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FUTURE AIRBORNE IR SPECTROMETERS: IMPROVED EFFICIENCY AND CALIBRATION

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ABSTRACT Ongoing and future spectroscopic investigations of interstellar ices, dust, molecules, solar system surfaces and atmospheric aerosols require spectra that are accurate in shape to about 1% over a significant fraction of the 3 to 30 micron range. Since resolving powers of 200 and higher are needed for this work, versatile and reliable airborne spectrometer are required. In addition, appropriate spectral standards must be established for this work. Considerations in developing both a suitable spectrometer and standards program will be described. A complementary area of development is the incorporation of sensitive 2-D arrays into spectrometer focal planes. This permits simultaneous spatial and spectral imaging with high sensitivity. The problems of high cost, fast readout electronics and small format are gradually being overcome in cameras and long slit spectrometers, offering the prospects of greatly increased efficiency.

INTRODUCTION

New objectives and refinements of old goals are making increasing demands on the sensitivity and accuracy of airborne spectrometers. Since we are severely limited in telescope apertures, we must look to improvements in instruments and techniques to meet these demands. The advent of IR-sensitive, 2-dimensional arrays offers an approach to improved sensitivity through greatly improved efficiency of photon usage. This development will be reviewed only briefly, since it is extensively covered elsewhere (McCreight et al., 1989,). We will then examine improvements in accuracy through reduction of systematic errors, particularly via improved infrared flux standards. The Kuiper Airborne Observatory (KAO) is well suited to measuring celestial standards through most of the 3-30 μm spectral range because of the high atmospheric transmission at 12.5 km altitude. Ongoing programs for establishing absolute flux standards offer the promise of reliable detection of spectral features which are 3% of the continuum amplitude and the likelihood of reducing this value to 1% as experience and data accumulate.

SOME OBJECTIVES FOR 3-30 MICRON SPECTROSCOPY: THE NEED FOR INCREASED SENSITIVITY & ACCURACY

Increased sensitivity is a requirement in many astronomical investigations typically because there are insufficient bright examples of a given phenomenon to characterize it or because of the increased information that can be gleaned from increased signal-to-noise. Studies of composition distribution in external galaxies are limited to only 5 or 6 with enough surface brightness to provide adequate S/N and these are bright because of unusual activity. Studies of molecular and atomic emission from low surface brightness objects in our own galaxy such as reflection nebulae and shock fronts are also sensitivity limited. Except in the case of rapidly varying phenomena, sensitivity improves with the square root of integration time. Consequently, an improvement in observing efficiency can be translated directly into sensitivity. This is especially true for spectral mapping applications, but holds even for point sources whose continuum spectrum is desired. Both situations benefit directly from the use of many detectors simultaneously. Ideally an instrument should provide one (2 for Nyquist sampling) detector at each spectral resolution element of interest. For extended sources it would provide additional rows of detectors (replacing the entrance aperture with a long slit) all simultaneously integrating to provide spatially distinct spectra. The incorporation of large 1-D arrays and small 2-D arrays in airborne spectrometers is already underway.

The need for improved flux calibrations is brought into focus by ambitious programs such as the measurement of mineralogically diagnostic spectral features of the Moon and asteroids in the thermal infrared (Sprague, et al. 1992 and these proceedings), aerosols and surface minerals on Mars (Pollack, et al. 1990), the measurement of impurities in ice clouds surrounding protostars (Tielens, et al. 1984), and in attempts to measure the spectral signature of debris associated with planet formation (Witteborn, et al. 1982). The diagnostic features in question are often a small perturbation upon a large continuum, but quite important if they can be recognized. While some features are narrow, others are very broad and require high relative accuracy across the spectrum. Whatever standard is used must have an accurately known spectrum. Cohen, et al. (1992a,b and these proceedings) have addressed the establishment of celestial standards using improved models (Kurucz 1991) of Sirius and Vega. We will show how this work is being extended to direct comparisons with an on-board blackbody standard.

Seven spectrometers used on the Kuiper Airborne Observatory (KAO) cover significant portions of the 3-30 micron range. Each is suited to one or more types of investigation with less overlap in capabilities than the wavelength range above would suggest. Some are suited to simultaneous broad spectral coverage, others to selected lines at very high resolution coupled with imaging capability, others have wide spectral access with high resolution. While most of the spectrometers are multiple detector devices, only KEGS (Herter et al. 1991) has a 2-D array. The potential advantages of such an array are presently limited by the high foreground radiation from the telescope, which fills the storage wells of each pixel very rapidly, and the tiny format of the available arrays which limits the spectral range that can be simultaneously viewed. Even so, the enormously increased number of pixels of array spectrometers dictates that their adaptation to airborne use presents the most promising path to observational efficiency. A brief survey of available IR arrays and some constraints on their use in airborne astronomy follows.

