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The SOFIA/SAFIRE Far-Infrared Spectrometer: Highlighting Submillimeter Astrophysics and Technology

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Abstract. The Submillimeter and Far-InfraRed Experiment (SAFIRE) on the SOFIA airborne observatory is an imaging spectrometer for wavelengths between 28 μm and 440 μm. Our design is a dual-band long-slit grating spectrometer, which provides broadband ($\sim$ 4000 km/s) observations in two lines simultaneously over a field of view roughly 10$''$ wide by 320$''$ long. The low backgrounds in spectroscopy require very sensitive detectors with noise equivalent powers of order 10^{-18} W/$\sqrt{\text{Hz}}$. We are developing a kilopixel, filled detector array for SAFIRE in a 32×40 format. The detector consists of a transition edge sensor (TES) bolometer array, a per-pixel broadband absorbing backshort array, and a NIST SQUID multiplexer readout array. This general type of array has been used successfully in the GISMO instrument, so we extrapolate to the sensitivity needed for airborne spectroscopy. Much of the cryogenic, electronics, and software infrastructure for SAFIRE have been developed. I provide here an overview of the progress on SAFIRE.

SAFIRE Science Goals

The SOFIA airborne observatory (Becklin et al. 2007) will be one of the primary facilities for far-infrared and submillimeter astronomy for twenty years, and will likely be the only readily available far-infrared platform for the coming decade. Currently, SOFIA is making progress toward Early Science observations in the later part of 2010. Its first light instrument suite was chosen to provide broad imaging and spectroscopic capabilities well-suited to studying Milky Way sources and galaxies out to moderate ($z \sim 1$) distance.

SAFIRE (Benford et al. 2003a) has high priority science goals aiming to answer three interrelated questions concerning this development of galaxies from the epoch of peak star, galaxy, and quasar formation to the present epoch. The first question concerns the physics of ultraluminous infrared galaxies, which will be addressed by studying in detail the star formation in nearby galaxies, probing physical conditions spatially and kinematically in a wide variety of far-infrared diagnostic lines. The second question concerns the evolution of matter in the universe, which will be addressed by measuring the star formation rate out to a redshift of ~ 1 and using bright diagnostic lines of even higher redshift sources. The third question concerns the physics of the nuclei of galaxies, addressed by measuring both nearby and distant sources in lines which characterize parameters of AGN, and also by studying in detail the center of our own galaxy.

In order to pursue the above science goals, the requirements for SAFIRE's observational capability specify a wavelength coverage up to $\gtrsim$400μm in order to be able to see C II at $z = 1.5$ and a velocity resolution of around 200 km/s.

Additionally, detecting distant galaxies requires instrument sensitivity at the SOFIA-limited level. Spatial/kinematic studies of nearby galaxies require the ability to make rapid data cubes. The highest profile lines expected for SAFIRE observations are among the brightest emission lines from star forming galaxies at any wavelength: C II 158 μm, O I 63 and 145 μm, N II 122 and 205 μm, O III 52 and 88 μm, C I 371 μm, CO high-J lines at 434 μm, 370 μm, etc.

SAFIRE Instrument Description

The above science requirements drive SAFIRE to provide capability for extragalactic spectroscopy at $\lambda > 100\,\mu$m with broadband coverage. It must also feature sufficient spectral resolving power, a large field of view, and atmosphere-limited sensitivity; with these features, it is competitive with other instruments. Compared to Herschel, SAFIRE is as fast for line mapping as PACS and faster than SPIRE (scaled for spectral resolution at the same sensitivity), as shown in Figure 1.

