3 - 13 µm Spectra of Geosynchronous Satellites

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ABSTRACT

We report 3-13 µm spectra of three geosynchronous satellites using The Aerospace Corporation's Broadband Array Spectrograph System (BASS) on the AEOS 3.7 meter telescope at Haleakala in December 2005. The satellites observed were NORAD 21639 (TDRS 5), 11145 (DSCS 2-12) and 15629 (INTELSAT 510). The spectra showed structure indicative of the satellites' surface material, temperature and cross section as viewed from the observatory. A brief summary of how to analyze such spectra to retrieve surface material composition, temperature and geometrical cross section is included.

1. INTRODUCTION

Spectroscopy of artificial satellites is a relatively new field. With the advent of large detector arrays and rapidly slewing telescopes, spectroscopy of satellites has become more feasible. Recent work at AEOS in the near infrared [1-3] have shown the utility of optical spectra in identifying and characterizing satellites. In December 2005 we had the opportunity to observe several satellites in the thermal infrared (3 – 13 µm). Presented here are some preliminary spectra and a discussion of how they might be interpreted.

2. OBSERVATIONS

The observations were taken during December 2005 using the Broadband Array Spectrograph System (BASS) [4] on the AEOS 3.7 meter telescope [5] on Haleakala. Observations were made of the satellites using the standard double beam chopping/nodding technique. To perform absolute radiometric calibration, we used α CMa as a standard star. For the results presented here, we adopted as a flux model for α CMa one in which its magnitudes was –1.41 at every wavelength with zero magnitude at 10 µm corresponding to 1.26×10^{-16} W cm^{-2} µm^{-1}. The true flux models are slightly different from the magnitudes listed above and vary with wavelength by a small amount. Integration times were between about 5 and 15 minutes on each satellite.

Geosynchronous satellites are relatively easy to observe because they remain virtually stationary in the sky. LEOs and HEOs are more difficult because of their motion but we have developed and validated techniques for successfully observing them. While they are available for a shorter time than GEOs, LEOS and HEOS are relatively brighter because they are closer than GEOS and thus less time is required to obtain corresponding signal to noise ratios (SNRs).

Figure 1 shows the spectrum of NORAD 21639 (TDRS 5) and Figure 2 shows the spectra of all three satellites: NORAD 21639 (TDRS 5), 11145 (DSCS 2-12) and 15629 (INTELSAT 510). Only a few minutes was spent on each satellite and thus the SNRs are smaller than they might otherwise be. By simply integrating longer, higher SNR spectra can be obtained.