IMPROVED OBSERVATIONAL EFFICIENCY WITH LARGE ARRAYS

Large detector arrays with at least 100 pixels in the dispersion direction offer significant improvements in efficiency over the familiar banks of 10 to 40 discrete detectors that have

been the mainstay of thermal IR spectroscopy in recent years. HIFOGS, a spectrometer incorporating a linear array of 120+ detectors (Witteborn, et al., 1991) extends discrete detector technology to further exploit the advantages of simultaneous spectral coverage across a wide band. The use of a large bank of Fabry mirrors to image the pupil onto the discrete detectors matched in position at each resolution element is well adapted to spectroscopy of point sources. When extended sources are studied, 2-D arrays provide a more efficient use of photons because they can provide one dimension of spatial information simultaneously with one dimension of spectral dispersion. Alternatively 2-D arrays can be used with an echelle grating with a cross disperser (or some other means of formatting a broad spectrum into a series of rows) so that much more of the array can be used for spectral dispersion. 2-D array technology implicitly includes the use of a bonded or even monolithic multiplexer which enables the entire array to be powered and sampled with only a few wires. Discrete detector arrays require at least one wire per detector element and become cumbersome with more than 100 or so elements. As arrays become larger and storage wells deeper, the monolithic arrays become more advantageous and will clearly become the choice of spectrometer builders. Table 1 lists arrays suitable for work in portions of the 3-30 micron range that have been available recently. Performance values are only estimates and will certainly depend on details of the operating conditions not fully discussed here.

TABLE 1 Available 2-D Detector Arrays†

Manufacturer	Material	# of Pixels	Spectral Range µm	Rough Guess Q.E.	Well Cap. (electrons)
Aerojet	Si:As IBC*	20 x 64	5-26	20-50%	10^6
		96 x 96	5-26	20-50%	10^6
Amber	InSb	128 x 128	1-5.5	~60%	4×10^7
	InSb	256 x 256	1-5.5		4×10^7
	Si:Ga	128 x 128	5-18		4×10^7
Hughes	Si:As IBC	58 x 62	5-26	20-50%	$\sim 10^6$
		128 x 128	5-26	20-50%	
Rockwell	Si:As IBC	20 x 64	5-26	20-50%	$\sim 10^6$
		128 x 128	5-26	20-50%	10^7
SBRC	InSb	58 x 62	1-5	65%	$\sim 10^6$
		256 x 256	1-5	65%	

*Impurity Band Conductor
†We are indebted to Craig McCreight for providing most of these estimates. More recent/ accurate information may be obtained directly. Gordon Stacey, Cornell (personal comm.) is obtaining a 128x128 Si:Sb array from SBRC (Santa Barbara Research Center) for an echelle spectrometer.

The large 2-D arrays are expensive and require a large initial investment in electronics and data analysis software. Their use for spectroscopy requires fast optics because of the small physical size of the pixels (typically 50 microns on a side). Their advantages are enormous, however. This is especially well demonstrated by the UKIRT CGS-4 InSb array spectrometer (Mountain and Ramsey, 1991).

IMPROVED SPECTRAL FLUX ACCURACY

In attempting to provide spectra suitable for identification of mineral features and other low-to-medium resolving power, low-contrast features in spectra, it is important to minimize systematic errors. We list a few sources of systematic errors here, but will discuss only the last one in detail.

1. Irregularities in response across detectors: The effects are greatly reduced by using Fabry mirrors to image the pupil onto the detector. The block of Fabry mirrors used in HIFOGS can be lined up quite well with the corresponding detectors, but the mirrors themselves may have defects such as pits or scratches which can result in small flux errors when comparing sources of different spatial extent.

2. Nonlinear detector, amplifier or readout response: These effects are controlled by monitoring signals at various stages of amplification to make sure that they do not exceed their design values and by keeping the detector temperature constant.

3. Alignment sensitivity to temperature change, grating motion, aperture selection: These effects can be minimized by good design and operation. The optical bench must be carefully annealed and stress relieved with careful consideration of differential contraction effects on alignment and focus if different materials are employed. Laser alignment of optical elements must verify that the spectrum is properly dispersed across the Fabry bank at all desired grating positions.

4. Polarization of source versus spectrometer orientation: The grating efficiency versus wavelength function is quite different for light polarized along the dispersion than light perpendicular to it. This presents no problem except for polarized sources, but must be considered in cases where the radiation is scattered or is emitted by aligned grains.