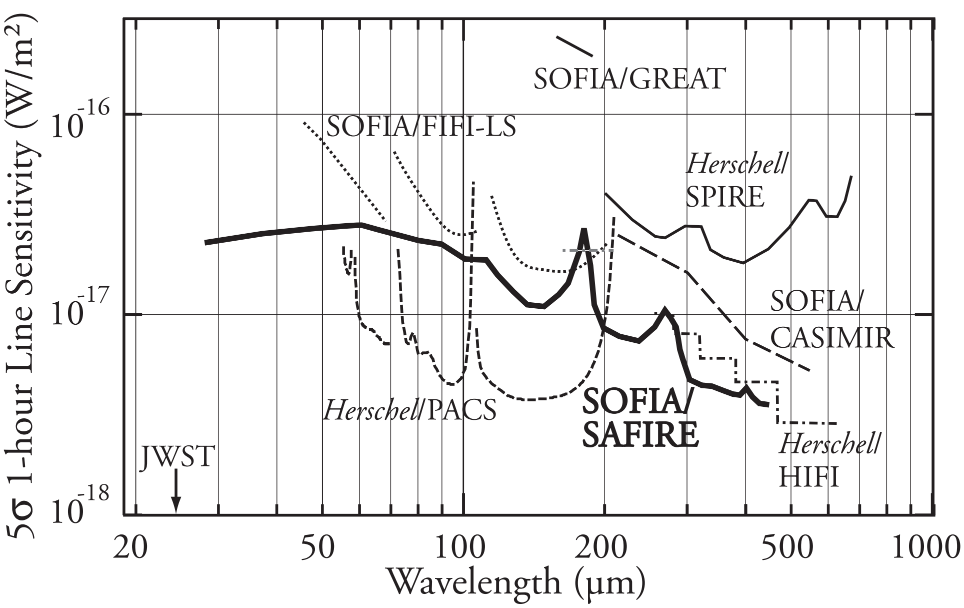

Figure 1. SAFIRE's sensitivity is competitive with other facilities, while enabling an areal coverage equal to or superior to that of the other spectrometers shown and with an unprecedented broad wavelength range.

SAFIRE's optical design has been implemented as a multi-grating long-slit spectrometer as shown in Figure 2. A set of interchangeable gratings, each operated in first order for maximum bandwidth, has been notionally specified. Two gratings can be installed during any flight campaign, enabling a flexible wavelength coverage tailored to an observing program. Nominally, the light path is divided by a dichroic into a short wavelength ($\lambda < 100\,\mu$m) and a long wavelength ($\lambda > 100\,\mu$m) channel. The velocity resolution is shown in Figure 3; the total instantaneous bandwidth ranges between ~ 2000 and ~ 6500 km/s.