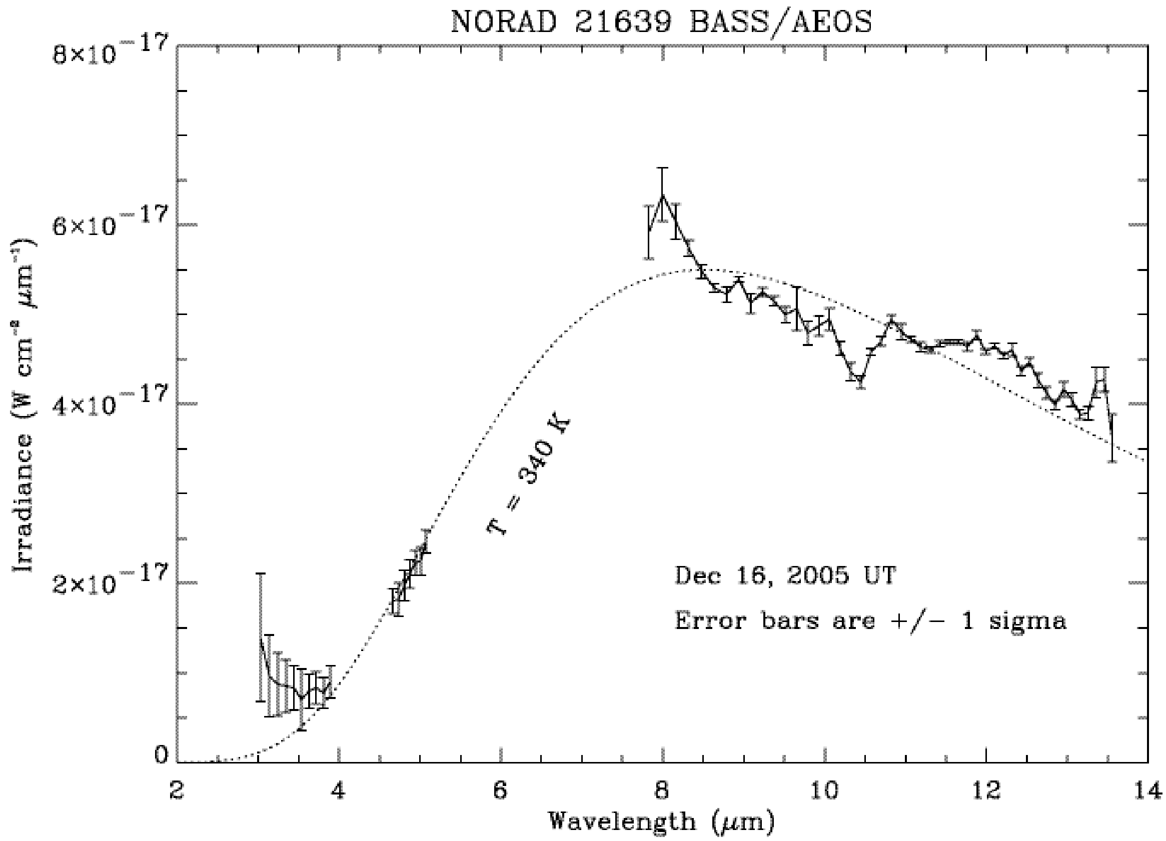

Figure 1 - Spectrum of NORAD 21639 (TDRS 5) taken with BASS on AEOS in Dec, 2005. The spectral energy distribution is roughly Planckian with some significant spectral features that are indicative of non-Planckian emission. The most significant feature is an absorption near 10.4 μm, probably due to solid state absorption features in some of the outer material of the spacecraft. The apparent emission feature near 8 μm may be partially due to incomplete cancellation of atmospheric effects. The upturn at shorter wavelengths is due to scattered sunlight.

In Figure 1, the gross spectral energy distribution is well approximated by a Planck function. Based on the peak emission near 8 μm, the spectra show emission that is characteristic of an object near 360 K, its color temperature. This is somewhat hotter than radiative energy balance would predict for a sunlit object 1 AU from the Sun, i.e. 278 K, Observations of thermal emission from comet dust show similarly higher-than-expected color temperatures [6-9], an energy-balance effect that results from high absorption in the visible and low emissivity in the infrared. To the extent that the color temperature is related to thermodynamic temperature, the excess is probably due in part to the materials such as thermal blankets. These are designed to be poor radiators and poor absorbers, i.e. very different than black bodies. Solar cells are composed of semiconductors (silicon) and this material behaves differently from a black body. Satellites also have internal power supplies and radiative dissipation of system heat may contribute to the excess temperature.

Despite the noise in the spectra of 11145 (DSCS 2-12) and 15629 (INTELSAT 510) in Figure 2 due to short integration times, the three spectra show clear differences in shape. This is not unexpected in view of the different outer materials of each satellite. It does indicate, however, that satellites can be distinguished based on their spectra.

