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Progress report on FORCAST grism spectroscopy as a future general observer instrument mode on SOFIA

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ABSTRACT

We have implemented and tested a suite of grisms that will enable a moderate-resolution mid-infrared spectroscopic mode in FORCAST, the facility mid-infrared camera on SOFIA. We have tested the hardware for the spectral modes extensively in the laboratory with grisms installed in the FORCAST filter wheels. The grisms perform as designed, consistently producing spectra at resolving powers in the 200-1200 range at wavelengths from 5 to 38 microns. In anticipation of offering this capability as a SOFIA general observer mode, we are developing software for reduction and analysis of FORCAST spectra, a spectrophotometric calibration plan, and detailed plans for in-flight tests prior to commissioning the modes. We present a brief summary of the FORCAST grism spectroscopic system and a status report.

Keywords: infrared, spectrograph, grism

1. INTRODUCTION

One of the great strengths of the Stratospheric Observatory for Infrared Astronomy (SOFIA) is the breadth of capabilities it offers including high resolution spectroscopy over a broad range of wavelengths. We have developed a suite of grisms for use in the Faint Object Infrared Camera for the SOFIA Telescope (FORCAST[1]). The FORCAST grism project builds on the strengths of SOFIA by covering a significant amount of previously uncovered territory in wavelength-resolving power space (Figure 1), without the need for an additional costly and complex instrument. The capabilities added by the grism suite include R~100 and R~1200 spectroscopy from 5 to 13 μm and R~150 spectroscopy from 18 to 38 μm. The mid-IR spectroscopic capability made available by the FORCAST grisms finds significant uses across the whole range of proposed SOFIA science. Many of the areas of early science highlighted in the White Papers emerging from workshops at recent AAS meetings can only be thoroughly explored if this capability becomes available during the first few years of SOFIA operations. A few examples of the astrophysical investigations in which grism spectroscopy on SOFIA would play a critical role are observations of: evolution of refractory grains from their formation to their incorporation in protoplanetary bodies; large molecules like the polycyclic aromatic hydrocarbons (PAH's), which many broad spectroscopic features in the mid-IR that mediate the processing of stellar energy by the interstellar medium in our own Galaxy and in other galaxies; dense molecular clouds including depletion of volatiles to form icy mantles on dust grains in the coldest and densest part of the clouds.

FORCAST grism spectroscopy also exemplifies the utility of SOFIA in bridging the capabilities of other infrared observatories and offering higher spatial and spectral resolution than current infrared space observatories. Herschel, for example, does not cover the FORCAST wavelength range for imaging or spectroscopy and JWST will not offer imaging or spectroscopy beyond 28 μm. FORCAST grism spectroscopy will span this gap enabling more and richer scientific investigations.

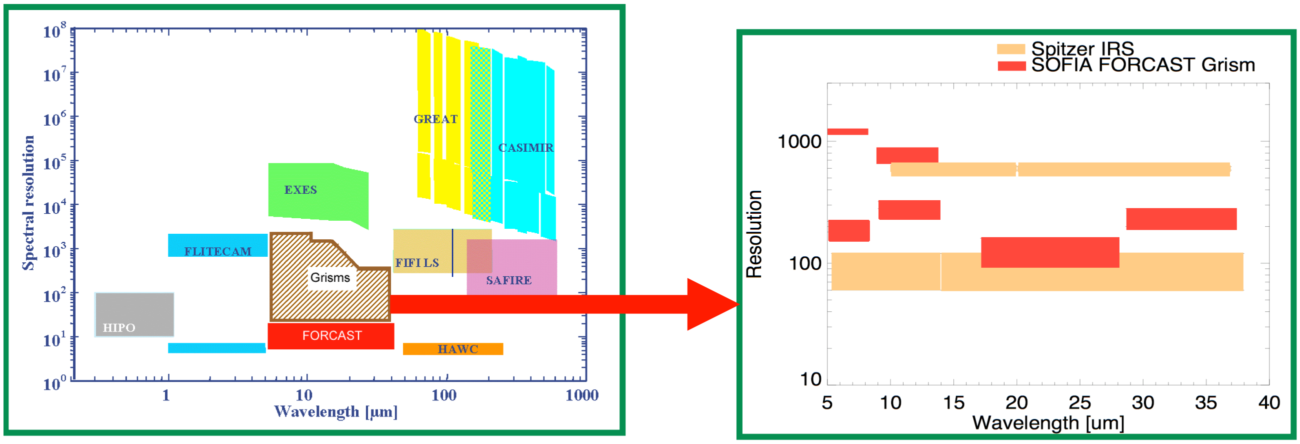

Figure 1. (Adapted from Ennico et al. 2006) Observational capabilities of SOFIA expressed in terms of spectral resolving power vs. wavelength including FORCAST imaging modes (Left plot, solid RED box at lower center) and the new grism spectroscopy modes (hatched box at center). Right plot: Grism spectroscopy modes compared to the Spitzer IRS. 5-40 µm sensitivity range of FORCAST vs. spectral resolving power with all grism modes represented (RED) and compared to the spectral range of the Spitzer Infrared Spectrograph (GOLD).