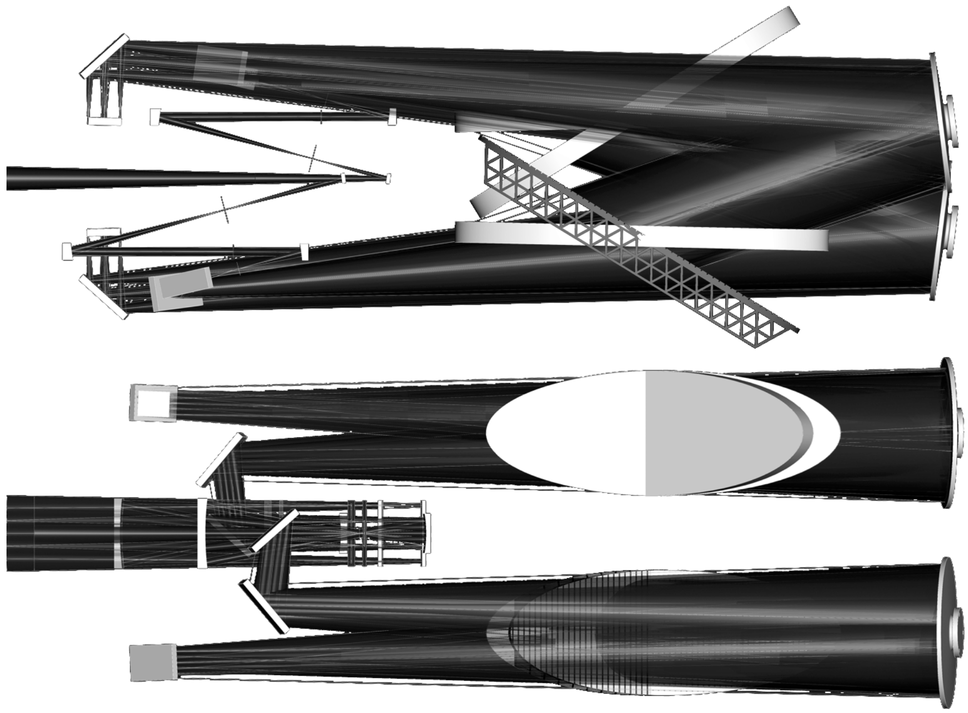

Figure 2. SAFIRE's optical design is a symmetric dual first order Littrow configuration long slit grating spectrometer. This permits broadband observations in two lines simultaneously over a large field of view. It also incorporates a 4 K foreoptics enclosure containing Lyot stops, field stops, a dichroic, band limiting filters, and stray light suppression.

The SAFIRE cryostat is a novel one for SOFIA, incorporating a pulse tube cooler to provide the 3 K base temperature for the optics and a 50 K temperature for the radiation shields. Based on a PT-405 cooler (Cryomech Inc.), SAFIRE's available instrument volume for cryogenic optics is significantly greater than would be possible with stored cryogens. We have conducted extensive lab tests on two of these coolers when operated at off-vertical tilt angles, as will be the case on SOFIA; angles up to $\pm 30^\circ$ are allowable to maintain sufficient performance. An adiabatic demagnetization refrigerator provides a base cooling temperature of $\lesssim$100 mK for the bolometer array. Two prototype coolers for SAFIRE have been produced (High Precision Devices Inc.) and were found to have sufficient overall performance and a base temperature of around 40 mK.

SAFIRE Bolometer Array Design

The core of SAFIRE is its detector array: a 32×40 filled array of superconducting transition edge sensor (TES) bolometers (Benford et al. 2003b, 2008). The saturation power (design: $\sim$ 1 pW) and noise equivalent power (design: $\lesssim 10^{-18}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$) are challenging but should be possible with present techniques. We have recently fielded the GISMO camera (Staguhn et al. 2008) at the IRAM