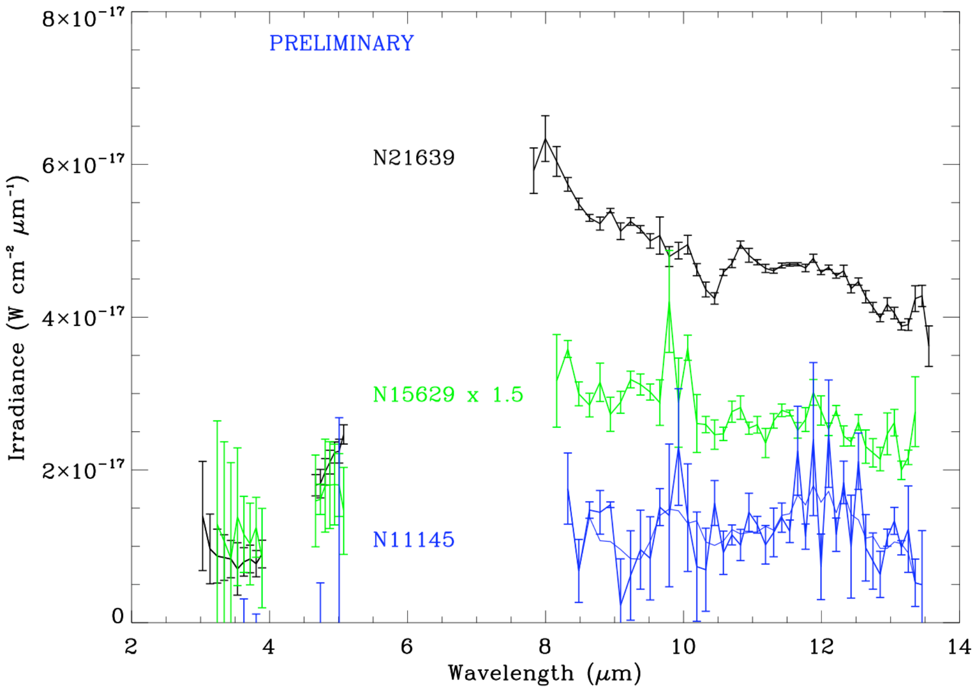

Figure 2 - NORAD 21639 (TDRS 5), 11145 (DSCS 2-12) and 15629 (INTELSAT 510), separated vertically for clarity. Note that N21639 and N15629 have similar signal levels near 5 microns but are very different in the 8-13 μm region. The different shapes of the spectra show that satellites can be distinguished from one another based on their thermal infrared spectra.

While the spectral energy distributions shown in Figure 2 are grossly Planckian, there are spectral features indicative of emissivity variations and each satellite shows different features. For example, N21639 shows a strong minimum near 10.4 μm that the others do not. This is probably due to a solid state absorption feature in one the spacecraft's outer covering.

3. INTERPRETING THE SPECTRA OF SATELLITES

The radiative equilibrium of an object in space requires that the energy absorbed be equal to the energy radiated,

absorbed = emitted

$$Io\,(1-A) = C\varepsilon\sigma T^4 \qquad (1)$$

where Io is the solar insolation, $A(\lambda)$ is the albedo, σ is Stefan's constant, $\varepsilon(\lambda)$ is the emissivity of the object and T is its temperature. C is a geometrical term that is related to speed of rotation in relation to the satellite's thermalization time. For an isothermal blackbody, which corresponds to a small, rapidly rotating particle, C = 4. For a slowly rotating body, C = 2. For a black body, A = 0.0 and ε = 1.0, though spacecraft are not expected to behave as such. For this example we have assumed that A and ε are not wavelength dependent. In general, however, the emissivity and albedo are functions of wavelength and therefore in real-world usage, Equation (1) would be an integral. The wavelength dependence of the albedo is most important in the visible and near IR where most of the solar radiation that is heating the spacecraft is present. Similarly, emissivity is most important longward of about 4 microns where thermal emission balances the incoming solar radiation. Equation (1) can be rewritten as

$$T = (Io(1-A)/(C\varepsilon\sigma))^{1/4} \quad (2)$$

At the Earth's distance from the sun, T = 278 K for a black body. This equation shows that the lower the albedo (darker the spacecraft), the more energy is absorbed, thereby raising its temperature. Similarly, as ε drops below unity, the ability to radiate decreases and the spacecraft must equilibrate at a higher temperature to maintain radiative energy balance (Figure 2). For satellites in low earth orbit, Io must include thermal radiation and scattered sunlight from the Earth. At geosynchronous altitudes, the Earth term is small.