2. TECHNICAL IMPLEMENTATION

The FORCAST grism project[2,3] was designed in close collaboration with the FORCAST team. The chief operational constraint was that the development and testing of the grisms should not interfere with or add risk to the schedule or performance of the camera selected by the original peer review for first-round SOFIA instrumentation. The chief physical constraint was that the spectroscopic capability would have to be added to FORCAST without changing the optical or mechanical design of the instrument and without requiring significant changes or additions to the FORCAST data acquisition software, both of which were very close to completion when our grism spectroscopy (ASTID) grant was approved. The remaining work on the grism modes can be completed in parallel with the FORCAST commissioning and thus will not distract FORCAST personnel from that essential work.

2.1 Optical subsystem

The use of grisms to provide the spectroscopic capability for FORCAST is dictated by the need for the center of the spectrum to follow the undeviated ray and appear on the detector at approximately the same position as would an undispersed image. An appropriately blazed grism can do this. The slit-width resolving-power product θR (θ in radians), which is a useful figure of merit for grisms, depends on the diameter of the collimated beam W, the sine of the grism opening angle δ, the telescope diameter D, and (n-1) where n is the refractive index of the grism material:

$$\theta R = (n-1)\frac{W\sin(\delta)}{D}$$

For our design W and D are fixed by the FORCAST collimated beam and the SOFIA primary mirror and δ is constrained by the clearance around the filter wheels. To get the best performance, one must therefore use a material with the highest possible n. Further, to achieve continuous wavelength coverage at high resolution (on a small detector) with cross-dispersed grisms, one of the grisms must have a very coarse ruling. Table 1 gives the characteristics of the 6 grisms in the FORCAST suite. These include four micro-machined silicon gratings (n=3.4), produced at the University of Texas[4] for use at 5-8 µm and 18-37 µm, and two ruled KRS5 gratings (n=2.4) for 8-13 µm, purchased from Zeiss Jena.

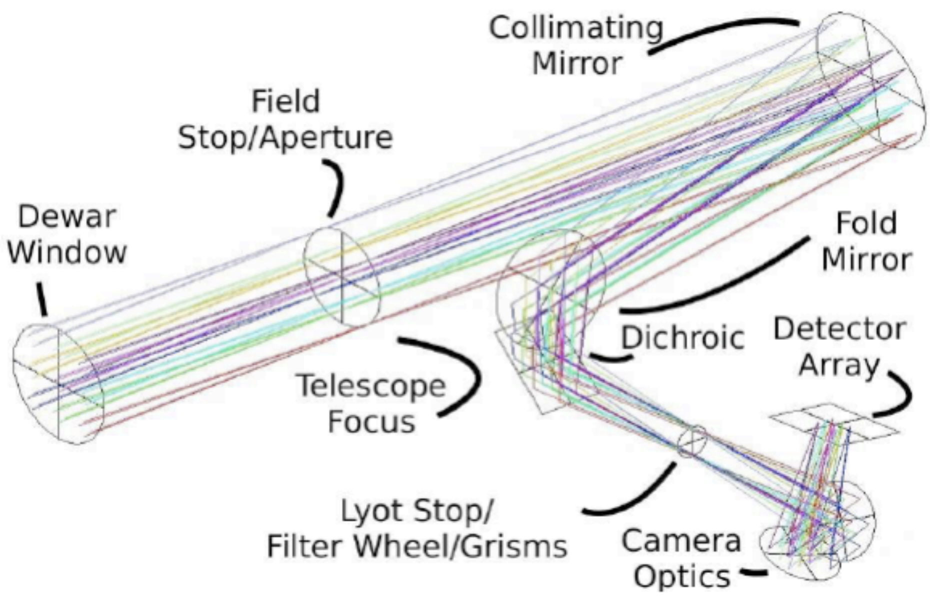

Figure 2. FORCAST optical layout and raytrace of a single camera/channel. Grisms will be located in dual filter wheels located near the Lyot stop.