5. Atmospheric variations, spatial and temporal. Water and ozone column densities in the line-of-sight vary with both time and location, a problem for the fast-moving KAO. Onboard water radiation-emission monitors provide some indication of the overhead water vapor. In spectrally simple sources the spectroscopic signatures of the water and other atmospheric lines on the observed objects provide the best measure of the atmospheric absorption. With the use of the HITRAN line list (Rothman et al., 1987) and an atmospheric model a match can be made to the absorption in one part of the spectrum to fix the signature of the unmixed component(s). The transmission can then be corrected for across the whole spectrum. This approach gets better as the resolving power increases.

6. Knowledge of spectral flux standards: Since spectra are generally referenced to a celestial flux standard, it is imperative that the correct spectrum of the standard be used. Recent progress and future plans for flux calibration are discussed below.

SPECTRAL FLUX CALIBRATIONS

The assumption that hot stars emit as blackbodies throughout the 3-30 micron range is inadequate even for Sirius which has no observed dust shell. Wavelength dependent opacity effects caused by free-free transitions in the atomic hydrogen atmosphere cause deviations up to 25% from a 10,000K Planck function in the Sirius 3-30 micron emission (Bell and Dreiling, 1981). Cooler stars (K1 and later) exhibit the fundamental bands of both CO (4.4-5.7μm) and SiO (7.8-10μm). Cohen et al. (1992a,b and these proceedings) have determined a spectrum of α Tau (Fig. 1) based on observed ratios of α Tau spectra to Sirius (α CMa) spectra and Kurucz's model of α CMa. While the model atmosphere is thought to be quite accurate, an independent method of calibrating the α CMa spectrum is prudent to rule out the possibility of a faint dust ring or other phenomena not considered in the model.

The most direct approach to a flux calibration is a comparison to a blackbody cavity of known temperature, since its spectrum is simply a Planck function. This approach has been

used with ground-based telescopes (e.g. Mountain et al. 1985) and is not without difficulty. We are engaged in a program to calibrate stars against a blackbody cavity onboard the KAO. The advantage of doing this from high altitude (12.5km) is the greatly reduced spectral absorption, especially in the water bands. Our method is described in Appendix A.

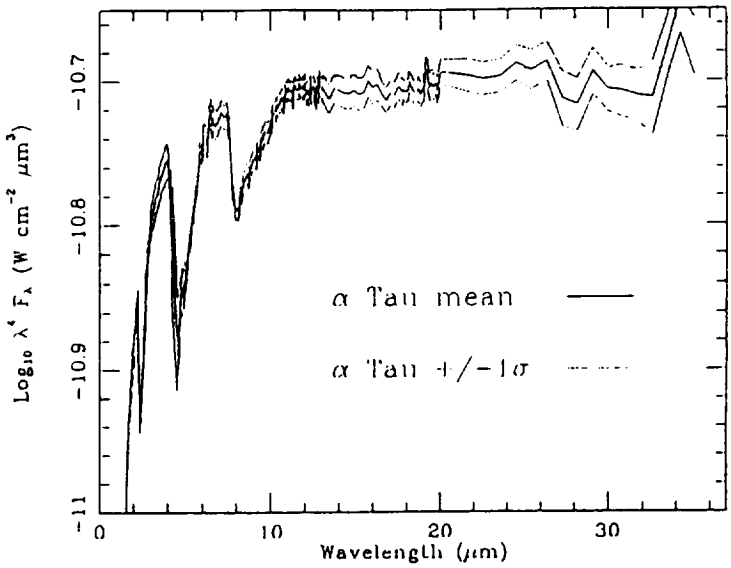

Fig. 1: The final α Tau complete spectrum: heavy line represents the spectrum itself; light continuous lines the 1-sigma bounds (Cohen et al. 1992a).

SOME DESIRED FEATURES IN A FUTURE SPECTROMETER

It is clear from the preceding discussion that a large array is a very desirable feature. Gratings have adequate efficiencies (50% or more) over no more than one octave. 1300 pixels in the direction of dispersion would permit simultaneous integration over a spectral octave with resolving power 1000. Broad coverage is important for efficient use of photons and study of solid state features. The high resolving power facilitates identification of molecular bands in astronomical sources as well as removal of terrestrial atmospheric absorption features. Additional rows of pixels (n by 1300) provide a means for spectral mapping of extended sources in one dimension. Values of n from 10 to 100 are desirable if readouts can be made fast enough (or storage wells deep enough). Response must be linear and readily calibrated for both flux response and wavelength assignments. Pixel sizes as large as 100 microns would simplify the spectrometer optics. Ideally the detector material would be sensitive over a very wide spectral range. Alternatively more than one array could be employed. As with all airborne spectrometers, ruggedness and light weight are required. Versatility is enhanced with externally selectable gratings, cut-on filters, neutral density filters, apertures and slits. Adequate maintenance and well-documented data-taking software, producing data files in an easily used (FITS) format are essential for such a powerful instrument. The excellent progress being made in ground-based spectrometers offers hope that advanced airborne spectrometers incorporating the features described here will soon become available.

