Terrestrial and Extraterrestrial Backgrounds

Astrophysics 542

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Overview

Observed light from an astrophysical source passes through:

- Local and diffuse ISM/IGM
- Solar system dust
- Terrestrial atmosphere
- Telescope optics

Each component contributes extinction, emission/scattering

- Strongly wavelength dependent
- Some components are spatially and/or temporally variable
- Beyond systematics, everything adds shot noise

Limited from the Ground

Goal of Observational Astronomy:

Measure brightnesses, positions of point or extended sources

Seeing matters.

Assume perfect calibration. Signal-to-noise ratio of a sky-limited, seeing-limited observation:

- Point source: $\sim \frac{\text{Flux}}{\text{Seeing} \times \sqrt{\text{Sky}}}$
- Extended source: $\sim \frac{\text{Flux}}{\text{Size} \times \sqrt{\text{Sky}}}$

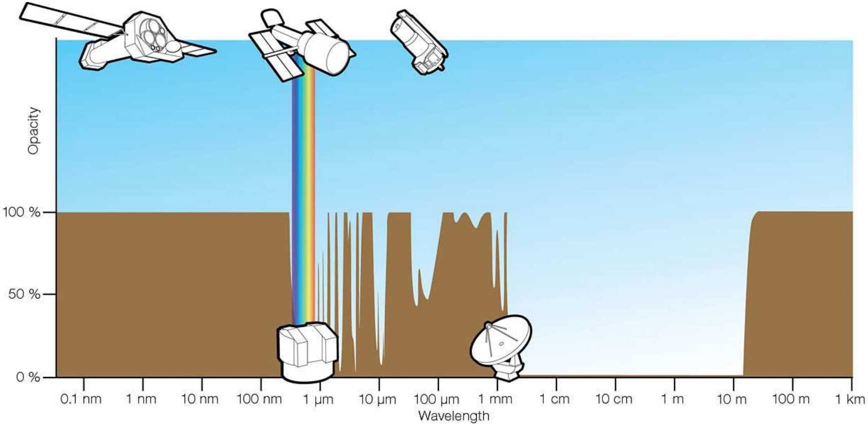
Sample limiting magnitudes: ~22 (SDSS, 2.5 m), ~28 (HSC, 8.2 m)

- Sky surface brightness limits depth of ground-based observations
- Atmospheric extinction, emission vary spatially and temporally

The limits given above assume perfect sky subtraction. Real life is worse.

Atmospheric Transmission

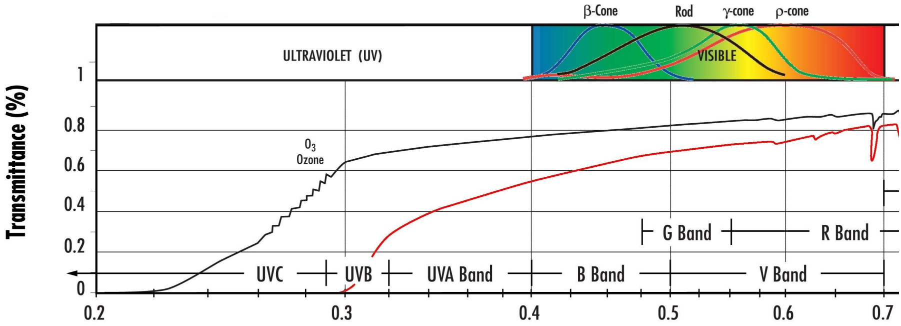
We observe where the atmosphere is transparent
Obligatory transmission spectrum (courtesy ESO):



Focus on optical and near-IR, 0.3–3 µm (UBVRIJHK)

