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A cryogenically cooled, multidetector spectrometer for infrared astronomy

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Abstract

A liquid-helium-cooled, 24-detector grating spectrometer has been developed and used for low-resolving-power astronomical observations in the 5-14- μm spectral range. The instrument has operated on the 91-cm Kuiper Airborne Observatory (KAO), the 3-m IRTF (Mauna Kea), the 3-m Shane telescope (Lick Observatory), and the 152-cm NASA and University of Arizona telescope (Mt. Lemmon, Ariz.). The detectors are discrete Si:B1 photoconductors with individual metal oxide semiconductor field-effect transistor (MOSFET) preamplifiers operating at 4 K. The system uses a liquid-helium-cooled slit, order-sorter filter, collimator mirror, grating, and camera mirror arranged in a Czerny-Turner configuration, with a cold stop added between the collimator mirror and the grating. The distances between components are chosen so that the collimator mirror images the telescope's secondary mirror onto the cold stop, thus providing a very effective baffle. Scattered radiation is effectively reduced by using liquid-helium-cooled, black baffles to divide the spectrometer into three separate compartments. The system noise-equivalent flux density, when used on the 152-cm telescope from 8 to 13 μm with a resolving power of 50, is $4.4 \times 10^{-17} \text{ W cm}^{-2} \mu\text{m}^{-1} \text{ Hz}^{-1/2}$. The main applications are for measuring continuum radiation levels and solid-state emission and absorption features in regions of star and planet formation.

Introduction

In astronomical research there is a continual effort to improve the sensitivity of the viewing instruments. This may be done either by gathering more photons or by making more efficient use of the ones collected. The need for greater sensitivity is particularly evident at the infrared wavelengths, at which the most important diagnostic spectral features of molecules and solids appear, but at which only the brightest objects have been studied. In response to this need, a multiple-detector grating spectrometer for use in the 5-14- μm micrometer range was built; it takes advantage of the greatly improved efficiency offered by simultaneously integrating at different wavelengths. Most earlier spectroscopic work in this wavelength range was done with circular, variable filter spectrometers with single detectors. A multiple-detector system with liquid-helium-cooled components was developed and demonstrated by Rank and Bregman.¹

The system described here uses similar electronics and data handling, but features improved detectors, optics, and internal baffling. So far the system has operated at resolving powers from 50 to 60, but resolving powers up to 300 can be accommodated with appropriate gratings. The primary purpose of the instrument was to study dust-emission features that might be associated with regions of planet formation. It has, in fact, been applied to a much broader variety of objects ranging from comets to Seyfert galaxies. Because of the strong emphasis on sensitivity inherent in its design, it is called the Faint Object Grating Spectrometer (FOGS). In this paper we describe briefly the design of the FOGS and then its performance characteristics when used with a ground-based telescope and with the Kuiper Airborne Observatory (KAO).

Design

The design of the FOGS was guided by the need for the highest possible sensitivity coupled with sufficient spectral resolving power to study the shapes of absorption features expected from silicates near 10 μm and from water ice near 6.3 μm , and the shapes of emission features from silicates near 10 μm and from silicon carbide near 11.3 μm . A resolving power of 50 is adequate for many purposes and permits study of the entire 8-13- μm spectral "window," with 24 detectors at a single setting of an appropriate grating. This window can be studied from large, ground-based telescopes at sufficiently dry sites. Use of the KAO at an altitude of 13 km to get above most of the atmospheric water permits the same instrument, with a different grating, to disperse the 5-8- μm spectral range across the same 24 detectors with a resolving power of 60. The sensitivity was optimized through the choice of detectors and minimization of stray infrared radiation.

The choice of detectors was dictated by quantum efficiency, noise performance, cost, and the ability to fabricate them in a package compatible with use in an existing spectrometer. (This latter condition was dictated by the desire to use some of the detectors before enough money was available to buy all the parts for a new spectrometer.) The most suitable

detectors available without additional development costs were the discrete Si:Bi detectors built by Aerojet Electro Systems. Laboratory tests showed that their quantum efficiencies were between 0.25 and 0.4 (Yee, personal communication, 1979). Their noise equivalent power is somewhat below $10^{-15} \text{ WHz}^{-1/2}$, which is smaller than fluctuation noise in the background radiation anticipated in the 2% spectral bands to be viewed by individual detectors, as shown below.