Most of the data shown in the spectra is the result of thermal emission from the satellite. The thermal irradiance I from a compositionally-homogeneous, lambertian emitter is given by

$$I(\lambda) = K\ \varepsilon(\lambda)\ P_T(\lambda) \quad (3)$$

where $P_T(\lambda)$ is the Planck function at a temperature T. K is a constant determined by the size and distance of the object. For an ideal blackbody, ε(λ) is unity at all wavelengths. Real materials, however, have a wavelength-dependent emissivity and it is by retrieving ε(λ) that the composition can be inferred. Such analyses have been used to study asteroids [10].

Satellites exteriors are made of many materials: aluminum, kapton, silicon solar cells, etc. Therefore the observed irradiance is the sum of the emission from each material weighted by the geometrical cross section s of each component. Owing to differences in A, ε and sun illumination geometries, different parts of the spacecraft will be at different temperatures.

$$I(\lambda) = K_i\ \varepsilon_i(\lambda)\ s_i\ P_{Ti}(\lambda) \quad (4)$$

Such models have been used to partially identify mineral components in comets [11,12]. It is also important to understand that the spectrum can change with viewing geometry, solar illumination, time since eclipse, duration in orbit, tumbling, etc. as T and K vary and material at different emissivities are exposed. To understand such time variations in detail, thermophysical models must be employed [13-16].

The above discussion assumes that there are no internal heat sources on the spacecraft and that its thermal configuration is determined entirely by radiative balance with the Sun. As a practical matter, many spacecraft have internal power sources that radiate energy, and LEOs receive significant visible and IR radiation from the Earth. Both additional sources must be included in a complete radiation budget. The ability to detect and characterize thermal emission from internal power sources is one of the compelling reasons to pursue IR observations of satellites.

4. DISCUSSION

One advantage of observing satellites in the thermal infrared is that they can be observed day or night, providing that they can be acquired during the day based on known positions and an infrared signal on which to peak-up, i.e. center in the bean for maximum signal. This allows the satellite to be observed at different solar illumination angles, thereby providing more information as to the satellite's properties. Even in eclipse, the satellite will have a thermal IR signature, something that optical and near IR observers cannot make use of.

The interpretation of thermal IR satellite spectra can take advantage of earlier studies of asteroid spectra. These analyses have revealed that in addition to wavelength-dependent emissivities, asteroids are not Lambertian emitters. Their emission does not show a simple cosine dependence on the angle from the normal but rather emit more efficiently in the backward direction (relative to the illumination source, the Sun), an effect called "beaming" [16,17,18]. The concept of beaming was developed within the context of Standard Thermal Models (STM) of asteroids [17,18] and is expected to occur on satellites as well, though there have been no studies of satellites on this topic to our knowledge.

