FAR-INFRARED EMISSIVITY MEASUREMENTS OF REFLECTIVE SURFACES

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Abstract

We have developed an instrument to measure the emissivity of reflective surfaces by comparing the thermal emission of a test sample to that of a reference surface. The instrument can accurately measure the emissivity of mirrors made from lightweight thermally insulating materials such as glass and metalized carbon fiber reinforced plastic (CFRP) composite. We report new far-infrared measurements at $\lambda_{eff} = 165\ \mu$m. The instrument has an absolute accuracy of $\Delta\ \varepsilon = 9 \times 10^{-4}$ and can reproducibly measure a difference in emissivity as small as $\Delta\ \varepsilon = 2 \times 10^{-4}$ between flat reflective surfaces. We have used the instrument to make measurements of mirror samples for ballon-borne (PRONAOS) and planned space-borne (FIRST) experiments. We measure an emissivity of $(6.05 \pm 1.24) \times 10^{-3}$ for gold evaporated on glass and $(6.75 \pm 1.17) \times 10^{-3}$ for aluminum evaporated on glass.

Keywords: emissivity, reflectance, millimeter, infrared, mirrors

1. INTRODUCTION

Thermal emission from ambient temperature mirrors limits the sensitivity of space-borne observatories such as COBRAS/SAMBA and FIRST[1] throughout the far-infrared and millimeter. Thermal emission from a simple 300 K mirror with an effective emissivity of 2.5×10^{-3}, for example, dominates the astrophysical sky brightness at $\lambda = 1$ mm by a factor of 10. For off-axis systems, such as COBAS/SAMBA, designed to minimize beam spillover onto warm emissive surfaces, emission from ambient temperature reflective mirrors dominates the photon background. Quantum fluctuations in the background are a fundamental source of noise and limit the sensitivity. Mirror emission can also produce systematic errors in photometry due to temperature drifts in the mirrors and non-uniformity in the emissivity across the mirror, even in a differential measurement. For these reasons it is important to characterize and minimize the emissivity of mirror surfaces at far-infrared and millimeter wavelengths.

Advances in composite mirror technology allow for the manufacture of large-aperture, lightweight mirrors with high surface accuracy for infrared and millimeter-wave astrophysics.[2,3] The rigidity and lightness of composite mirrors make them appropriate for numerous applications, including ground-based, balloon-borne, and planned space-borne observatories. The emissivity of such surfaces depends on the thickness of the coating and the method of application. Far-infrared emissivity of reflective surfaces is also a strong consideration in designing cryogenic systems with minimal parasitic heat load.

We have developed an instrument to determine the emissivity of room-temperature reflective surfaces at far-infrared and mm-wavelengths. The emissivity of an ideal metallic surface at near-millimeter wavelengths is several tenths of a percent. The instrument is capable of measuring the difference in millimeter-wave emissivity between flat reflective samples with a precision of $\Delta\varepsilon = 2 \times 10^{-4}$ without heating of the samples. It enables precise measurements of the emissivity of metal films evaporated on thermally insulating surfaces such as carbon fiber-reinforced plastic (CFRP) composite.

2. EMISSIVITY OF METAL FILMS

Incident radiation may be transmitted through a metal film, absorbed in the film, or reflected. Assuming that any radiation transmitted through the film is absorbed by material at the same temperature as the film, the effective emissivity of a metal-coated dielectric surface is given by $\varepsilon \equiv 1 - R$, where R is the reflectivity.

The emissivity of bulk metal at normal incidence is given by the Hagen-Rubens formula [4]

$$\varepsilon = \sqrt{\frac{16\pi c\varepsilon_0}{\lambda\sigma}}(mks),$$

where λ is the wavelength, ε_0 is the permittivity of free-space, c is the speed of light, and σ is the surface electrical conductivity. The emissivity of composite mirrors is dependent on the thickness of the reflective coating. When the thickness of the film is ~ 2 times greater than its skin depth, its emissivity approaches

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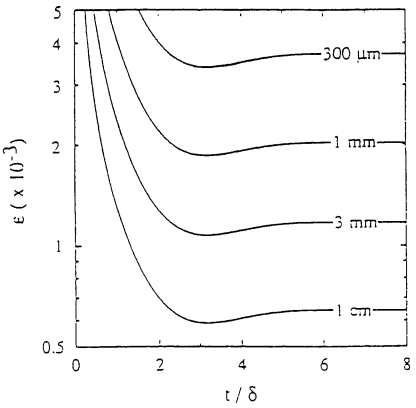

