The sky background: NIR and MIR

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This is a pedagogical report on the sky background missions with $\lambda > 1\,\mu$m. For a space-based facility the primary sky background in the wavelength range, 1–50 μm is due to interplanetary dust (zodiacal light) with the contribution from the ISM rising with longer wavelength and also with decreasing Galactic latitude. Small dust particles, concentrated in the ecliptic plane reflect solar rays and are also heated to about 300 K. The former results in a sky background between $0.2\,\mu$ and $3\,\mu$m and the latter peaks at $12\,\mu$m. The wavelength region below $0.2\,\mu$m is extremely dark (and motivates UVEX) and the wavelength region around $3\,\mu$m is dark relative to both the optical and MIR bands. At long wavelengths, warm interstellar dust dominates the sky background. I will be using IRTS and Akari as the starting point for this report. I chose these two missions because I know very little about them! The CIBER sub-orbital mission is very relevant[1] to the discussions here.

1 Simplified Sky Model

The background material is summarized in the Appendix. We now proceed to the finished product.

Our simplified sky model has the mid-R ($\lambda > 5\,\mu$m) emission arising from dust particles heated to, say, $T_d \approx 300$ K. Then the intensity should follow black body intensity but with a very small optical depth, τ_d:

$$I_\nu = \tau_d B_\nu(T_d)$$

where $B_\nu(T)$ is the black-body intensity (Planck function). From left panel of Figure 4, I find that, at $\lambda = 5\,\mu$m, $\lambda I_\lambda = 300\,\mathrm{nW\,m^2\,ster^{-1}}$. This translates to $I_\nu = 5 \times 10^{-18}$ $\mathrm{erg\,cm^{-2}\,s^{-1}\,ster^{-1}\,Hz^{-1}}$ at $\nu = 6 \times 10^{13}$ Hz. Comparing this intensity to the blackbody intensity at 300 K I find $\tau_d = 2.3 \times 10^{-8}$. The spectral resolution at this wavelength is 130. Thus, $\mathcal{I}/\mathcal{R} = 73\,R$.

[1] Most of the CIBER team members went on to become members of SPHEREx

In the optical and NIR bands, zodiacal light is due to scattering. Let us focus on the intensity of scattered light at high ecliptic latitudes. The intensity of the scattered light is given by

$$I_\nu = \left(\frac{\tau_s}{4\pi}\right) I_\nu(\odot)\Omega_\odot$$

where $I_\nu(\odot)$ is the intensity of the sun and $\Omega_\odot = \pi(\mathrm{R}_\odot/\mathrm{AU})^2$ is the solid angle of the sun as measured at earth.[2] Here, $\mathrm{R}_\odot$ is the radius of the Sun and AU stands for the astronomical unit. After reviewing Figure 5, I adopt λI_λ of $300\,\mathrm{nW\,m^{-2}\,ster^{-1}}$ at $\lambda = 1.5\,\mu\mathrm{m}$ corresponding to $\nu = 2\times10^{14}\,\mathrm{Hz}$. This translates to $I_\nu = 1.5\times10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,ster^{-1}\,Hz^{-1}}$. Setting $T_\odot = 5,880\,\mathrm{K}$ I find $\tau_s = 0.97\times10^{-8}$. The spectral resolution at this wavelength is $\mathcal{R} = 41$. Thus, $\mathcal{I}/\mathcal{R} = 69\,R$. The simplified model is plotted in Figure 1.

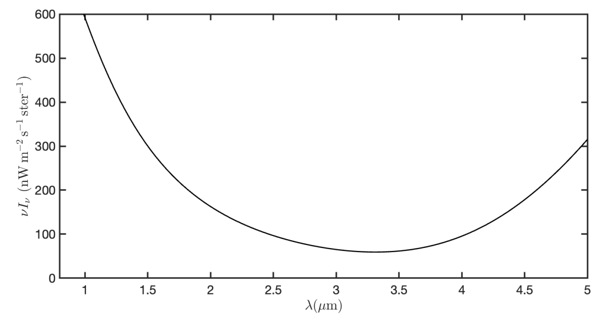

Figure 1: νf_ν of zodiacal emission of the simplified mode (normalized to ecliptic latitude of about 30°). This should be compared against left panel of Figure 4.

At optical wavelengths, the optical depth from the Earth to the sun due to zodiacal dust is approximately 10^{-7}. Note that this line-of-sight is at ecliptic latitude of 0°. The zodiacal emission falls by a factor of two at ecliptic latitude of 30°. Our inferred optical depths are at high ecliptic latitudes and are expected to be smaller. I am slightly disquieted by the small values, though.