The background radiation is dominated over much of the spectral range of interest by thermal emission from the telescope optics and the Dewar window. Their combined emissivity ϵ is about 0.3 and temperatures, T , are typically 280 K. The spectrometer slit aperture was chosen to be round (1.0 mm in diameter) for the nominal design. This provides a 9-arcsec field of view (FOV) on the f/17 Mt. Lemmon 152-cm telescope and a 14-arcsec FOV on the KAO. The resulting background radiation power P arriving at the detector at wavelength L is, from the Planck radiation law,

$$P = \epsilon \pi D^2 \Omega \Delta L c_1 / \{4L^5 [\exp(c_2/LT) - 1]\}$$

where D is the diameter of the slit aperture; Ω is the solid angle of the acceptance cone, determined by the cold baffling in the spectrometer; ΔL is the spectral band arriving at a single detector; c_1 is $3.74 \times 10^{-12} \text{ Wcm}^2$; and c_2 is 1.438 cm deg. For ideal cold baffling in the spectrometer and an f/17 system, Ω is 0.0027 sr. The resulting background power is $3.1 \times 10^{-9} \text{ W}$ and the fluctuation noise power is $7.5 \times 10^{-15} \text{ WHz}^{-1/2}$. The backgrounds actually detected must be multiplied by the quantum efficiency η , and the fluctuation noise power detected by $\eta^{1/2}$. Consequently, the detected 5- μm fluctuation noise power is $1.6 \times 10^{-15} \text{ WHz}^{-1/2}$, so the intrinsic detector noise of $1 \times 10^{-15} \text{ WHz}^{-1/2}$ is somewhat smaller than the smallest anticipated fluctuation noise power. The detectors have rectangular collecting surfaces that are 1.0 mm wide by 3.0 mm long. Width is measured along the direction of dispersion. The detectors were fabricated in groups of six, with center-to-center distances of 1.27 mm. The overall detector packages, including source-follower preamplifiers are 7.62 mm wide, 20.0 mm long, and 6.5 mm high. Four packages arranged along the direction of dispersion cover the wavelength range to be studied in a total dispersion distance of 30.5 mm.

A Czerny-Turner optical configuration was chosen for ease of conversion from one wavelength range to another and for ease of baffling against stray radiation. The conversion from the 8-14- μm range to the 5-8- μm range requires only replacing the grating and an order-sorting filter. The gratings are used in first-order and are chosen to give reasonably high efficiencies (50%) in both polarizations over the range of operation. The grating used for 8-13- μm work is a Bausch and Lomb replica on borosilicate Crown glass with 50 grooves/mm, and a blaze angle of 13°. When used with the optical components and spacings given in Table 1, this grating provides a spectral resolution of 0.22 μm between detector elements. The grating used for 5-8- μm work is similar, but with 90 grooves/mm and a blaze of 17.45°, providing a spectral resolution of 0.11 μm between detector elements.

Table 1. Optical Parameters

Optical Element	Size, mm	Focal length, mm	Distance from Preceding Optical Element, mm
Slit aperture, diameter	1	--	--
Collimator mirror, diameter (parabola)	13	120	120
Pupil, diameter	10	--	120
Grating	26 x 26	flat	42
Camera mirror (sphere)	20 x 60	125	160
Bank of 24 Fabry mirrors	1.27 x 3.0	8.1	125
Detectors	1.0 x 3.0	--	7.7