Figure 1: The calculated effective emissivity ($\varepsilon \equiv 1$ - R) of aluminum-coated composite mirrors, plotted as a function of film thickness over skin depth t / δ, for wavelengths λ= 1 cm, 3 mm, 1 mm, and 300 μm. The emissivity is calculated for an incident angle of 45°, averaging over polarization, assuming the electrical conductivity of bulk aluminum $\sigma = 3.7 \times 10^7\ \Omega^{-1}\ m^{-1}$. The skin depth depends on the electrical conductivity and the wavelength. For bulk aluminum, the emissivity can be extrapolated with high accuracy to other wavelengths and electrical conductivities by scaling the curves by $\varepsilon' = \varepsilon(\lambda\sigma/\lambda'\sigma')^{1/2}$.

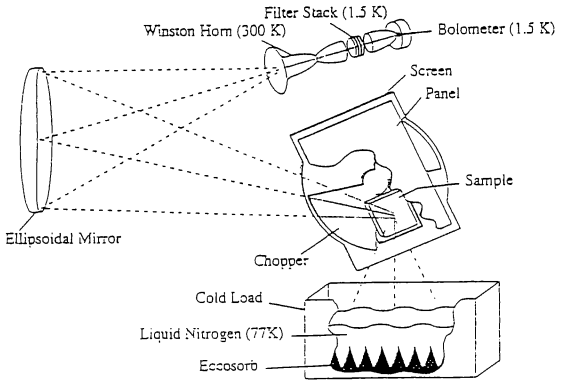

Figure 2: A schematic of the emissivitometer. In the time-reversed sense, radiation detected by a ^{4}He bolometer passes through a cold filter stack and is collimated by a room temperature back-to-back Winston horn with an apodizing flare. The radiation reflects off an off-axis ellipsoidal mirror, passes through a screen, is modulated by a chopper, passes through a panel, and is focused onto a reflective sample mounted on the panel. The radiation is reflected into a 77 K cold load alternately by the reflective chopper blade and by the sample. The cold load consists of foam Eccosorb submerged in a bath of liquid nitrogen.

that of bulk metal,[4] as demonstrated in Fig 1. However the risk of separation of a metal film from the dielectric supporting surface because of differential thermal contraction increases with film thickness.

The emissivity of a mirror depends on the surface electrical conductivity which can depend on the surface composition and surface quality of the mirror. Cleanliness of the mirror may also be a factor in determing the effective emissivity (see Fourmond et al. in these proceedings.) Thus direct measurements are necessary.

3. INSTRUMENT

The instrument and results at λ = 1 mm are described elsewhere.[5] We briefly summarize the operation of the instrument and report new results at λ = 165 μm. The instrument measures the difference in emissivity between reflective surfaces by comparing the thermal emission of a test sample to that of a reference surface. The absolute emissivity of the reference surface is obtained by heating the sample.

The instrument, shown schematically in Fig. 2, consists of a detector, a filter stack, a room-temperature Winston feedhorn, an ellipsoidal mirror, a sample holder placed behind a reflective chopper and screen, and a liquid nitrogen load. The detector is a superfluid 4He composite bolometer placed behind a cooled filter stack. The filter consists of a 100 μm-long-wavelength-pass filter which provides a high degree of rejection of short-wavelength radiation.[6] Rejection of long-wavelength radiation, for $\lambda \geq 2$ mm, is provided by the wave guide cutoff of a thick grill filter.[7]

The room-temperature Winston feedhorn is positioned at one focus of the off-axis ellipsoidal mirror to couple the radiation to the detector. An apodizing flare is coupled with the feedhorn to reduce diffraction. The edges of the ellipsoidal mirror are baffled with Eccosorb foam to intercept radiation spilling past the mirror edge. The chopper and sample are positioned at the second focus of the off-axis ellipsoidal mirror so that the detector alternately views the sample and the chopper. The chopper is modulated at 11 Hz. An aluminum screen is placed in front of the chopper and sample holder to minimize modulation of stray radiation by the chopper.

