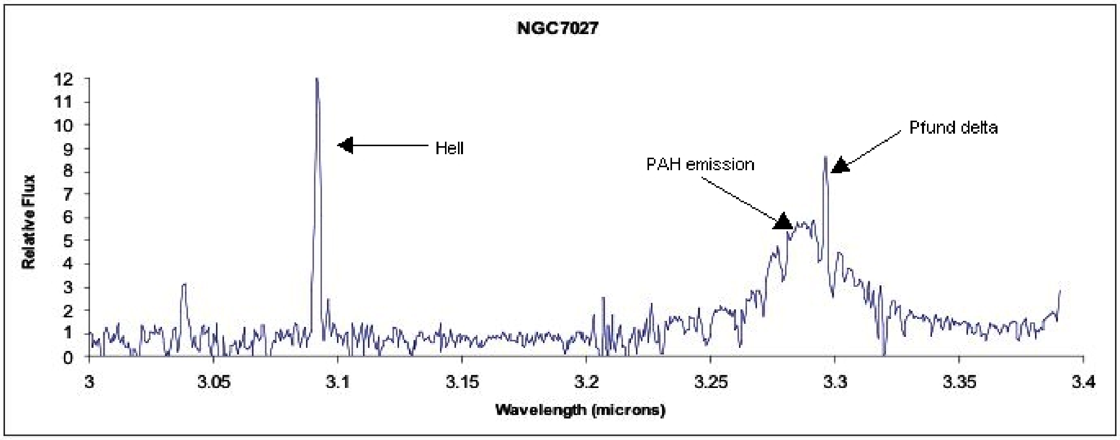

Figure 6. The 3 micron spectrum of NGC 7027. Absorption features are residual water lines in the Earth's atmosphere.

5.2 Sensitivity

The sensitivity of the spectroscopic mode depends upon the band in use. The limit for a SNR of 10 with 20 minutes total integration time is J=13, H=15, K=14.5. For bands with coverage longwards of about 3 microns, the observations are severely background limited, with maximum integration times of 5 seconds in the CLM band and maximum integration times of 3 seconds in the BLM band. In the CLM band objects with L=12 are detectable with an average SNR of 5 over a 10 minute total integration time at Lick Observatory. Longer integration times are difficult due to atmospheric variability. The ALM band saturates even in the shortest integration time (0.3 seconds). Of course, with the much lower backgrounds from SOFIA, these bands will no longer be so heavily background-limited.

5.3 Observing & Data Reduction

The FLITECAM spectroscopy mode is fully integrated with the FLITECAM observing software, including the automated observing modes required by SOFIA. Slit position, targeting and nod patterns are adjusted through a graphical user interface (GUI) on the main observer's computer. Observations can be taken either by manually inserting the appropriate grisms and filters, or by loading a pre-written script into the Automated Observing Request (AOR) interface.

FITS files from FLITECAM's spectroscopy mode can be reduced like any output from a CCD spectrometer would be reduced, but a specialized data reduction package, FLITESPEC will also be included. FLITESPEC is simply a version of REDSPEC (the data reduction package developed for NIRSPEC, the UCLA built echelle spectrometer at Keck Observatory) that has been optimized for handling FLITECAM spectroscopic data. The package automatically applies the correct wavelength solution flat and dark frames, but allows the user to select the trace size and location before producing a fully reduced, science-ready data set.

5.4 Wavelength solutions and stability

Using the same technique as in the lab, we are able to find wavelength solutions for all eight ground-usable bands at the telescope. Comparing the wavelength solutions at several times throughout a night and between several nights shows the spectral shift to be less than 2 pixels. The most fully characterized grism is the C grism (130.2 ln/mm). The m=3 order of this grism includes the Brγ emission feature, while the m=2 order includes the 3.3μm PAH emission feature. The wavelengths solutions for these two bands are below;

CKw (m=3 order) : λ= 2.044+ 4.400*10^{-4}(pixel),
CLM (m=2 order) : λ= 3.064+6.529*10^{-4} (pixel)

6. SCIENCE POTENTIAL

6.1 Ground-based Science

While FLITECAM was originally designed for use exclusively aboard SOFIA, it is also attractive for ground-based investigations. Even at sites with high backgrounds (such as Lick observatory) FLITECAM is capable of performing spectroscopy in the thermal infrared. With R~2000 resolution, FLITECAM can easily resolve emission lines found in Planetary nebulae, star-forming regions and emission-line stars. Also, with its 2′ long slit, FLITECAM can examine long strips of extended objects with a single positioning.