A schematic of the spectrometer, including the optical layout, is shown in Figure 1. Light enters through a potassium bromide window at the Dewar bottom and strikes a 45° flat that directs the beam to the entrance (or slit) aperture and order-sorting filter. An important feature for proper baffling is the placement of the collimator mirror so that it images the telescope secondary onto a black, cold stop (the pupil). Light from off-axis sources consequently cannot pass beyond the pupil unless it scatters off of one of the telescope mirrors into the main optical beam. Furthermore, each component that must dissipate off-axis or out-of-band radiation is surrounded by a blackened chamber, lighttight except along the optical axis, so that scattered radiation cannot easily reach the detectors. Zeroth-order radiation from the grating strikes a blackened panel not directly viewed by the detectors; 3M Nextel Velvet was used as the blackening agent. The dispersed

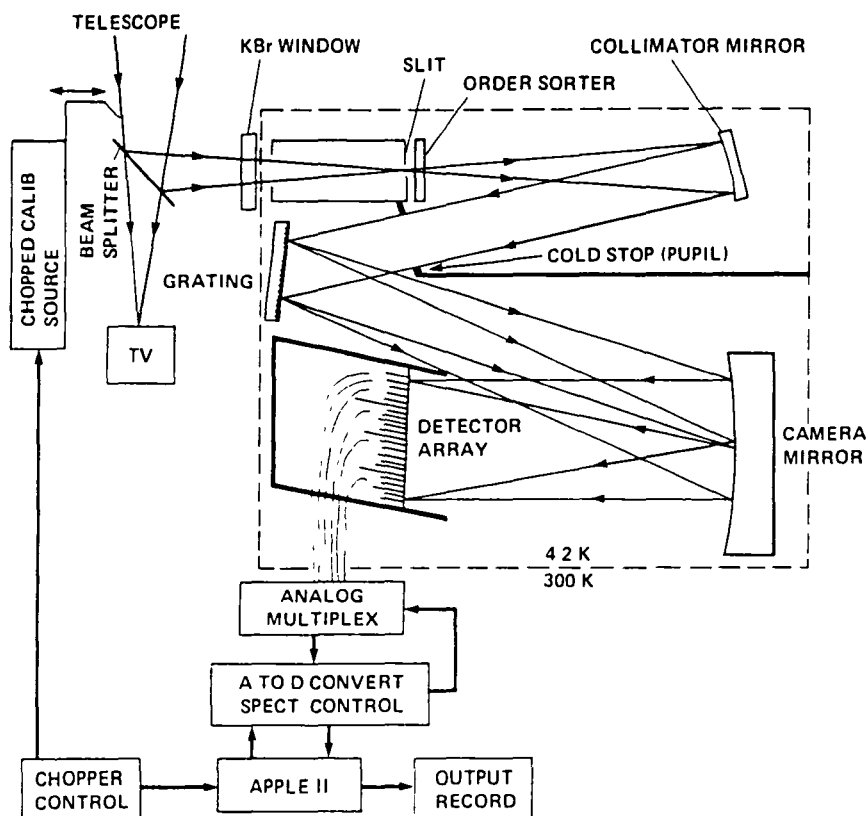


Figure 1. Schematic drawing of the Faint Object Grating Spectrometer (FOGS). The 24 detectors are Si:B1 photoconductors. The 24 individual Fabry mirrors are not shown separately since they are part of the detector assembly. The beam splitter is a thin gold film that reflects nearly all infrared radiation, but allows 50% of the visible light to reach a TV camera, parfocal with the slit. This permits guiding on the object whose spectrum is being taken. The chopped calibration source may be moved into the field of view when needed.

bolted to the bench and glued with rubber cement² to the backs of the mirrors. The entire optical and detector assembly is enclosed by blackened aluminum surfaces held at a temperature near 4.2 K. The optical components may be cooled from 77 K to 4.2 K in about 1 hr. Cooling from room temperature to 77 K takes 3 to 5 hr. At present, there are no moving parts in the spectrometer. All alignment is done before the Dewar is closed up. Wavelength selection must also be done before the Dewar is closed. This is accomplished by aiming a helium-neon laser beam through the spectrometer (with the order-sorter filter removed). A high-order image nearest the blaze angle will be brightest and may be used to set the grating angle. After pump-out and cool-down, the setting can be checked against a known calibration standard, such as an ammonia absorption cell.