2 Application to SPHEREx

SPHEREx provides an all-sky catalog of low-resolution spectra (0.75–5 μm) at a pixel resolution of $6'' \times 6''$. The spectral resolution, $\Delta\lambda/\lambda$ varies between 40 and 140. Each pixel has a 1-D spectra with 102 channels.

Let the bandwidth of a given image be $\Delta\nu$. Then the band-integrated sky intensity is $I_\nu\Delta\nu$ and the corresponding photon intensity is $\mathcal{I}/\mathcal{R}$ where $\mathcal{I} = I_\nu/h$ and $\mathcal{R} = \nu/\Delta\nu$. The quantity $\mathcal{I}/\mathcal{R}$ is plotted in Figure 2.

[2]We are computing specifically the emission, say, at the ecliptic poles.

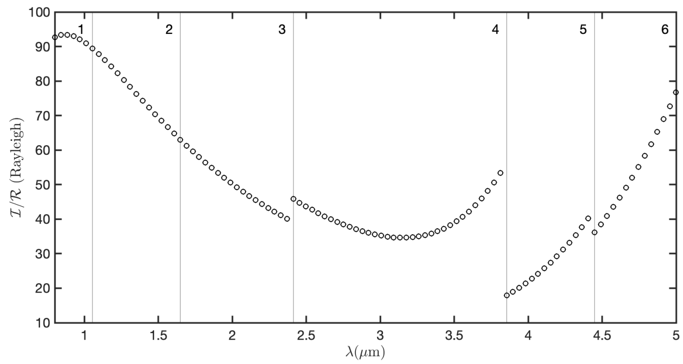

Figure 2: Sky brightness in Rayleighs divided by the spectral resolution in each of the six SPHEREx bands. The vertical lines mark the boundaries of the six bands (band 1 is at the extreme left and band 6 at the extreme right).

2.1 Sensitivity: Diffuse Emission

Say your goal is to search for a spectral line in the sky (e.g., a recombination line). We assume that this line is unresolved by the spectrometer. Let A be the collecting area of the imager, Ω is the field-of-view and η is the photon-to-electron efficiency. The signal is $\alpha\mathcal{S}\eta A\Omega t$ where $\mathcal{S}$ is the surface brightness of the signal in Rayleigh (integrated over the line width), t is the integration time and α is the conversion factor between Rayleigh to the standard units $\mathrm{phot\,cm^{-2}\,s^{-1}\,ster^{-1}}$. The contribution from the sky is $\alpha\mathcal{I}\mathcal{R}^{-1}\eta A\Omega t$. Assuming only[3] Poisson fluctuations, and in the limit of weak signal, the the signal-to-noise ratio is given by

$$\mathrm{SNR} = \frac{\mathcal{S}}{\sqrt{\mathcal{I}}}(\alpha\eta A\Omega\mathcal{R}t)^{1/2} \tag{1}$$

Now, let us plug in the numbers. $A = \pi/4D^2 = 314\,\mathrm{cm}^2$ where $D = 20\,\mathrm{cm}$. Set, $\eta = 0.5$. $\alpha = 10^6/(4\pi)$. We find

$$\mathrm{SNR} = 1.86\times 10^3\Big(\frac{\mathcal{S}}{\sqrt{\mathcal{I}/\mathcal{R}}}\Big)\sqrt{\Omega}\Big(\frac{t}{900\,\mathrm{s}}\Big)^{1/2}$$

where Ω is now in square degrees.

2.2 Sensitivity: Point Sources

For point source the number photons from the source collected over time t is $S\Delta\nu\eta At/(h\nu)$ where S is the spectral flux density ($\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}$) of the source. The number of sky

[3] read noise and dark current are assumed to be negligible

photons is $I_\nu \Delta\nu \eta A t \delta\Omega/(h\nu)$ where $\delta\Omega$ is the solid angle of the detection beam. Assuming ony Poisson fluctuations from the sky and in the limit of faint sources the signal-to-noise ratio is given by

$$\mathrm{SNR} = \frac{S/h}{\sqrt{I_\nu/h}}\Big(\frac{\eta A t \mathcal{R}}{\delta\Omega}\Big)^{1/2} = \frac{\mathcal{S}}{\sqrt{I}}\Big(\frac{\alpha\eta A \mathcal{R} t}{\delta\Omega}\Big)^{1/2}$$

A IRTS & Akari (Astro-F)

IRTS (Infrared Telescope in Space; launched in 1995 was Japan's first orbiting IR telescope (Matsumoto et al. 1996). It was one of the sub-systems placed on the Space Flyer Unit. The 15-cm liquid helium cooled telescope had four focal plane instruments and the experiment observed about 7% of the sky between 1 μm to 1 mm. Of interest here are two spectrometers: NIRS (1.4–4 μm with a spectral resolution of 0.12 μm) and MIRS (4.5–11.7 μm and a spectral resolution of 0.3 μm). The pre-launch summary of the mission can be found in Figure 3.