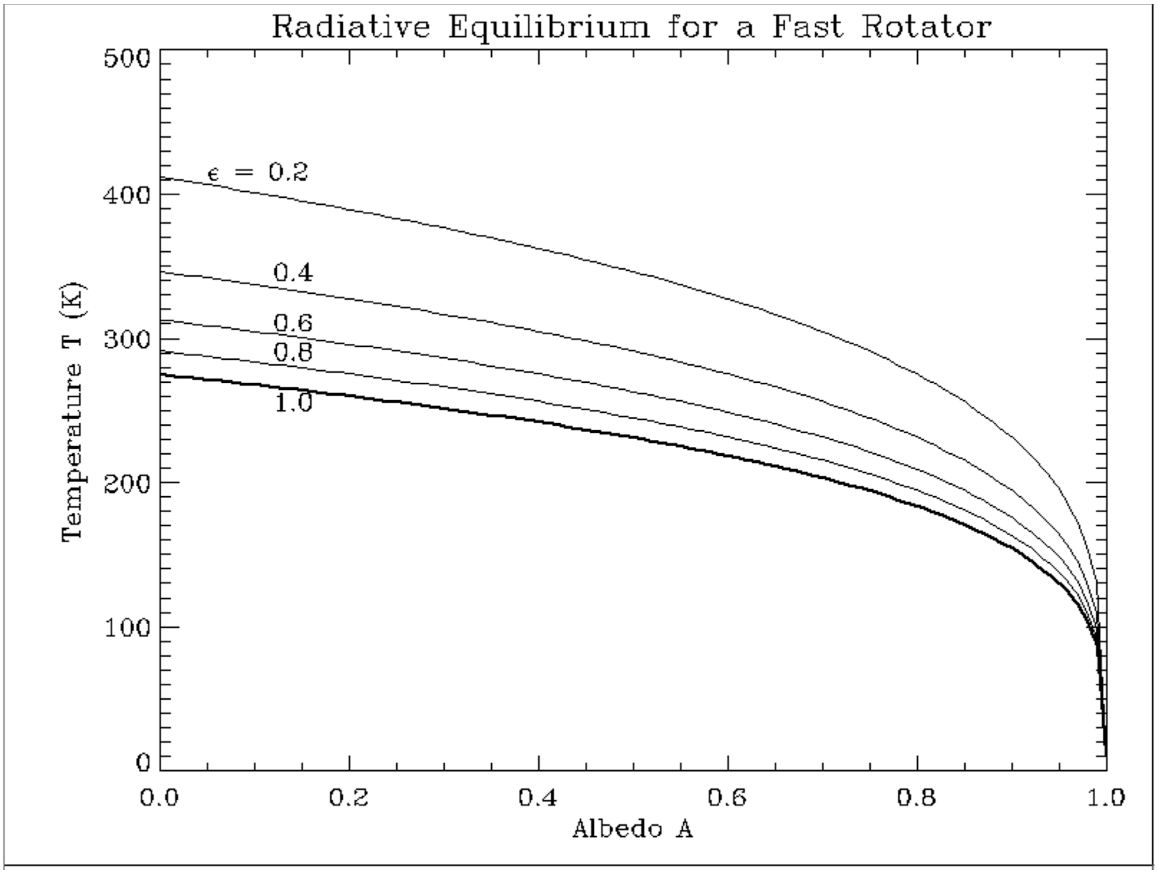

Figure 3 - Temperature on the surface of a solar illuminated material (normal incidence) as a function of albedo at a distance of 1 A.U. from the Earth. The different curves correspond to different emissivities.

Equation (4) cannot be analytically decomposed to retrieve the emissivities, cross sections and temperatures because the observed spectrum is an integral. There are an infinite number of possible combinations of ε, s, K and T that can be combined to produce I(λ). Therefore, the best approach to retrieving the composition of the satellite is to take the emissivity of known materials and model the spectra using different values of ε and T (Figure 3). Such an approach has shown some promise when applied to comets [11,12].

Another parameter that can affect a satellites radiative equilibrium temperature is the angle at which the sun strikes a surface. The greatest heating will occur when incident sunlight is normal to the surface. As the surface becomes more and more inclined to the sun angle, it absorbs less radiation and therefore its temperature is lower.

Modeling of satellite spectra requires some knowledge – perhaps detailed knowledge – of the satellite's geometry. Thus we are in a chicken-and-egg situation: we can only retrieve shape, geometry and composition by modeling the spectra, yet to model the spectra we need to know its shape, geometry and composition! To make any progress, we need to start with simple materials and perform a multivariate analysis by allowing ε, e and T to vary and search for maxima in the cross correlation of the predicted spectra and the actual one. While this does not guarantee uniqueness in the solution, it may constrain some of the parameters and therefore shrink the parameter space for characterization. For example, any solution in which T is higher than the material's melting temperature can be ruled out.

Alternatively, a database of spectra can be compiled and organized along the lines of known satellite properties: country of origin, satellite function, orbital parameters, duration in space, etc. Such an approach does not guarantee uniqueness but does provide probabilistic guidelines for identification and may in some circumstances achieve near certainty.

5. SUMMARY AND CONCLUSIONS

We have presented three thermal infrared spectra of geosynchronous satellites and provided a framework for interpreting them. The spectra can be improved by integrating on them longer: only a few minutes were spent on each satellite and thus the signal-to-noise ratios are small. We anticipate obtaining more spectra and modeling them based on known properties provided by the satellite manufacturers.

6. ACKNOWLEDGMENTS

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