FORCAST has an aperture wheel, at the position of its cold field stop (Figure 2), that has extra positions available to house the slits required for the different grism modes. Both the long wavelength and short wavelength cameras of FORCAST contain an image of the telescope secondary, intended as a location for a cold pupil stop. There are two filter wheels in each camera, located within 1 cm of this Lyot stop. One wheel can hold the high-order grisms intended for use at R=1000-2000 at 5.5-13 µm. The other wheel can hold the 1st and 2nd order grisms used for low resolution long-slit spectroscopy and for cross-dispersion of the higher order devices. All grisms were designed and fabricated to fit in the existing FORCAST fliter wheels along with the existing suite of bandpass filters; each grism requires a single filter space in its filter wheel.

To enable all grism spectroscopy modes simultaneously will require 6 of the existing 20 filter positions in FORCAST. However the grisms can be interchanged and removed just as if they were filters so their incorporation in FORCAST will not preclude any of the existing or planned imaging capabilities.

2.2 Data reduction and analysis software

The software for the grism spectroscopy modes takes three forms: in-flight Data Acquisition software, in-flight Data Analysis (Quick Look) software, and a post-flight data reduction pipeline for batch reduction of FORCAST spectra by the SOFIA Data Cycle System (DCS).

2.2.1 Data acquisition software

The data acquisition for grism modes uses the existing software for FORCAST imaging. The only additions to the existing FORCAST software are incorporating grism and slit selection into the controls for filter wheels and aperture wheels, respectively, and saving spectroscopy-related data in the FITS headers. These changes involve editing FORCAST instrument initialization files (i.e. no additional programming). FORCAST grism spectroscopy will require only one observing mode that is not currently available with the existing FORCAST data acquisition software: slit scanning. A slit scanning mode can be added to the FORCAST repertoire by writing a script in the existing FORCAST data acquisition macro language currently used for scripting FORCAST observations. Thus, grism spectroscopy requires no new development/coding of the FORCAST data acquisition software.

2.2.2 In-flight quick-look data analysis software

The grism spectroscopy data reduction and analysis software runs the existing FORCAST imaging data reduction pipeline and then implements spectral extraction from the 2-dimensional FITS data files. The data reduction pipeline automatically reduces pre-extraction spectral images. We have developed an interactive quick-look spectral extraction tool in IDL that is based on the FORCAST imaging quick-look tool. Both are graphical interfaces to the FORCAST data reduction pipeline[5]. The final version will do automatic extractions of spectra from FORCAST data taken in all six grism spectroscopy modes.

The quick-look spectral extraction and calibration package provides quick extraction, wavelength calibration, and some basic spectral analysis tools. The current software will extract spectra in both long-slit and cross-dispersed modes. This quick-look software is under development and a complete version will be available by Sept. 2010 as part of the current USRA-funded effort.

2.2.3 Data reduction pipeline

The pipeline data reduction package will permit hands-off reduction, extraction, and calibration of FORCAST mid-IR spectra. Eventually there will also be proposal and observation planning software, written with general users in mind and made available through the SOFIA project (DCS). We will support these by providing our detailed astronomical observation templates (AOTs) in an interface control document to USRA. The grism spectroscopy pipeline is under development and will be available by Sept. 2010 as part of the current USRA-funded effort. The data reduction and analysis software is described in detail by Deen et al. 2010[5] (these proceedings).

2.3 Observing Modes and Astronomical Observation Templates

The FORCAST grism subsystem is designed to have 6 operating modes: long-slit spectroscopy at R=100-200 for bands at 5-8 mm, 8-13.7 μm, 18-28 μm and 29-40 μm, plus cross dispersed full instantaneous coverage of 5-8 μm at R=1500 and 8-14 μm at R=800. These modes are described in detail in a FORCAST Grism Spectroscopy astronomical observation templates (AOT) document developed under our ASTID grant. Revised detailed descriptions of the AOTs will be submitted to the SOFIA DCS as part of commissioning.

Table 1. FORCAST Grism Spectroscopy Modes

Grism	Wavelength coverage	Resolving power	Slits	Grism material	Grism physical properties	Selected features/lines of astrophysical interest
1	4.9-8.1 μm	200	2” x 3’	Si	σ=25μm, γ=6.16°, m=1	PAH emission, aliphatic hydrocarbons, H_2, H_2O, CH_4
2	4.9-8.1 μm	1200	2” x 15”	Si	σ=87μm, γ=32.6°, m=15-23*	PAH emission, H_2, H_2O, CH_4
3	8.4-13.7 μm	300	2” x 3’	KRS-5	σ=32μm, γ=15.2°, m=1	Amorphous and crystalline silicates, NH_3, PAH
4	8.4-13.7 μm	800	2” x 15”	KRS-5	σ=130μm, γ=36.8°, m=8-11**	Amorphous and crystalline silicates, NH_3, PAH
5	17.1-28.1 μm	140	3” x 3’	Si	σ=87μm, γ=6.16°, m=1	Crystalline silicates, H_2
6	28.6-37.4 μm	250	3” x 3’	Si	σ=142μm, γ=11.07°, m=2	Crystalline silicates

FORCAST spectra will be taken by a combination of chopping and/or nodding along the slit. Relative response will be flux calibrated by observing bright continuum objects. In some cases, a spectral mapping (slit-scanning) capability can be very powerful. This mode will be implemented in collaboration with the telescope team using scripts written in the existing FORCAST data acquisition scripting language.

