SAFIRE: FAR-INFRARED IMAGING SPECTROSCOPY WITH SOFIA

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ABSTRACT

The Submillimeter and Far-InfraRed Experiment (SAFIRE) on the SOFIA airborne observatory is an imaging Fabry-Perot spectrometer operating at wavelengths between 100µm and 700µm. SAFIRE's key science goal is to investigate line emission in galaxies at wavelengths not visible from the ground, and to map the variation in this line emission in nearby galaxies. SOFIA will fly at an altitude where the atmosphere is mostly transparent, permitting SAFIRE to achieve a high point source sensitivity at most wavelengths. With a field of view of 160''x320'' at a spectral resolution of ~200km/s, when SAFIRE achieved first light in 2006, it will add substantial capability to the first light instrument complement of SOFIA. SAFIRE's top priority observations will be to measure emission lines in the Galactic center, to map emission lines in nearby galaxies, and to understand the physics of the cores of ultraluminous galaxies from the local region to the high redshift universe through far-infrared fine-structure line emission.

SCIENCE MOTIVATION

The Submillimeter and Far-InfraRed Experiment (SAFIRE) on the SOFIA airborne observatory is designed to be a wide-field imaging spectrometer with moderate spectral resolving power. It will achieve a resolution of about 200km/s, continuously tunable over the 100µm-700µm range. In this paper, we describe the highest priority science projects for SAFIRE which have helped motivate the design of the instrument, discuss the design in broad terms, and predict the performance of the SAFIRE instrument.

SAFIRE is envisioned as a wide-field spectrometer for measuring line emission from galaxies, specifically concentrating on the far-infrared (100µm-300µm) atomic fine-structure lines (both locally and redshifted) and on submillimeter lines (300µm-650µm) which are not easily accessible from ground-based facilities. It will be a powerful tool for studying such topics as:

- Powering of Ultraluminous Infrared Galaxies
- ISM cooling traced by FIR fine structure lines
- Evolution of Matter in Universe
- Diagnostics of Active Galactic Nuclei
- Star formation in the Galaxy
- Star formation out to high redshifts

SAFIRE's unique capabilities enable a wide variety of science goals. Some high level initial science projects can be chosen even at this point, several years before SAFIRE's first light. Since the results of the ISO satellite, it has become very important to be able to detect redshifted CII (158µm) from ULIRGs such as Arp220 or Mrk231, which SAFIRE can do out to z~1. At longer wavelengths (λ>160µm) where ISO was not as effective and where ground-based telescopes cannot observe, SAFIRE will be an important instrument for characterizing the line emission from a variety of galaxies. Finally, projects which require large area imaging spectroscopy – for instance, the study of the Galactic center, where measuring the spatial structure of emission lines will be revealing – are ideal for SAFIRE's large detector array.

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As a representative investigation, let us consider how SAFIRE can be used to study the region of the circumnuclear ring at the Galactic center (Figure 1). One possible project is to determine the mass and physical size of the ring itself, using the CI line ratios, which trace gas column density and temperature, but are insensitive to gas density. Since it is estimated that this gas only remains in the ring for ~10^4 years, where is the gas reservoir that replenishes the ring? SAFIRE can observe the CII 158µm and OI 145µm lines, which trace gas excitation and kinematics at high spatial resolution over broad regions. There is also the question of whether the excitation mechanism for the bright molecular line emission from the ring arises from radiation from stellar cluster or from shock heating. Mid- and high-*J* CO line ratios trace excitation of molecular gas; shock excited material will be broadly distributed, whereas UV excitation should be seen only near the exciting stars. Another diagnostic is to observe the OH 163µm line, which is radiatively pumped; when compared with CO, this measurement can decouple shock from UV excitation.

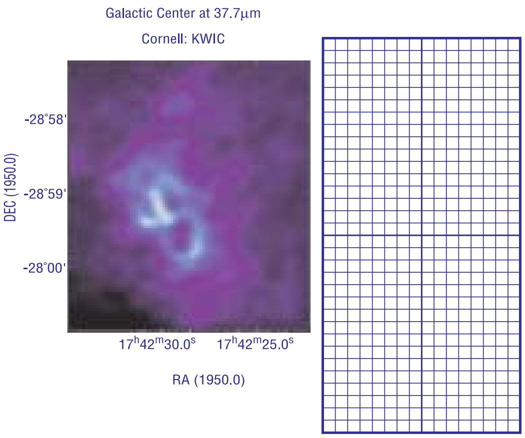


Figure 1. KAO/KWIC 38µm image of the Galactic center and the SAFIRE array format.