Signals from the Si:B1 photoconductor detectors are conditioned for transmission out of the Dewar by adjacent source-follower amplifiers (using specially selected 3N163 MOSFETs) operating at the detector temperatures, near 4 K. The load resistors are 3×10^8 ohm dies. A regulated power supply maintains a common drain voltage of -10 V and an adjustable, positive (0 to 10 V), common detector bias. Each amplifier output is further amplified by a warm (external to the Dewar) amplifier which also serves to integrate the resultant signal with a time-constant longer than the sampling time, but shorter than the optical modulation (chopping) time. The signals, in turn, are sampled by an analog multiplexer, further amplified, digitized, and finally stored by the computer controller.³ In this way, phase-sensitive detection is done digitally by the computer.

radiation from the grating is focused by the camera mirror onto 24 adjacent Fabry mirrors which form 24 images (at different wavelengths) of the pupil onto detectors facing them. The use of the Fabry mirrors ensures that radiation in the telescope's light cone arriving at any part of the slit aperture will be spread over the same spot on the detector. This reduces errors in wavelength and intensity caused by the interaction of image motion across the aperture and variations in quantum efficiency across individual detectors. Fabrication of the multiple Fabry optics was modeled after the technique used by Erickson (personal communication, 1982).

The glass optical components are mounted in Invar frames which are held, in turn, to aluminum frames by spring-loaded screw-adjustment mechanisms. The aluminum frames are bolted to an aluminum optical bench which is bolted to the 20-cm-diam copper bottom-plate of a Dewar (Infrared Laboratories, catalog No. HD3-8, with extended length). Compliance for thermal expansion between the aluminum and copper and between the aluminum and Invar interfaces is provided by the screws. Thermal contact between the glass and the optical bench is provided by copper straps

Operation

The spectrometer is operated at the focal plane of an astronomical telescope equipped with a movable secondary or tertiary mirror (called the chopper). The purpose of moving the mirror is to place, alternately, the object-plus-background radiation and then the background radiation alone on the detectors. The resulting difference in signal is a measure of radiation from the object alone. The computer initiates a sampling sequence of the 24 integrated outputs in phase with the chopper. All detectors are sampled several times after each motion of the chopper mirror. The data storage program automatically stores signals from opposite ends of the travel of the mirror for each detector and then subtracts the sums sequentially. As the sequence of detector interrogations is repeated, the new data are added to those already stored. After a preset period of data accumulation, the results are presented on a TV screen; they may also be stored on a magnetic disk. The position of each detector corresponds to a wavelength, which may be calibrated by comparison with absorption spectra taken through gas cells (typically ammonia or methane) or through polystyrene. Fluxes are determined by comparisons with spectra of bright, standard stars. Relative spectral response is established by comparison with a laboratory blackbody. The wavelength calibrations are made at least once during each night of observing. Comparisons with standard stars are made several times during each night of observing to provide not only flux comparisons, but also a means of correcting for the atmospheric absorption spectrum.

Performance

Observations made with the FOGS on the Mt. Lemmon 152-cm telescope produced spectra with one-sigma errors in individual channels ($0.22\text{-}\mu\text{m}$ resolution) of about $1 \times 10^{-18} \text{ Wcm}^{-2} \mu\text{m}^{-1}$ in 30 min near $8.4 \mu\text{m}$. This corresponds to a system noise-equivalent flux density (NEFD) of $4.7 \times 10^{-17} \text{ Wcm}^{-2} \text{ Hz}^{-1/2}$. On the KAO, the FOGS uses the same f/17 cone. When operating with the same slit aperture diameter of 1 mm, with a resolution of $0.11 \mu\text{m}$ at $6.2 \mu\text{m}$, the background is lower. The signal is reduced by both the bandwidth and the aperture reduction (91 cm for KAO versus 152 for Mt. Lemmon). The resulting system NEFD for FOGS on the KAO is $1.4 \times 10^{-16} \text{ Wcm}^{-2} \mu\text{m}^{-1} \text{ Hz}^{-1/2}$ at $6.2 \mu\text{m}$. In 30 min of integration, a one-sigma error of about $3 \times 10^{-18} \text{ Wcm}^{-2} \mu\text{m}^{-1}$ can be obtained. Since this performance is being attained simultaneously in 24 channels, the desired spectrum can be obtained much faster than with a single detector instrument, even if it has a somewhat better detector.