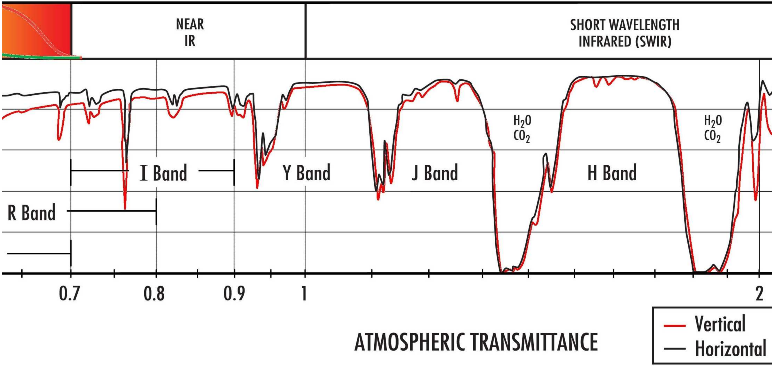
Atmospheric Transmission

MODTRAN atmospheric model, courtesy Raytheon



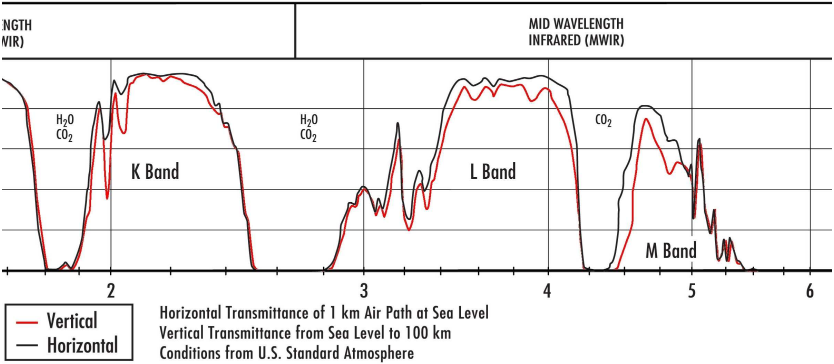
Atmospheric Transmission

MODTRAN atmospheric model, courtesy Raytheon



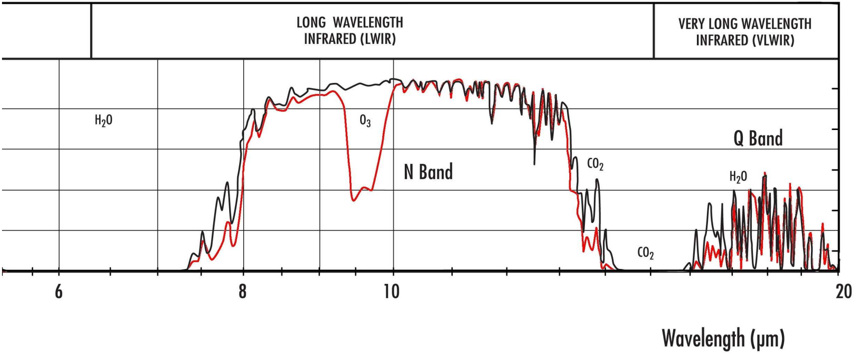
Atmospheric Transmission

MODTRAN atmospheric model, courtesy Raytheon



Atmospheric Transmission

MODTRAN atmospheric model, courtesy Raytheon



Atmospheric Transmission

Observing bands coincide with atmospheric windows

Opacity dominated by H_2O, CO_2, O_3

Terrestrial Emission

Terrestrial background is composed of:

1. Human light pollution
2. Scattered moonlight
3. Line emission, especially from O, O_2, Na, OH
4. Thermal emission at $\sim$270 K

Aurora, Airglow

ISS

Scattered Moonlight

Originally a solar spectrum (nearly a 5800 blackbody)

- Rayleigh scattering ⇒ diffuse light is very blue

Brightness depends on lunar phase, altitude, distance from source

Typical values at Mauna Kea:

Nights from New Moon	Sky Brightness (mag/arcsec^2)			
	U	B	V	R
$\lesssim 3$	21.3	22.1	21.3	20.4
$\lesssim 7$	19.2	20.9	20.7	19.9
$\lesssim 11$	17.3	19.5	19.5	19.1
$\lesssim 14$	15.0	17.5	18.0	17.9