Another advantage of FLITECAM is its ability to produce narrow-band images of targeted regions to help identify regions of particular interest for spectroscopy. The dual imaging and spectroscopy modes allow investigation of dust and ice emission features not only spectrally, but also spatially, a capability not available on dedicated spectrometers.
Because the SOFIA project requires automated data reduction of dithered images, FLITECAM has a Data Reduction Pipeline (DRP) that runs automatically in the background and produces flat-fielded reduced images. With the FLITECAM DRP, developed by Ralph Shuping (USRA), we can make narrow-band images of extended regions and use those images to precisely place the FLITECAM slit all in real-time at the telescope. Such a technique will be most useful for mapping dust and/or ice distributions in large regions like HII regions and reflection nebulae, and using the spectroscopy mode for confirmation and analysis of spectroscopic features.

6.2 Airborne Science

Of course, FLITECAM's true scientific potential lies with SOFIA. Reduced water vapor levels and a lower thermal background compared to even the best ground-based observatories will make FLITECAM 10-20 more sensitive in certain parts of the 1-5 micron region. Figure 7 shows the estimated water vapor levels for the 1-5 micron band expected aboard SOFIA as compared to those at Mauna Kea. When aboard SOFIA, FLITECAM will be the only instrument with spectroscopic capabilities from 1-5 microns with access to features obscured from the ground. While Spitzer has far lower backgrounds and better image quality than we expect from SOFIA, it has neither the narrow-band capability nor the spectroscopic capabilities of FLITECAM from 1-5 microns, and it is a limited lifetime mission.

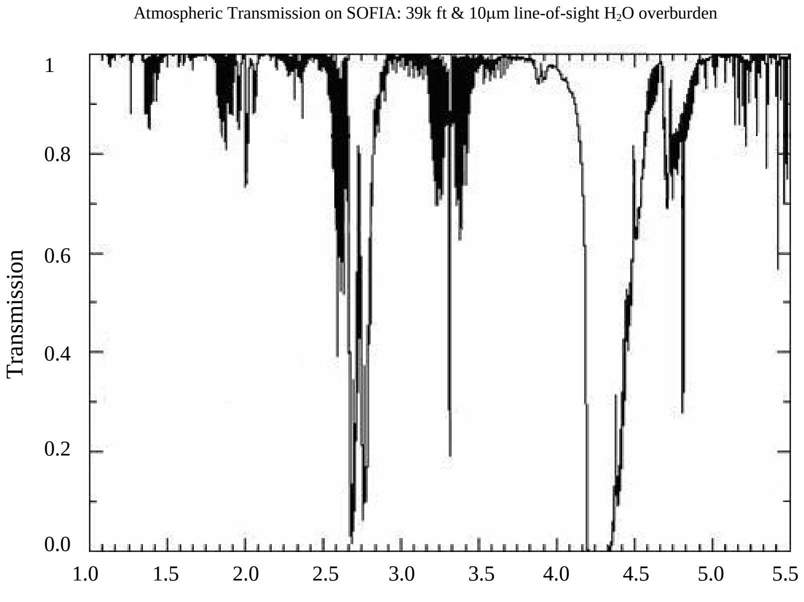

Figure 7. Expected atmospheric transmission for SOFIA. From Greene et al [2]

The reduced water vapor levels will make observations of interstellar water-ice features possible, and opens all but the 4.2 - 4.4 micron CO_2 region open for imaging and spectroscopy[2]. In the 1-5 micron band the main advantage from SOFIA comes from the low backgrounds. Aboard SOFIA the ALM grims-order sorting filter band (4.4 - 5.5 microns) will no longer saturate, allowing spectroscopy of Brα and Pfβ emission features and observations of SiO, H_2 and CO molecules[2]. Also, the CLM and BLM bands will be capable of much longer integration times, and will thus be able to investigate fainter objects. Finally, in all measurements, especially the L & M bands, the backgrounds will vary on a much longer timescale than in ground-based observing. This will make FLITECAM capable of obtaining higher signal to noise ratios for extended and faint objects than its current ground-based limits allow.

