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A LIQUID-HELIUM-COOLED GRATING SPECTROMETER FOR FAR INFRARED ASTRONOMICAL OBSERVATIONS

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A liquid-helium-cooled grating spectrometer has been constructed and used to make low-resolution far-infrared spectrometric observations of astronomical sources from the U.S. National Aeronautics and Space Administration (NASA) Lear Jet. A grating instrument was chosen for this application because it is simply constructed, is insensitive to vibration, weighs little, and is small. These are important considerations for observations with the 30-cm Lear Jet telescope. Moreover, since our detectors behave as though background limited, the sensitivity of a cooled grating instrument is competitive with a multiplexing spectrometer.

The instrument is shown schematically in Figure 1. The focus end of the spectrometer is bolted to the cold work surface of a liquid helium Dewar; the rest of the instrument is covered by a vapor-cooled radiation shield. The warmest parts of the frame are kept at a temperature < 20 K under operating conditions. This keeps the background flux on the detectors, from inside the instrument, small compared to radiation entering through the polyethylene window from the atmosphere and telescope. To eliminate scattered light, the inside of the instrument is coated with an absorbing paint, and the direct reflection from the secondary mirror to the detectors is blocked by a black mask on the secondary.

The spectrometer has a focal ratio of $f6.5$, and a 40-cm focal length. The entrance slit is 2.2×2.9 mm^2, which defines a beam of $4'.5 \times 6'$ on the sky when used on the Learscope. The focal ratio and length can be conveniently changed by substituting different secondary mirrors.

The instrument frame is constructed entirely from aluminum, and occupies a cylindrical volume approximately 13 cm in diameter and 26 cm in length within the Dewar. The primary and secondary pyrex mirrors are spherical and coated with aluminium. They are spring or clip mounted to avoid breakage during cooldown, but the instrument retains its alignment well even after many cryogenic cycles. The Dewar capacity is 2.5 liters, and its hold time is approximately eleven hours.

After a liquid nitrogen precooling phase, three helium transfers (about 12 liters, including transfer losses) over a period of two to three hours are required to bring the system to liquid helium temperature.

The spectrometer is scanned in wavelength by rotating the grating with a stepping motor located on the outside bottom of the Dewar. The motor connects via a fiberglass shaft that runs through a vacuum coupling to a pair of bevel gears, a worm, and a sector gear

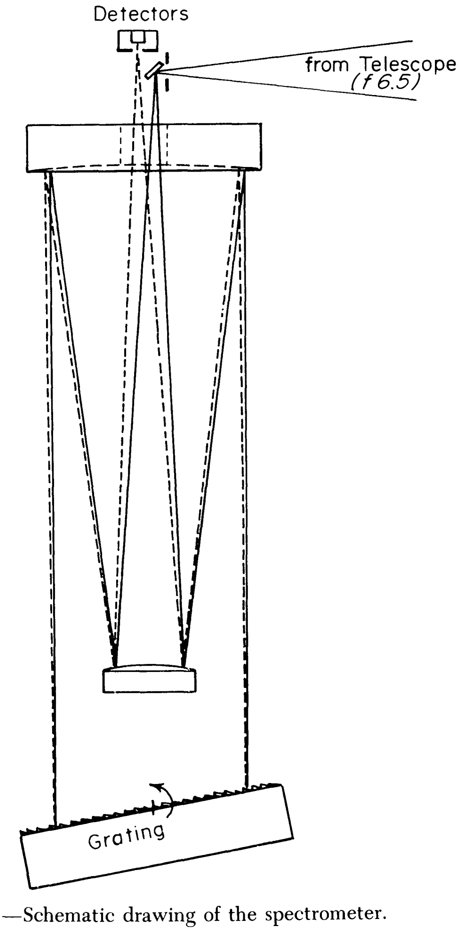

FIG. 1—Schematic drawing of the spectrometer.

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which combine to rotate the grating mount. The spectral resolution and wavelength coverage are determined by the slit sizes and grating blaze angle. We have employed gratings with groove spacings ranging from 0.10 to 1.75 mm, blazed at $\sim$ 90 μ. Both custom-made aluminum gratings and standard Bausch and Lomb replica gratings have been used. The instrument has been used over the wavelength range from 45 μ to 115 μ, at resolving powers ranging from 10 to 150. The theoretical maximum resolving power of the instrument is $\sim$ 700 at 90 μ, but the limited guiding accuracy of the Lear telescope has constrained us to use fairly large slits and a correspondingly lower resolving power.