Gemini Observatory

Airglow: Species and Reactions

OH Vibrational-Rotational Levels at ~85 km

- OH is very short-lived
- Produced by $O_3 + \gamma \rightarrow O + O_2, \quad O + H_2O \rightarrow 2OH$
- Very strong, closely spaced bands in the near-IR

[O I] auroral lines at ~90 km

- Collisionally excited forbidden lines at 5577, 6300 Å

Na D lines at ~90 km

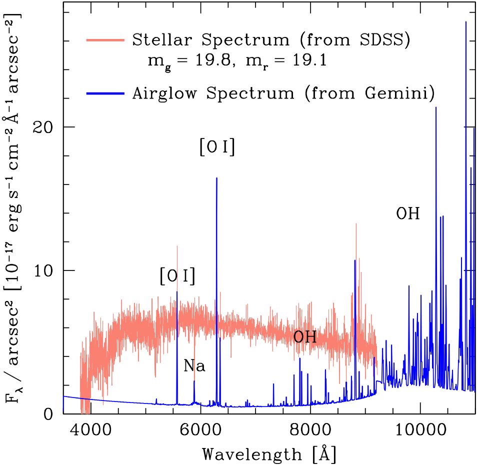
- Na from meteorites is collisionally excited

All lines vary spatially, with lunar phase, and with solar activity

Airglow Spectrum I: Optical

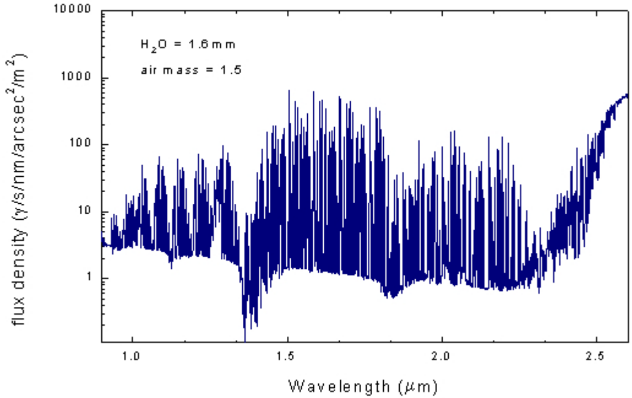
Visible spectrum: combination of

- Moonlight
- Blended O_2 lines (2600–3800 Å)
- Blended NO_2 bands (5000–6500 Å)
- Narrow line emission ([O I], Na, OH)



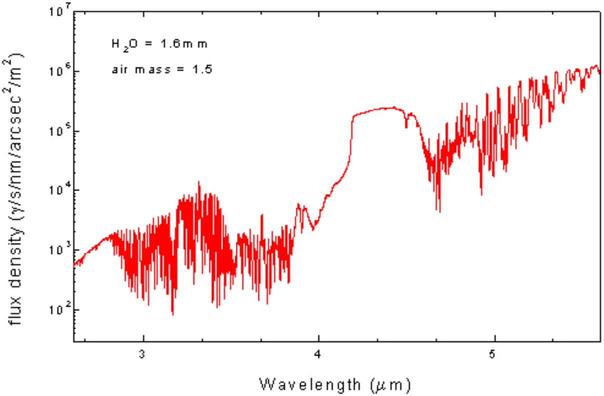
Note: stellar spectrum was taken through 7 arcsec^2 fiber

Airglow Spectrum II: Near and Mid-IR



OH bands dominate from 1–2.5 μm.
Thermal emission becomes significant at ∼2–3 μm.

Airglow Spectrum II: Near and Mid-IR



Thermal emission dominates from 3–5 μm.
Mid-IR background is much more intense.