4. METHOD

The output of the detector is electronically amplified and demodulated by a lock-in amplifier referenced to the drive frequency of the chopper. The instrument is calibrated by removing the reflective sample from the aluminum panel so that the detector alternately views the cold load in reflection off the chopper blade and the room. We define the brightness of a black-

body source in Rayleigh-Jeans antenna temperature units, so that its brightness is given by the temperature of the source. The responsivity G of the instrument may thus be obtained,

$$G = S_{\rm cal}/(\mathcal{T}_{\rm room} - \mathcal{T}_{\rm load})[V/K],$$

where $S_{\rm cal}$ is the calibration signal and $\mathcal{T}_{\rm room}$ and $\mathcal{T}_{\rm load}$ are the antenna temperature of the room and the cold load, respectively. Assuming that the cold load is $(95 \pm 5)\%$ absorbing, $\mathcal{T}_{\rm room} - \mathcal{T}_{\rm load} = (207 \pm 11)K$. We use the calibration signal to define the phase of the optical signal with respect to the reference drive signal from the chopper.

When a reflective sample is placed in the aperture of the aluminum panel, the signal from the detector is given by

$$S = G[\varepsilon_{\rm s}(T_{\rm s} - \mathcal{T}_{\rm load}) - \varepsilon_{\rm ch}(T_{\rm ch} - \mathcal{T}_{\rm load})] + S_{\rm offset},$$

where $\varepsilon_{\rm s}$ and $T_{\rm s}$ are the emissivity and temperature of the sample and $\varepsilon_{\rm ch}$ and $T_{\rm ch}$ are the emissivity and temperature of the chopper blade. The term $S_{\rm offset}$ is due to an instrumental offset further explained in section 5. Assuming that $S_{\rm offset}$ remains stable, the difference in emissivity between a sample and a reference surface, $\Delta\varepsilon_{\rm s} = \varepsilon_{\rm s} - \varepsilon_{\rm ref}$, may be determined by differencing the signals obtained in subsequent measurements of the sample and the reference surface,

$$\Delta\varepsilon_{\rm s} = (\frac{S_{\rm s} - S_{\rm ref}}{\mathcal{T}_{\rm room} - \mathcal{T}_{\rm load}})G^{-1} = \frac{\Delta S}{S_{\rm cal}},$$

where $\Delta S = S_{\rm s} - S_{\rm ref}$ and we have assumed $T_{\rm s} = T_{\rm ref} = \mathcal{T}_{\rm room}$. The absolute emissivity of a reference sample is obtained by placing it into the detector beam and heating the reference sample. The change in the signal ΔS due to a change in the reference sample temperature $\Delta T_{\rm s}$ can be determined in the presence of a stable instrumental offset and gives the emissivity of the reference surface,

$$\varepsilon_{\rm s} = \Delta S/(G\Delta T_{\rm s}).$$

The reference sample must have a uniform temperature and therefore must be thermally conductive.

Scattering at the sample surface will increase the measured emissivity using the differencing technique, since radiation scattered through large angles will originate at ambient temperature rather than in the cold load. Thus, the quantity that is actually measured is the sum of the emission and the large angle scattering. This is an upper limit on the emissivity, and is the quantity of interest in estimating the effective emissivity of a telescope in which radiation scattered through large angles by the mirror surface will eventually be intercepted by a warm surface. Scattering at the surface of the reference sample does not affect the emissivity determined by heating the sample.

5. MEASUREMENTS

A small optical lamp is used to align the instrument. We place the lamp at the position of Winston horn, then adjust the position of the ellipsoidal mirror and aluminum panel to obtain the best focus on the sample. The angle of the aluminum panel is adjusted to be at $(45 \pm 2)°$. When all the radiation from the light source is reflected into the cold load by both sample and the chopper blade, we carefully remove the lamp and insert the dewar into the setup with the Winston horn placed at the position of lamp.

We use two aluminum surfaces as our reference surfaces. Both samples consist of a 7 mm-thick polished block of 6061-T6 aluminum alloy. Aluminum reference (2) is commercially polished and coated with 1 μm of evaporated aluminum,[8] whereas reference (1) was polished by hand with diamond compound and is uncoated. In order to verify the performance of the instrument, we also measure the emissivity of a reference surface consisting of a polished block of 6061-T6 aluminum alloy coated with 1 μm evaporated gold.[8]

We measure an instrumental offset of $\varepsilon_{\rm offset} = S_{\rm offset}/S_{\rm cal} = 8 \times 10^{-2}$ with an aluminum reference surface placed on the panel. An offset can be produced by radiation scattering off the edges of the chopper blade onto emissive room-temperature surfaces, or by a misalignment between the chopper blade and the sample. The instrument is designed to measure emissivity in the presence of an offset that is stable. We frequently monitor the instrumental offset by inserting the aluminum reference surface (2) and find a drift of $d\varepsilon/dt = 1.6 \times 10^{-3}$/h. Since the differencing measurements can be taken within couple of minutes for each sample, such a drift in offset is negligible.