Akari[4] (launched in 2006), also a cryogenic mission (Murakami et al. 2007), carried two instruments behind 68.5-cm telescope: InfraRed Camera (IRC) which had three cameras covering the range 1.8–5.5 μm, 5.8–14.1 μm and 12.4–26.5 μm, each capable of direct imaging and very low resolution slit spectroscopy and the Far Infrared Surveyor (FIS) also with three cameras covering 50-180 μm.

The sky spectrum towards the North Ecliptic Pole (NEP), as observed by Akarai/IRS, is shown in Figure 3. This overview figure shows the various components to the sky spectrum. In decreasing order they are zodiacal light and diffuse galactic light. The extragalactic background light is presumably below the levels shown here.

B Cosmic Infrared Background Experiment (CIBER)

CIBER is a series of sub-orbital experiments. CIBER-1 carried a low-resolution (spectral resolution of 15–25) imaging spectrometer operating in the range 0.7–2.1 μ, two wide-field imagers (1.2 μm and 1.6 μm) and a narrow field (centered on Ca H&K) imager (Zemcov et al. 2010).

In Figure 5 I display a low resolution spectrum of the zodiacal light in the near-IR band and also the latitude dependence of the emission of zodiacal light.

C Attic

The radial dependence of the number density of zodi particles, around 1 AU, has been obtained by missions en route to Venus or asteroids. $n(r) \propto r^n$ where $n = -1.3 \pm 0.08$ (Tsumura et al. 2023).

[4]Formally, Astro-F. Prior to launch it was also called as IRIS for Infrared Imaging Surveyor.