Variability of Airglow

Image taken shortly before sunrise

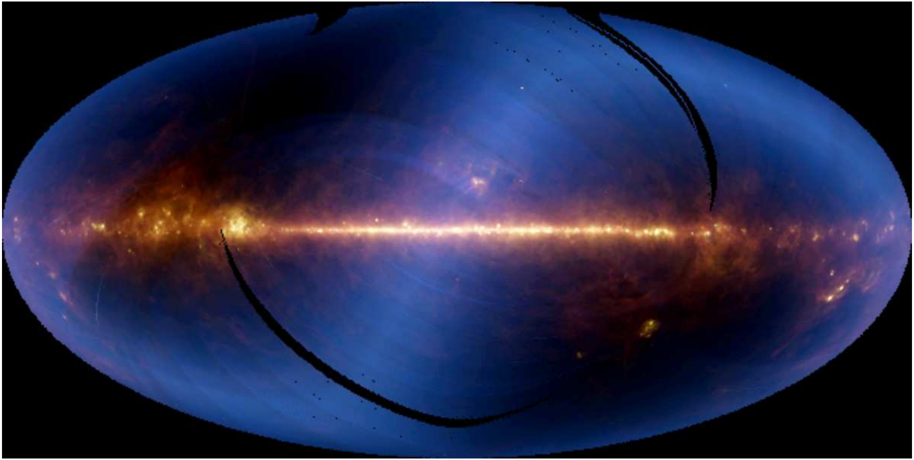
- Whitish cone of gegenschein
- Red airglow (largely OH) is banded

OH lines vary by 5–10% over 5–15 minutes

Solar wind causes much of the airglow
$\Rightarrow$ Airglow varies by factor of $\sim$2 over solar cycle!

©Doug Zubenel

The IPM and ISM



Blue = 12 μm, Red = 100 μm Credit: IRAS

Zodiacal Light

Zodiacal (interplanetary) dust at ~200 K

- Negligible extinction
- Concentrated near the ecliptic
- Particles ~100 μm, ≫ 5000 Å
  - Solar spectrum
- Thermal emission at ~10 μm, scattering in optical

Interplanetary dust cloud replenished: comets? (Nesvorný et al., 2010)

- 85–95% from Jupiter family comets
- Remainder from asteroids, long-period comets

Y. Beletsky, ESO

Zodiacal Light

Zodiacal light depends strongly on position

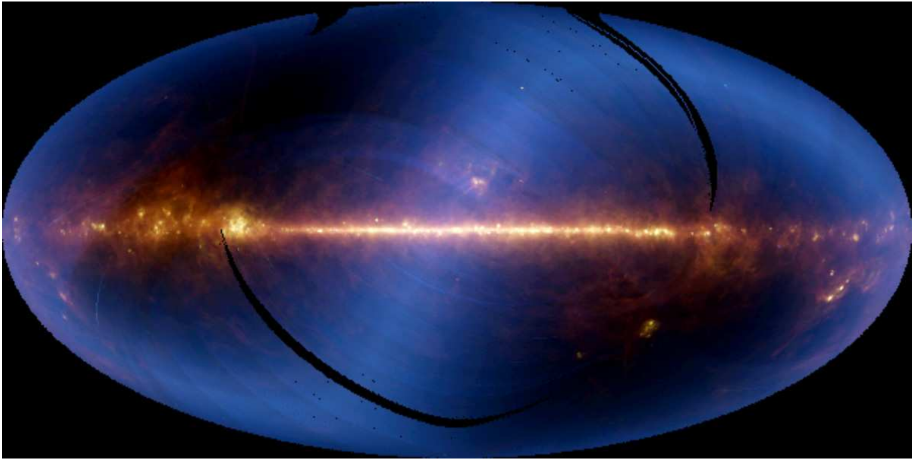
- Concentrated near ecliptic
- Strongest before sunrise, after sunset ("false dawn")

Surface brightness at zenith, dark night: ∼22–23 mag/arcsec^2

- ∼40% as strong as airglow

Surface brightness can be several times higher

The ISM



Blue = 12 μm, Red = 100 μm

Credit: IRAS

The ISM

Interstellar dust at ~20 K

- Concentrated in galactic plane
- $0.01 \lesssim \tau_{opt} \lesssim 30$
  - Extinction matters!