SAFIRE can be compared to other SOFIA first light instruments on the basis of its wavelength coverage, spectral resolution, and imaging area. A spectral resolution well suited to galaxies at λ>200µm is not covered by any other instrument. SAFIRE also has a very large instantaneous field-of-view (160’’x320’’ with 10’’ pixels), which is designed to enable it to map nearby galaxies quickly and efficiently. Simultaneous imaging has the obvious benefit of increasing the speed of observation, and additionally has the benefit of reducing the systematic errors associated with raster and jiggle mapping.

SAFIRE INSTRUMENT DESCRIPTION

SAFIRE’s detectors are the most technologically advanced component, and have received much of the attention to date because of their relatively high development needs. A prototype instrument for the demonstration of these detectors is described elsewhere[1]. The detectors are cooled by an adiabatic demagnetization refrigerator built for SAFIRE, and similar to that used in the HAWC instrument[2]. In order to modularize these two components for testing, an insertable cryostat has been fabricated at the Goddard Space Flight Center (Figure 2). This cryostat is installed in the main cryostat, which is a custom- built LN_2/LHe dewar from Precision Cryogenics[3]. An optics plate is mounted in this cryostat on the 4.2K surface. The two Fabry-Perot mechanisms and the filter wheel, together with other optical components and baffling, are mounted on this optics plate. A light-tight shield surrounds the optics plate. Almost all the analog portions of the detector electronics are mounted on the insertable cryostat, in order to keep them within a single electrically shielded environment; digital electronics are mounted in a chassis on the side of the cryostat. Finally, software for the commanding of the instrument, data acquisition and display, and housekeeping information and control is being developed. The software, called Instrument Remote Control (IRC[4]), is designed to be a platform-independent, extensible, modular environment usable for many SOFIA and related instruments.

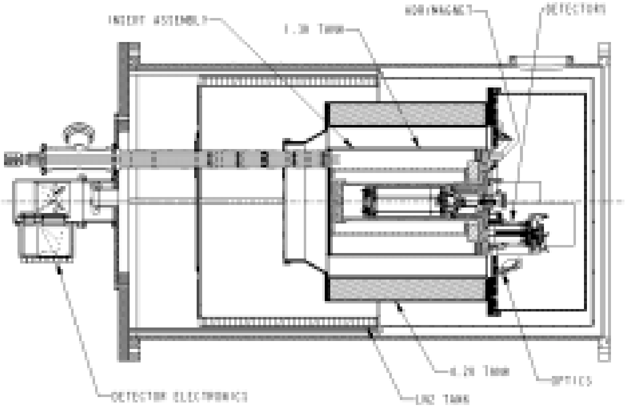


Figure 2. Section view of the SAFIRE instrument, showing the major components. The digital data acquisition electronics and housekeeping electronics are not shown. The instrument is operated in the vertical orientation.

SAFIRE DETECTOR ARRAY

Recent research had led to a new approach to building arrays of many bolometers. Instead of a semiconducting thermistor, a superconducting transition edge sensor (TES) is used to read out the detector temperature. A TES bolometer has a faster response time than an identically designed, same-sensitivity semiconducting bolometer (or a more sensitive bolometer for the same response time) due to the strong negative electrothermal feedback intrinsic in a voltage-biased TES[5]. TES bolometers are inherently low impedance devices, so they are well matched to being read out by DC SQUID amplifiers[6]. These amplifiers have a large noise margin over the TES Johnson noise and bolometer phonon noise. This permits the bolometer to be read out in a multiplexed fashion by a suitable SQUID multiplexer[7], potentially vastly reducing the amplifier size and the wire count. Because SQUID multiplexed amplifiers operate at the base temperature of the bolometer, they can be coupled very closely, removing the complex interfaces necessary with semiconducting bolometers. In light of these advantages, we have chosen to develop an array of multiplexed superconducting bolometers for SAFIRE. Herein, we describe the TES bolometers we have manufactured and tested, the electronics of SQUID multiplexed readouts, and the design and assembly of a 512-element bolometer array.

Engineering a working large bolometer array is a major challenge. At GSFC, we have developed an approach that enables the detectors to be close-packed (>95% filling factor) with the wiring brought out behind the focal plane surface. A very thin Si or SiNx membrane can be folded through large angles without breaking. We manufacture rectangular detector chips that are close-packed linear arrays of 8 or 32 bolometers, as shown in Figure 3. These chips can be folded in half and glued (either to themselves or to a handling structure) as shown in Figure 4. The wiring bond pads are at the lower left edge of the PUD chip.