The instrument uses two Ge:Ga photoconductive detectors (Moore and Shenker 1965) which have been produced following the procedures of Pipher (1971). These detectors are mounted directly to the cold work surface of the Dewar, and operate at $\sim$ 4.2 K. One detector works in the wavelength range from 45 μ to 80 μ in first and second order of the grating, with a CaF_2 filter; a diamond scatter filter (Armstrong and Low 1973) cuts off short wavelength light and KRS-5 acts as a long-wavelength cut-off filter. The second detector works longward of 60 μ in first order, with BaF_2 plus the CaF_2 and scatter filter blocking light at shorter wavelengths.

The spectrometer employs very simple cooled MOSFET coupled transimpedance preamplifiers (Wyatt, Baker, and Frodsham 1974), for which the circuit is shown in Figure 2. The MOSFETs and the feedback resistors are mounted as close as possible to the detectors. Microphonic noise is not a problem in spite of the relatively high vibration levels encountered in the aircraft. Linearity of the response is sufficient to permit use of the moon to give a spectral calibration even for faint infrared sources. The accuracy of this approach was confirmed by observations of Mars, whose brightness as a function of wavelength and time of observation has been calculated by Wright (1976). The noise of the preamplifier is about 1.5 microvolts-Hz$^{-0.5}$, which is far less than detector noise under normal operating conditions.

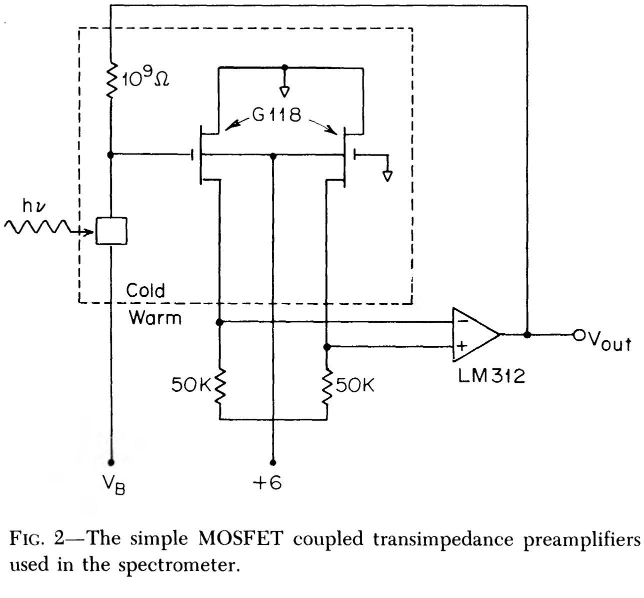

FIG. 2—The simple MOSFET coupled transimpedance preamplifiers used in the spectrometer.

In laboratory tests without an integrating cavity at $\sim$ 85 μ effective wavelength and backgrounds of $\sim$ 10^{-8} watts, these detectors gave measured photon NEP's of 1×10^{-13} w-Hz$^{-0.5}$. This is about a factor of 10 larger than the theoretical background limit for a photoconductor under these conditions. The current responsivity was approximately one ampere per watt at the optimum bias voltage.

In actual observations of M42 and Venus on the aircraft, the observed system NEP at a resolving power of 150 was about 4×10^{-13} watts-Hz$^{-0.5}$ at 88 μ and 9×10^{-13} watts-Hz$^{-0.5}$ at 52 μ. No corrections were made for telescope, chopper, and atmospheric losses. Noise contributions from guiding errors which generally dominated over the detector noise were included. The derived system efficiency is $\sim$ 10%, again including telescope, chopper, and atmospheric losses.

Normally a calibration spectrum is obtained with a laboratory source prior to each Lear Jet flight. For this calibration the spectrometer views a liquid-nitrogen-cooled blackbody source placed $\sim$ 70 cm from the polyethylene vacuum window. The solid angle subtended by the source has a diameter of $\sim$ 8°. It equals the angular diameter subtended by the wobbling secondary mirror at the entrance slit of the spectrometer during flight. Figure 3 compares preflight and in-flight spectra obtained on typical days. The inflight spectrum was obtained at a cruising altitude of 13.5 km. The preflight spectrum was taken at sea level, at Moffett Field, California. The spectral resolving power is $\sim$ 120 in both spectra. The lunar spectrum shows somewhat shallower absorption features than the spectrum of water vapor in 70 cm of normal air traversed at sea level. The water vapor features are pressure broadened in the lower atmosphere. A more detailed comparison of the two curves would require a curve-of-growth analysis of the water vapor features.

The spectral resolving power attained by the instrument varies with the source viewed. Compact sources whose images do not fill the entire entrance slit width produce spectra with a resolving power of $\sim$ 150 while extended sources like the moon provide a resolving power of 120. Similarly a small shift in the position of a spectral feature is produced if a small source is imaged first at one side and then the other of the entrance slit. Both of these problems could be overcome to a large extent by using a field lens in front of the entrance slit.