APPENDIX A: A Method of Airborne Absolute Spectral Flux Calibration

Initially a raw spectrum of a star is obtained through a known air mass from the KAO at 12.5 km altitude. Next an image of the second exit aperture of the blackbody cavity (BBC) is projected onto the spectrometer entrance aperture in place of the star (Fig. 2). The blackbody radiation arrives in an f/17 cone just as the star radiation does. Modulation is accomplished by a blade chopper (reflective on the cavity side, black towards the spectrometer) placed between the BBC second exit aperture and the BBC's first exit aperture. The second aperture defines the area of the blackbody that is observed. The first aperture serves to confine the cavity radiation so that it is as nearly Planckian as possible. The BBC itself will be calibrated against one or more laboratory spectral standard blackbodies under the same heating conditions as previously used. These are determined from temperature probes placed in deep, small bore holes in the heavy aluminum bar in which the cavity was formed. The cavity is heated at one end and heavily insulated elsewhere to minimize thermal gradients. We will see that to properly measure poorly known quantities like the chopper blade emissivity function and the true cavity temperature, we must measure the BBC spectrum at three temperatures, T_1, T_2 and T_3.

We can relate the raw spectra of the BBC, $R_i(\lambda)$, to the Planck function $P(\lambda,T_i)$ and the instrument responsive function $F(\lambda)$ at each wavelength, λ, by the relations

$$R_i(\lambda) = P(\lambda,T_i)\, F(\lambda) - P(\lambda,T_o)\, F(\lambda)\, E(\lambda), \tag{1}$$

where T_o is the air temperature outside the cavity and $E(\lambda)$ is the wavelength dependent emissivity of the "black" paint on the chopper blade whose temperature is well approximated by T_o. The radiation from the chopper blade is a significant quantity because aircraft safety limits T_i to values below about 450K. From the equations for $R_1(\lambda)$, $R_2(\lambda)$ and $R_3(\lambda)$ measured at the three temperatures, we have

$$[R_1(\lambda) - R_3(\lambda)]/[R_2(\lambda) - R_3(l)] = [P(\lambda,T_1) - P(\lambda,T_3)]/[P(\lambda,T_2) - P(\lambda,T_3)] \tag{2}$$

The term on the left is measured, that on the right is theoretical except for the true cavity temperatures, T_i. There are differences between the measured temperatures T_i (measured) and true T_i. These are caused by thermal gradients in the BBC enclosure, which in turn are caused by heat flow to surrounding air and supports. These errors must be proportional to the difference between the temperature at the location of the measurement and the outside air (and support structure). Thus to a good approximation:

$$T_i = T_i(\text{measured}) + A(T_i(\text{measured}) - T_o)\,; \quad i = 1,2,3. \tag{3}$$

The values of T_i determined from (3) are substituted into equation (2) for successive values of A (a constant with respect to i) until equation (2) is best satisfied for all values of l. (A least squares approach may be used.)

The instrument response function is then

$$F(\lambda) = [R_1(\lambda) - R_3(\lambda)]/[\,P(\lambda,T_i) - P(\lambda,T_3)] \tag{4}$$

The uncorrected star spectrum, $US(\lambda)$, is obtained from the raw star spectrum $RS(\lambda)$ from

$$US(\lambda) = RS(\lambda)/F(\lambda) \tag{5}$$

While in principle we might know the second exit aperture size well enough to attempt an absolute flux calibration, we will actually use (5), after transmission corrections, as a spectral shape calibration only. We will rely on absolute photometry for absolute flux determination.

The uncorrected spectrum must now be corrected for transmission of the atmosphere and the telescope. One method for correcting atmospheric transmission is to measure the star through two significantly different air masses and then use the ratio of the two raw stellar spectra to determine atmospheric transmission assuming Beer's Law. Since in airborne measurements the water content (typically between 5 and 20 precipitable microns) is variable with time and observing location, it is sometimes better to just use the spectral signature of water in some part of the spectrum where the star is expected to have no features. The water spectrum is then matched with a terrestrial atmospheric model and the HITRAN line data base to determine the entire atmosphere transmission including well mixed species such as CO_2, N_2O, CH_4, O_2 as well as H_2O and O_3.