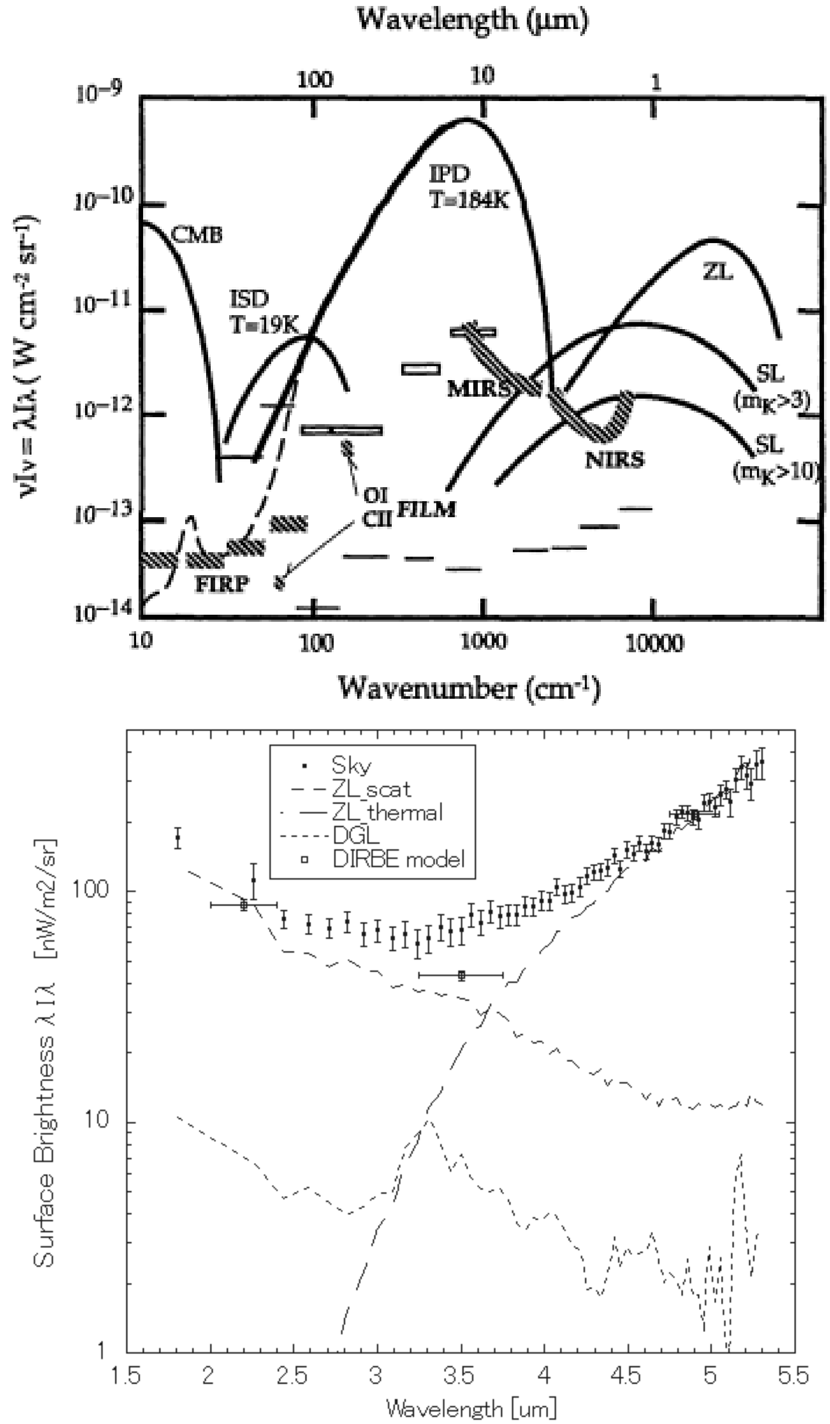

Figure 3: (**Top**): Pre-launch summary figure from IRTS team (Matsumoto 1995). The thick curves represent sky brightness due to CMB, interstellar dust (ISD), interplanetary dust (IPD) and zodiacal light (ZL). The sensitivity of the imaging spectrometers are shown in hatched lines. The thin horizontal stubs are COBE detection limits. I do not know what the two curved lines marked as "SL" stand for. Note that a temperature of 184 K has been assigned to IPD. This is incorrect. The closer answer is 284 K and perhaps even 300 K.
(**Bottom**): Sky spectrum towards the North Ecliptic Pole (NEP) as observed by Akari IRC. From Tsumura et al. (2013). The decomposition into zodiacal light (scattered), zodiacal light (thermal emitted), Diffuse Galactic Light (DGL) are marked by the legend. DIRBE, a 10-channel photometer covering the wavelength range 1.25–240 μm, was one of the instruments of COBE.

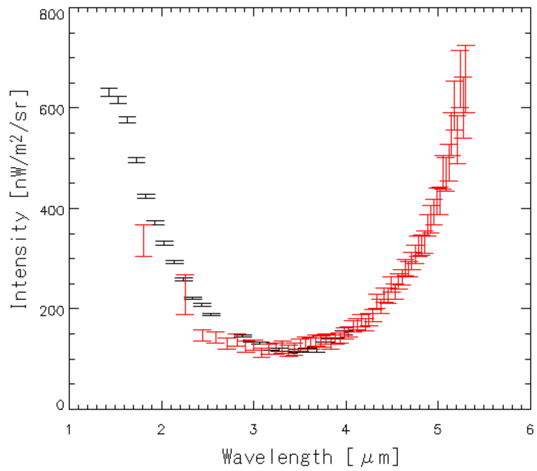

Figure 4: Akari IRC (red) & IRTS (black) spectrum of the sky at ecliptic coordinates, $(\lambda, \beta) = (130°, 20°)$. The contribution of unresolved faint stars in the IRTS spectrum was subtracted using a model. From Tsumura et al. 2013).

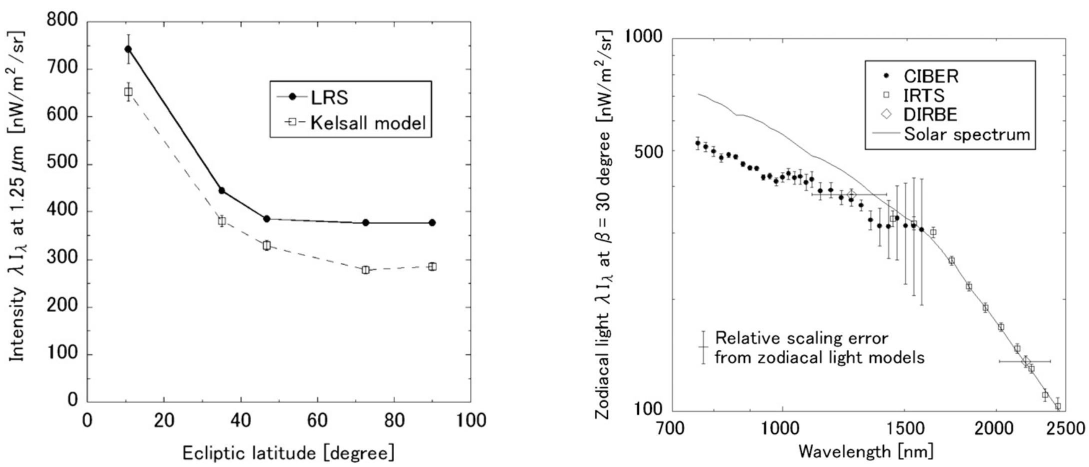

Figure 5: Left: The latitude dependence of zodiacal light at 1.25 μm (after subtracting star light), as measured by CIBER. Right: The low resolution NIR spectrum of zodiacal light as measured by CIBER. From Tsumura et al. (2010). The intensity is scaled to ecliptic latitude of 30°.