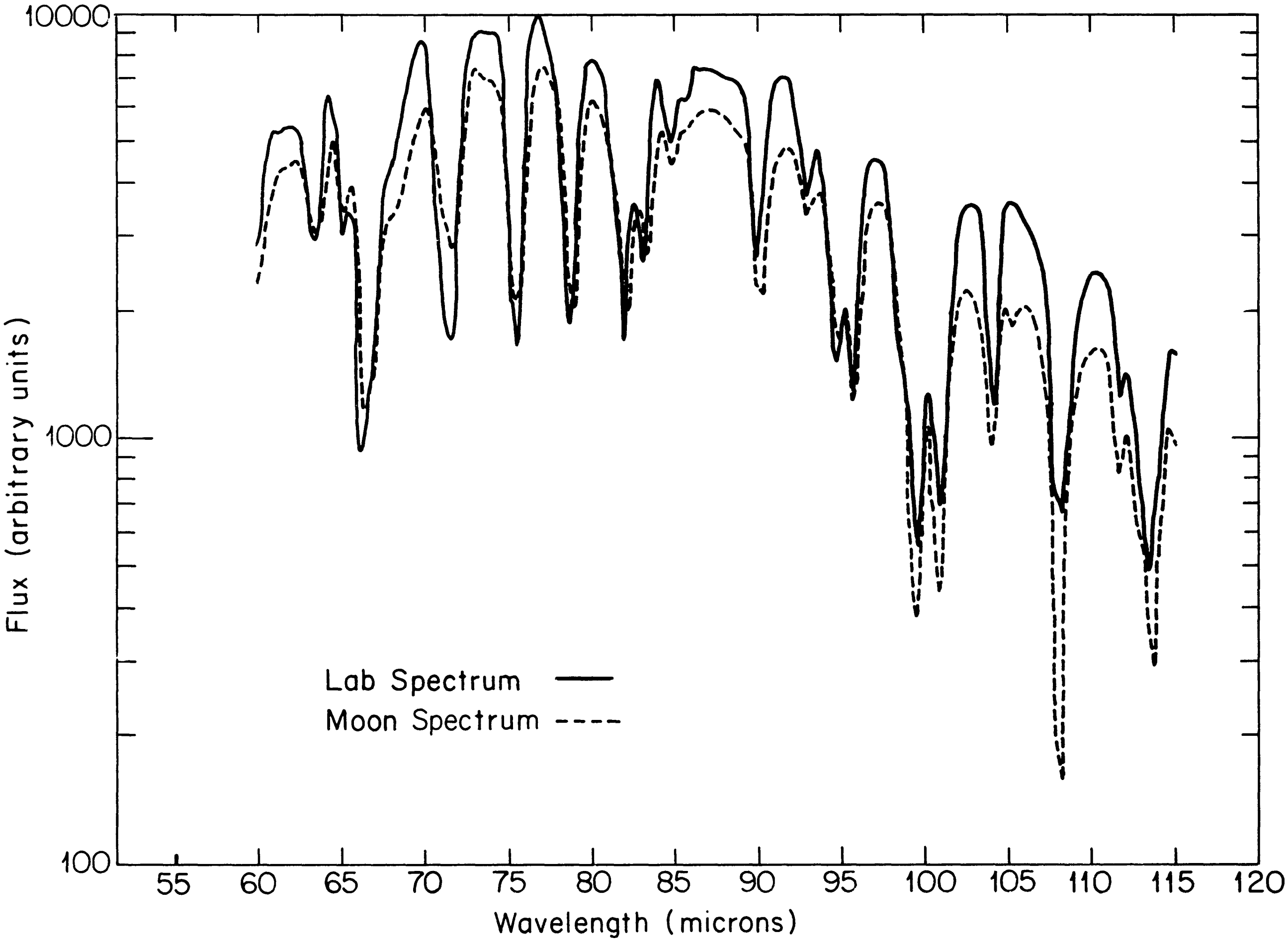

FIG. 3—Spectrum of the moon as seen from a Lear Jet altitude of 13.5 km and a preflight calibration spectrum of a laboratory source seen through a path length of 70 cm of air at sea level.

The reader can gain a clear understanding of the capability of the instrument from published spectra. Low-resolution spectra ($\lambda/\Delta\lambda \sim$ 10–30) are given by Ward, Gull, and Harwit (1977*a,b*). High-resolution spectral line data are given by Ward et al. (1975) and Dain et al. (1978) ([O III] 88.16 μ), and Melnick et al. (1978) and Melnick, Gull, and Harwit (1978) ([O III] 51.8 μ and [O I] 63 μ).

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