The use of a 24-detector system covering the entire band-pass of interest has two important advantages over scanning, single-detector systems. First, if the quantum efficiencies were comparable, the proposed system would be 24 times faster in obtaining spectra of comparable quality. Actually, since the quantum efficiencies of the Si:Bi detectors average to only half that of the best single detector used at $6 \mu\text{m}$, the advantage in speed is reduced to a factor of 6—still a very important advantage. Second, the multiple-detector system is relatively insensitive to temporary pointing errors and variations in seeing conditions, which can cause erroneous spectral features in scanning systems.

Although the FOGS is relatively simple and convenient to use, care must be exercised in ensuring that the object is centered on the slit. When a spectrum A_1 of an astronomical object A has been obtained, it is typically divided by a spectrum S_1 of a bright standard star S obtained through a similar air mass. The quotient is then multiplied by the known (through theoretical extrapolation or previous measurement) spectrum Q_1 of the standard. The resulting spectrum

$$F_1 = A_1 Q_1 / S_1$$

represents our determination of the actual spectrum of the astronomical object. This procedure can lead to an error if there are systematic differences in the pointing of the telescope on object A and standard S. The error arises because a shift in star position at the slit aperture appears as a shift in the spectrum on the Fabry array. Consequently, a deep atmospheric feature in A_1 and S_1 is not properly corrected when one is divided by the other. Tests at the Mt. Lemmon 152-cm telescope using a 1-mm aperture showed that pointing errors of up to 0.2 mm in any direction produced negligible errors in the 8-13- μm range, which includes the deep, sharp ozone-absorption feature. Pointing errors of 0.5 mm produced a serious spectral distortion (30% in several channels), however. Differential refraction causes a separation between the visual images used for guiding and the infrared image when observing at large angles from the zenith. This effect coupled with a small amount of flexure in the spectrometer produces errors in boresight of up to 0.2 mm. Such errors are readily avoided by reboresighting on a bright object in the part of the sky under study.

Samples of FOGS spectra

Some spectra obtained with the FOGS are shown in Figures 2-5. Figure 2 is a spectrum of Alpha Orionis which exhibits a well-known, bright, silicate emission feature. Figure 3 is a spectrum of AFCRL 2232 showing its broad silicon carbide emission feature. Figure 4 is a spectrum of a solar type star with a 10- μ m magnitude of about +3.5 illustrating the FOGS performance on a relatively faint object. Figure 5 is a spectrum of the Red Rectangle (HD 44179) taken from the KAO with a 20-arcsec beam diameter. Emission features believed associated with dust are clearly defined at 6.2 and 7.7 μ m. A number of FOGS spectra have already been used in published articles. These include an 8-13- μ m spectrum of the Seyfert galaxy Markarian 231 (Reference 4), 5-8- μ m spectra of the reflection nebulae, NGC 7023 and NGC 2023 (Reference 5), 5-8- μ m spectra of absorption features in regions of star formation,⁶ and 8-13- μ m spectra of asteroids⁷ and Comet IRAS-Araki-Alcock.⁸ Additional articles on FOGS spectra are in press or in preparation.