In the previous measurements at $\lambda = 1$ mm, a 90% transmissive Styrofoam lid was placed over the cold load to reduce possible drifts caused by cooling of baffles, chopper, or sample. However, we removed the Styrofoam lid during our measurements, because with our wide spectral band, the instrument is sensitive to water that can condense on the Styrofoam lid and produce a significant instrumental drift. The dewar window is continuously flushed with dry nitrogen gas to prevent condensation. We monitor the calibration signal over 3 hours and find a small fractional drift of 2×10^{-3}/h.

For the absolute measurements, the cold load is not needed, and we place a reference sample in the detector beam and measure change in signal by varying its temperature. The reference sample is suspended by a fiberglass tube to thermally isolate it from the aluminum panel. We monitor the instrumental offset by placing a separate room-temperature gold-coated-

aluminum surface on the aluminum panel before and after the measurement. In this manner we determine the typical error introduced by heating the baffles or the chopper to be negligible, $\Delta\varepsilon = 3 \times 10^{-5}$.

During the heating measurements the sample is necessarily separated from the aluminum panel, and mulitple reflections can occur between the panel and sample. If the edges of the aperture are fully viewed by the detector, this effect can lead to a large overestimate of the emissivity. We minimize edge effects by using an aperture which is significantly larger than the beam size of the sample, and by carefully placing the focus in the middle of the aperture.

6. RESULTS

The results of heating measurements shown in Table 1 include statistical error, the error from the stability of the offset and the responsivity and a calibration error of 5%. The accuracy with which absolute emissivity can be determined is thus limited by the uncertainty in the emissivity of the reference sample.

During the differencing measurements, we observe a significant rotational dependence in emissivity among some samples. Curvature of the sample surface or variation of the emissivity over the surface of the sample can possibly cause such variation. A small curvature of the sample surface can reflect radiation into different areas of the cold load, and thereby vary the instrumental offset. This variation typically is several times larger than we observed earlier at λ = 1 mm, and may be related to the reduced aperture used to measure smaller samples.

Fortunately, the rotational dependence of the samples is small in comparison to the uncertainties in the absolute emissivity. The evaporated glass samples show negligible signal variation when rotated by 180°. We calculate the emissivity of each sample tabulated in Table 1 by averaging measurements of the emissivity obtained for several different sample orientations.

The measured emissivity of the best aluminum surface, $(6.75 \pm 1.17) \times 10^{-3}$ for aluminum evaporated on glass, approaches the calculated emissivity of bulk aluminum, 4.93×10^{-3}, at $\lambda = 165$ μm and $\theta = 45°$. The measured emissivity of the commercially polished, coated aluminum reference surface (2), $(9.15 \pm 0.86) \times 10^{-3}$, is virtually the same as that of the hand-polished, uncoated aluminum reference surface (1), $(9.5 \pm 0.88) \times 10^{-3}$. The minimum emissivity is measured for gold evaporated on glass, measured emissivity, $(6.05 \pm 1.24) \times 10^{-3}$. The measured emissivities of reference surfaces obtained with the heating technique agree with the values obtained with the differencing technique, comfirming the performance of the instrument.

TABLE 1: Measured Emissivities at $\lambda = 164$ μm

Sample	Absolute Emissivity[a] ε_s [x 10^{-3}]	Absolute Emissivity[b] [x 10^{-3}]	Difference Emissvity ε_s - ε_s(Al ref) [x 10^{-3}]
Al ref (2)	9.15 ± 0.86	—	—
Al ref (1)	11.7 ± 1.2	9.5 ± 0.88	0.35 ± 0.4
Au on Al ref	7.32 ± 0.49	7.25 ± 0.88	-1.9 ± 0.3
Bi on Al ref	—	31.25 ± 0.91	22.1 ± 0.3
Au on glass	—	6.05± 1.24	-3.1 ± 0.9
Al on glass	—	6.75± 1.17	-2.4 ± 0.8

[a] Absolute emissivity determined using the heating technique.
[b] Absolute emissivity determined using the differencing technique

7. CONCLUSIONS

We have developed an instrument to measure the difference in emissivity between reflective surfaces by comparing the thermal emission of a test sample to that of a reference surface. The instrument relies on a simple differencing technique, and requires no heating of the sample. One can measure directly the emissivity of any flat reflective surfaces at near-millimeter wavelengths. The technique may also be used to determine the absorption of transmissive materials. In the near future, we will continue obtaining more complete spectral information with the filter wheel.

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