The reflective optics of the telescope are coated with aluminum (somewhat oxidized) and a protective silicon monoxide layer. The resulting absorption can be measured on the ground in a fairly straight-forward way. Figure 3 illustrates how this could be done in flight, thus making sure that the surfaces have not changed since the star itself was measured. Radiation from the blackbody cavity is directed through the telescope optics and then a portion reflected back by mirrors (modified corner cubes) mounted on the secondary mirror support "spider". The radiation then goes back through the telescope and its spectrum is measured at the spectrometer. The resulting spectrum has experienced absorption on all surfaces twice. The beam splitter is then removed and the ellipsoidal mirror of figure 2 inserted to allow measurement of the same radiation with no absorption. A mask is inserted so that its virtual image is of the same size and location as the modified corner cubes. Thus the radiation coming through both paths fills the spectrometer pupil the same way. The ratio of the average of these two spectra to the second (short path) spectrum is the telescope transmission spectrum.

A preliminary result, still uncorrected for atmospheric and telescope transmission, is shown in figure 4. Subsequent measurement of the optics transmission on the ground verifies that after correction for atmospheric transmission, most of the difference between the measured Sirius spectrum and Kurucz model is accounted for by optics absorption.

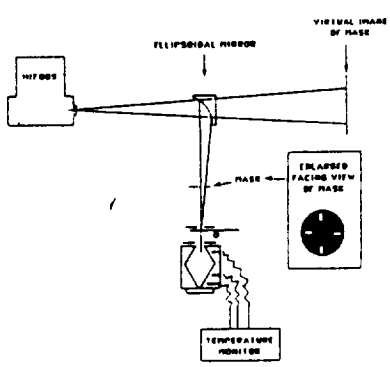

Fig. 2: Radiation from the cavity arrives at HIFOGS in an f/17 cone. When the mask is inserted, it is intended to approximate the pattern formed by the corner cubes in Fig. 3.

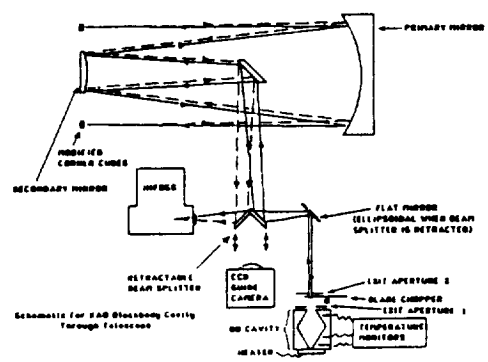

Fig. 3: Radiation from the cavity passes twice through the telescope reaching HIFOGS in an f/17 cone.

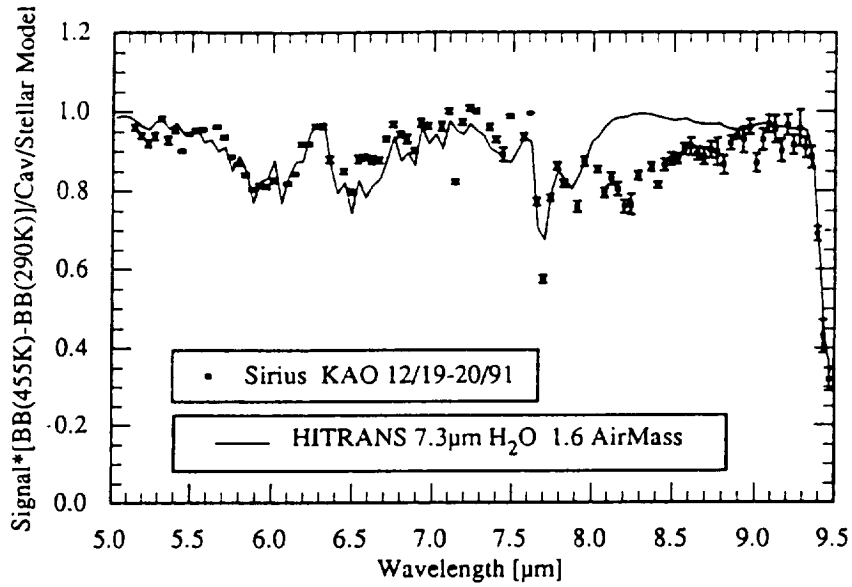

Fig. 4: Use of the blackbody cavity standard: The ratio of the raw Sirius spectrum to the raw cavity spectrum is multiplied by the ratio of the theoretical cavity spectrum to the Kurucz model. The result should agree with the product of atmospheric transmission (solid line) and optics transmission (not yet included).

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