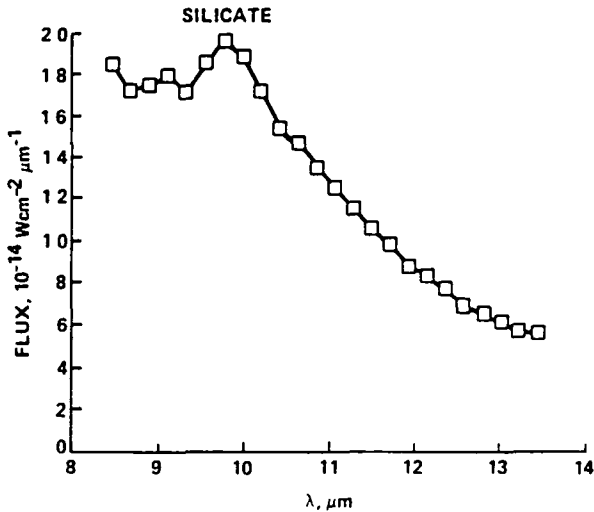


Figure 2. A spectrum of Alpha Orionis showing its prominent silicate emission feature which arises from circumstellar dust.

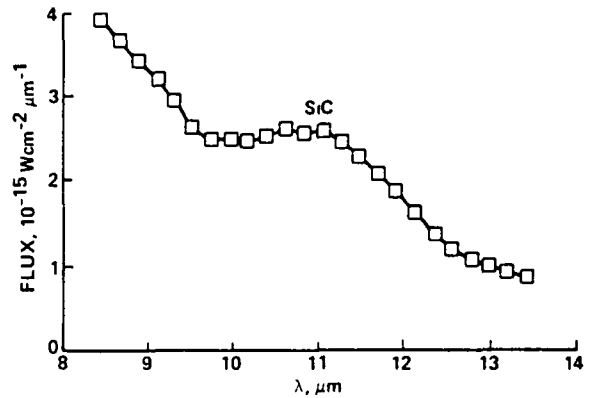


Figure 3. A spectrum of the carbon star AFCRL 2232 showing the broad emission feature attributed to circumstellar silicon carbide.

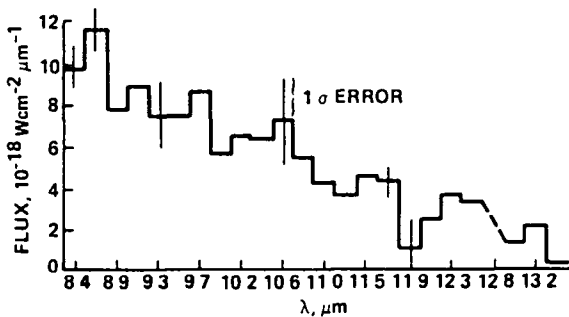


Figure 4. A spectrum of Eta Coronae Borealis, a G2V star with visual magnitude +4.9. Integration time was 32 min, using the Mt. Lemmon 152-cm telescope.

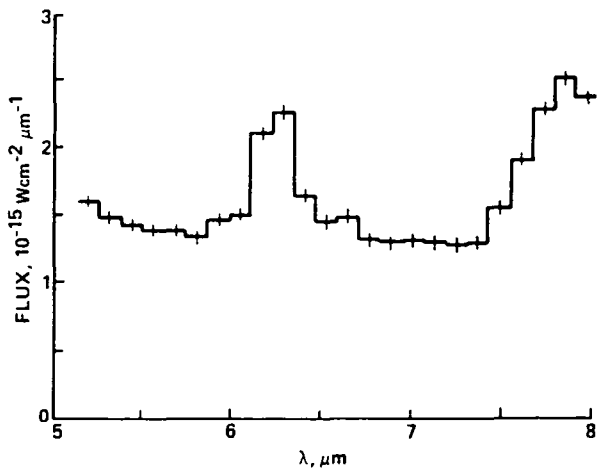


Figure 5. A spectrum of HD44179 (the Red Rectangle) obtained from the KAO with 12 min of integration. The unknown dust emission features near 6.2 and 7.7 μ m are prominent.

Concluding Remarks

The anticipated improvements in efficiency stemming from the use of multiple-detector systems have been realized in the FOGS. The spectra are obtained with about 6 times the efficiency of the best single-detector scanning devices and some of the problems inherent in slow, sequential spectral sampling are avoided. The limiting sensitivity is about one magnitude fainter than for the best single-detector devices for obtaining spectra at comparable resolving powers in comparable integration times.

Acknowledgments

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