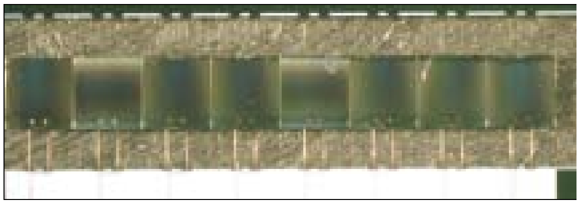


Figure 3. Linear 1x8 bolometer array

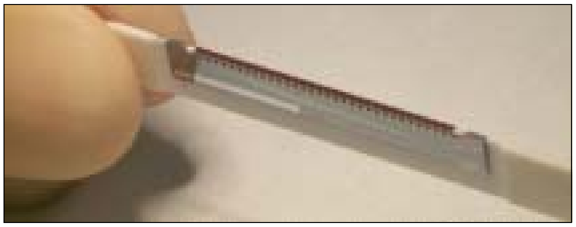


Figure 4. Folded 1x32 array from HAWC[8].

We have used the PUD architecture and have tried to simplify the engineering (as compared to HAWC/SHARC-II arrays) and to minimize the size and weight of the array assembly. The detectors in this case are multiplexed superconducting transition edge sensor (TES) bolometers. Multiplexed TES bolometers are a new development, but several discussions can be found in the literature[9,10,11]. The circuit diagram for a multiplexed bolometer array using superconducting sensors and SQUID multiplexers[7] is shown at right in Figure 5. The fundamental unit is a 1x32 detector array read out with a single 32-input multiplexer with a 2-stage SQUID amplifier. A 32-element Nyquist inductor integrates the signal before multiplexing, eliminating the noise penalty which would otherwise be present when sampling a detector for a shorter duration.

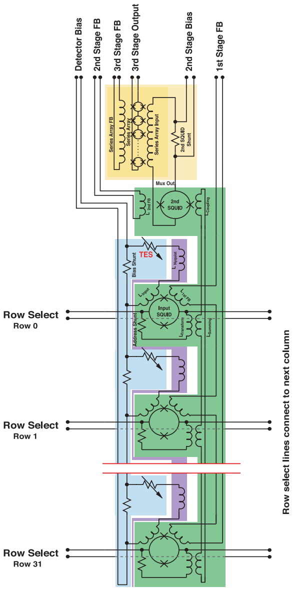
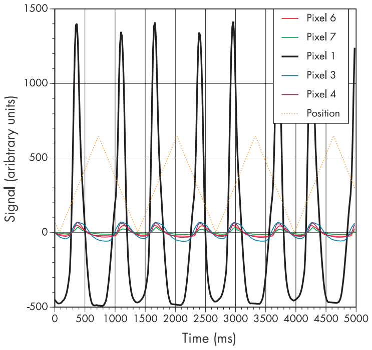


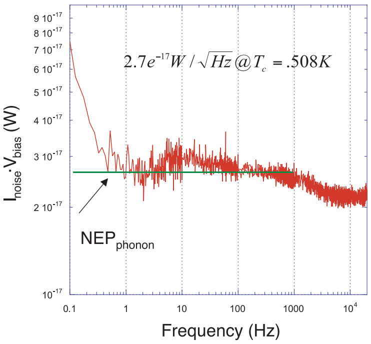
Figure 5. Schematic for a single 1x32 portion of a multiplexed TES bolometer array.

Individual components of the multiplexed TES bolometer system have been demonstrated. Multiplexed readout of Johnson noise has been achieved[11], optical efficiency has reached ~80%[9], crosstalk from channel to channel is less than 2%, and the response time is <2ms. To further illustrate the performance of the system, we show in Figure 6 the multiplexed readout of several detectors where only one is illuminated, as a light source is modulated on and off (some optical spillover is evident in the other detectors). Figure 7 illustrates that the fundamental phonon noise limit of the detector has been reached over a signal band of 1-100 Hz, with very little excess noise.

Figure 6. (near right) multiplexed readout of several detectors while modulating light on only one.

Figure 7. (far right) detector electrical noise showing near phonon-limited performance.





A complete array requires consideration of thermal, electrical, and mechanical factors. The array design for SAFIRE addresses the complexities of manufacturing a compact, functional detector array. Additionally, we have designed the array for ease of assembly and the option of repairing array elements at a later date. After testing each 1x32 subarray, the parts are stacked and wirebonded together. The final assembly of the mechanical prototype of the SAFIRE 16x32 array is shown in Figure 8.

Figure 8. Mechanical prototype array for SAFIRE.

CONCLUSION

SAFIRE fills a unique role for SOFIA, and its capabilities enable many science projects. Some highlights of enabled investigations include studies of the Galactic center, the study the spatial distribution of lines in nearby galaxies, the study of distant galaxies through their fine-structure line emission, and studies of ionized carbon emission from a variety of sources. SAFIRE is scheduled to acquire first light on SOFIA in 2006. Its detector array will consist of 16x32=512 bolometers. Pop-Up Detectors are used with superconducting thermistors and SQUID amplifiers to enable a compact array format. We have assembled a mechanical prototype array as a demonstration of the flight bolometer array.

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