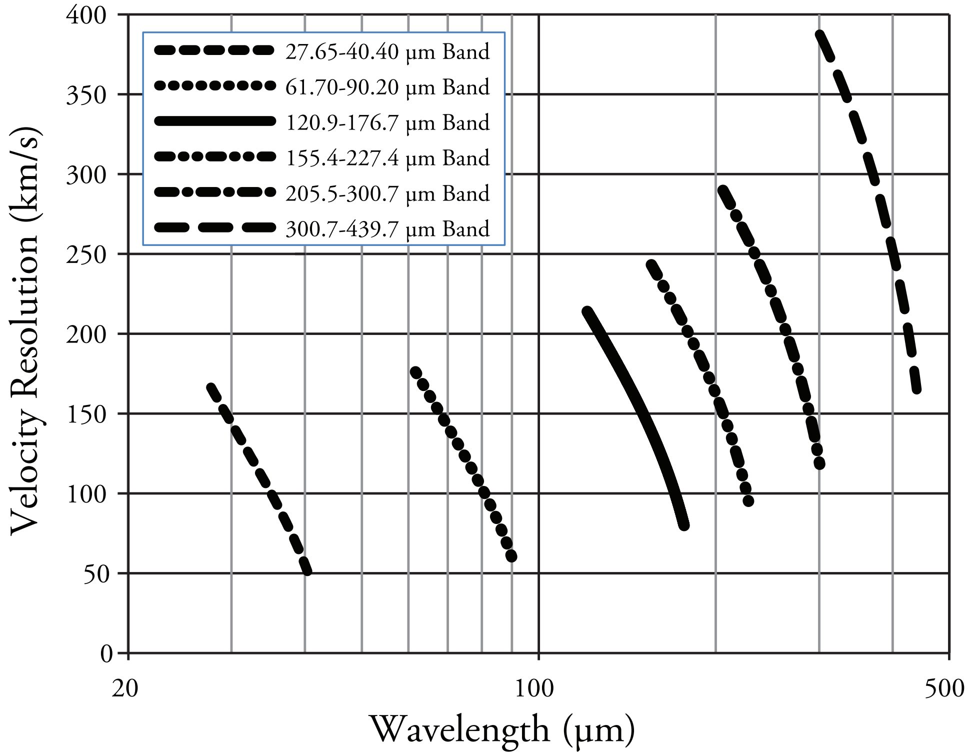

Figure 3. SAFIRE's velocity resolution is sufficient ($\simeq 100$ km/s) to resolve nearby galaxy lines for modest kinematic information, while coarsening to approximately the intrinsic linewdith ($\simeq 300$ km/s) at the longer wavelengths to optimize sensitivity for detecting redshifted lines in distant galaxies.

30 m telescope, and it has proven the core technologies of the TES bolometer array along with much of the infrastructure.

TES bolometers offer low noise, fast response time, linear performance, and easy SQUID multiplexing enabling kilopixel bolometer arrays. Prototype TES bolometer arrays and related technologies have been developed and used, and we have indium bump-bonded mechanical model arrays to dummy multiplexers, as shown in Figure 4. The Backshort-Under-Grid (BUG) detector architecture (Allen et al. 2006), which features integral backshorts under each pixel, has been successfully demonstrated and shows high optical efficiency in a nearly-filled array. Full-scale protoflight detector arrays are soon to be in production.

SAFIRE Status

In May 2009, NASA decided to de-select SAFIRE as a first light instrument, in order to compensate for increasing financial pressure from the SOFIA observatory platform (i.e., the airplane). Significant technology development and mature designs for much of SAFIRE are completed, and the project will await the next call for instrument proposals.

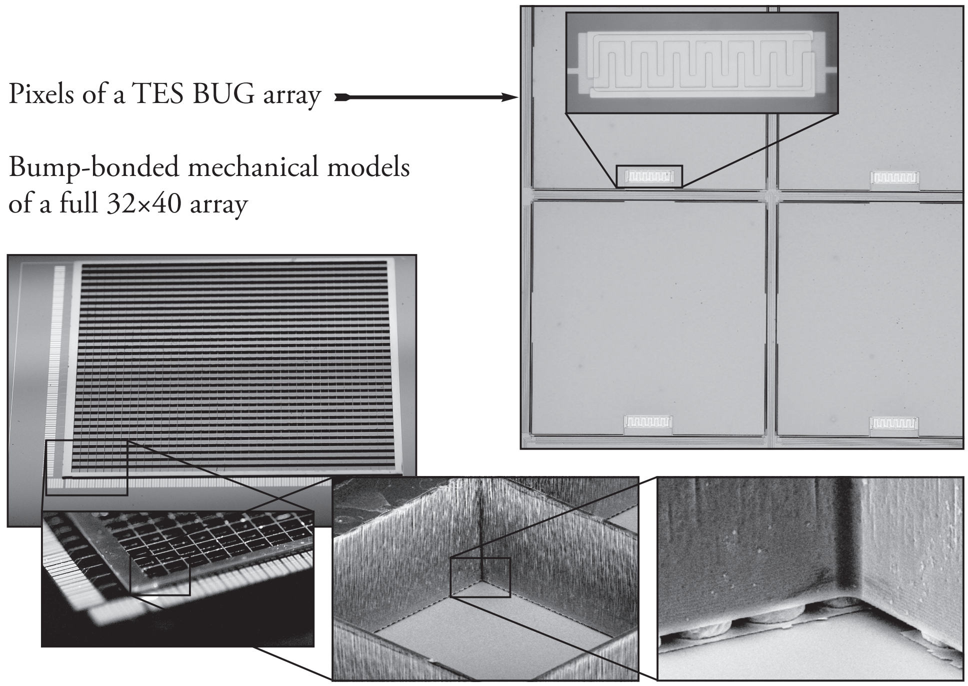

Figure 4. Nearly all the techniques required for producing backshort-under-grid bolometer arrays using superconducting transition edge sensors have been successfully demonstrated.

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