7. RESULTS

The FLITECAM spectroscopy mode is currently being used to conduct a survey of carbon-rich planetary nebulae and their evolutionary precursors. The goal of the study is to investigate the distribution and evolution of the 3.3 micron PAH emission feature as these nebulae evolve, and to compare this emission with atomic gas emission. We have obtained spectra for 23 nebulae in the K and L bands using the CKw and CLM grism-order sorting filter combinations. We have also obtained spectra of NGC 7027, a particularly interesting young PN in all eight of the unsaturated spectroscopic bands. Figure 8 shows the reduced three-micron spectra of targeted PNs. The broad rising feature in the spectra is the 3.3 micron PAH emission band. All spectra are to the same scale. We have also obtained K band spectra for each target in order to investigate the relationship between PAH emission and atomic emission.

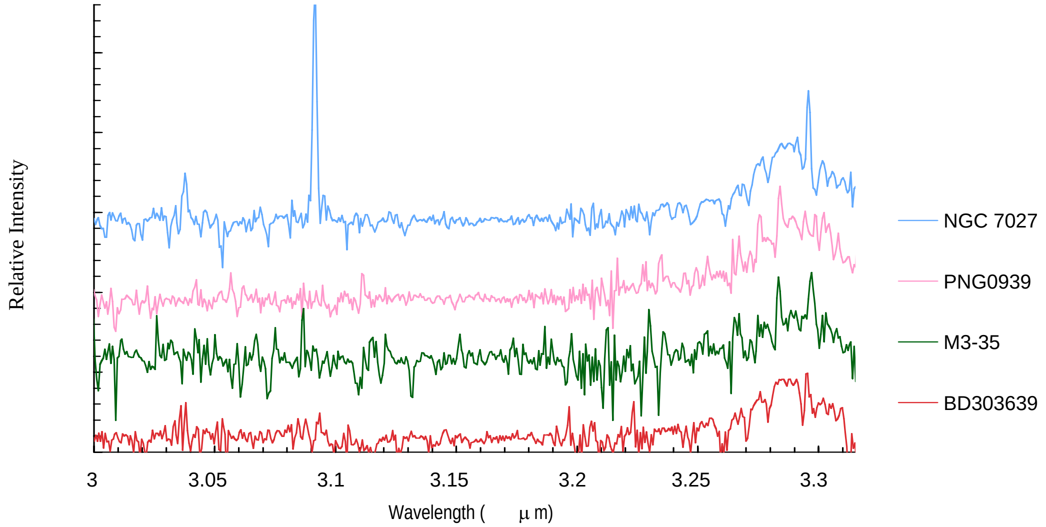

Figure 8. Reduced spectra of selected planetary nebulae.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Figer, D.F., McLean I.S. and Becklin, E. E., “FLITECAM: a 1-5 micron camera for testing the performance of SOFIA,” in *Infrared Astronomical Instrumentation*, A. Fowler, ed., *Proc. SPIE* **3354**, pp 1179-1184, 1998.
2. Greene, T. et al. 2002, Moderate Resolution Mid-IR Spectroscopy on SOFIA: Scientific Motivation and Recommended Implementations.
3. Horn, J. M., et al., *Proc. SPIE* 4014, pp. 65-76, 2000
4. Mainzer, A.K., McLean, I. S., 2003, ApJ, 597, 555
5. Mainzer, A.K., McLean, I. S., Aliado, T., Becklin, E. E., Brims, G., Goulter, J., Kress, E., Magnone, N., Milburn, J., Skulason, G., Spencer, M. 2003, *Proc. SPIE*
6. McLean, I. S., *Electronic Imaging in Astronomy*, Wiley-Praxis, 1997
7. Rayner, J. T., “Evaluation of a solid KRS-5 Grism for Infrared Astronomoy,” in *Infrared Astronomical Instrumentation*, A. Fowler, ed., *Proc. SPIE* **3354**, pp 289-294, 1998.