2.4 Spectral data calibration

Calibration of FORCAST grim spectra consists of: wavelength calibration, generation of order masks for use with flat field images, and registering of spectral formats on the FORCAST arrays (we refer to these as hardware calibration since they may change when the grisms are removed and replaced in the FORCAST filter wheels between flight series), and spectrophotometric flux calibration.

2.4.1 Hardware calibration

Wavelength calibration in the 5 - 8 µm and 17 - 37 µm ranges will come from laboratory spectra of water vapor lines and in the 8 - 14 µm range with selected molecular absorbers in a gas cell. These laboratory measurements will be refined in flight by use of telluric lines and by lines and features in bright astronomical sources for some bands. We are currently developing a absorbtion cell for use in wavelength calibrations of FORCAST grism spectra. Other calibrations will include use of bad pixel maps, dark and flat-field images, and order masks. The calibration images will be the same as those acquired and used for FORCAST image data reduction; the order masks allow flat-fielding of FORCAST spectra by blocking out inter-order pixels from the calibration process. All calibration data for FORCAST grism spectra will be available either as part of FORCAST imaging modes or by using existing software for wavelength calibration and order mask generation.

2.4.2 Spectrophotometric calibration

The current USRA funding (FY 2010) supports development of a detailed spectrophotometric flux calibration plan, which is in progress and will be available by Sept. 2010. The plan will involve: identification and observation (including ground-based and possibly SOFIA flight hours) of an all-sky network of calibration stars (A-type dwarfs and K-type giants); measuring the FORCAST point spread function as a function of wavelength and slit position for all spectral observing modes; and mapping the spectral response function along the slits for all spectral observing modes. We plan to model our calibration program after work on the Spitzer Infrared Spectrograph, but we realize that calibration of mid-IR spectra from SOFIA will require a more continuous effort since the infrared background and the PSF on the airborne platform will not be as stable as on a space-based platform. Calibrating mid-IR spectra on SOFIA will much more resemble ground-based calibration so that maximizing scientific return will require a very carefully planned, tested, and implemented calibration program.

3. PROJECT STATUS

The development of grisms for spectroscopy with FORCAST as well as development and testing of the resulting instrument hardware configurations have been supported by several peer-reviewed, competitive grant programs culminating in USRA financial support to make the FORCAST grism spectroscopy package available as a SOFIA facility-class observing mode. The following activities are funded by USRA and are on schedule for completion in 2010:

- Completion of flight-ready optical/mechanical components. Complete anti-reflection coating of logn-wavelength grisms (G5 & G6). Procurement of appropriate blocking filters for lab testing and flight operations and fabrication long slits and cross dispersion slits for flight are complete. Construction of and absorption cell for 9-13 micron wavelength calibration in the laboratory is in progress.
- Development of software necessary to acquire FORCAST data in grism mode. Improve software that controls observing modes and quick-look analysis and implement slit-scanning mode in software
- Development of software necessary for in-flight data quality verification (Quick Look). See Deen et al. (7735-259, these proceedings) for details and a demo of the data reduction and analysis software.

- Development of automatic (batch job) pipeline reduction/extraction of FORCAST spectra
- Preparation of a strategy for spectrophotometric flux calibration of grism mode data
- Specify FORCAST spectroscopic observing modes for DCS observation planning

A proposal to complete the following activities is currently under review by USRA for 2011-2012:

- Complete laboratory and in-flight characterization of FORCAST grsim spectroscopy as a Facility-class mode (contingent on FORCAST instrument availability)
- Carry out spectrophotometric flux-calibration strategy developed in 2010
- Science verification of all 6 FORCAST grism spectroscopy modes including routine operation of FORCAST in the grism mode as a facility instrument
- Implement pipeline data processing and support of post-processed grism mode data in the SOFIA data archive

Since the goal is a facility-class level of performance—where observing modes are well characterized and well documented, and where final data products are well-calibrated and of high quality—we have requested in-flight engineering time to test and baseline the various grism observing modes. We have also requested separate flight hours to conduct limited observations on actual astronomical targets that exercises the grism modes as they will be used by general SOFIA observers. To avoid wasting valuable flight time, we plan a series of lab tests in cooperation with USRA/NASA management to schedule hangar/line operations in preparation for commissioning and eventual science verification flights with FORCAST grisms.

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