Dust is extensively studied to correct for extinction

- Schlegel et al. (1998): Dust map, $>$ 6000 citations
- Savage & Mathis (1979): Dust observations, $>$ 2000 citations
- Burstein & Heiles (1982): Dust map, almost 2000 citations
- Cardelli et al. (1989): Extinction curve, nearly 4000 citations
- Rieke & Lebofsky (1985): Extinction curve, nearly 2000 citations

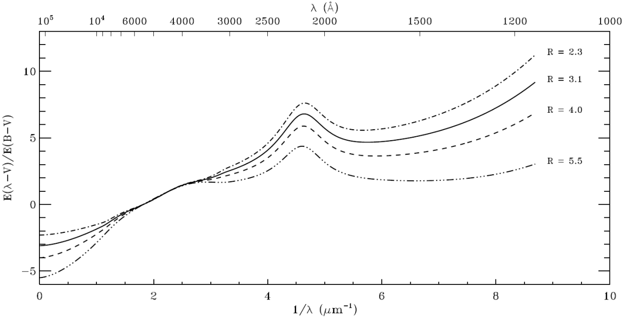
Extinction

Optical depth depends strongly on wavelength, position

Parameterize extinction by ratio of V-band optical depth to reddening:

$$R_V \equiv \frac{A(V)}{E(B-V)} = \frac{\tau_V}{\tau_B - \tau_V}$$

- Milky Way: $R_V \sim 3.1 \Rightarrow \frac{\tau_B}{\tau_V} \approx \frac{4}{3}$
- Function of grain sizes, compositions



Mapping Extinction: Making a Dust Map I

Start with blackbody formula, detailed balance:

$$F_\nu = \frac{2h\kappa_{abs}\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

$\longrightarrow$ Peak wavelength for 20 K dust $\approx$ 100 μm

Electric dipole theory, grain size $a \ll \lambda$:

- Apply a spatially uniform E-field, $\mathrm{Re}(E_0 e^{i\omega t})$
- $C_{abs} \propto \omega \cdot \mathrm{Im}(\alpha)$, $\quad \alpha =$ complex electric polarizability $\mathbf{P} = \alpha\mathbf{E}$
- Long wavelength limit: for insulators, $C_{abs} \propto \kappa_{abs} \sim \lambda^{-2} \propto \nu^2$

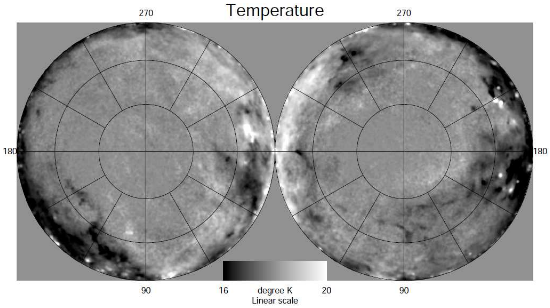
Mapping Extinction: Making a Dust Map II

First need to remove zodiacal light from far-infrared maps

- Solar system dust ~200 K, use COBE short wavelength data
- Maximize correlation of remaining light with 21 cm H I map

Next need dust temperature T:

- COBE took full-sky maps at 100 μm, 240 μm
- Two measurements of F_ν near peak $\nu \Rightarrow$ measure T



Mapping Extinction: Making a Dust Map III

$$F_\nu = \frac{2h\kappa_{abs}\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

IRAS has high-resolution (several arcminute) 100 μm data

- $F_{100\,\mu m}$, $T \Rightarrow \tau_{100\,\mu m}$, optical depth at 100 μm
- $h\nu/kT \approx 6$ for $T \approx 20$ K, $\lambda = 100$ μm $\Rightarrow F_\nu \sim \exp(-h\nu/kT)$

  $\Rightarrow \frac{d\ \ln F_\nu}{d\ \ln T} \approx -h\nu/kT \approx 6$

  $\Rightarrow \tau_{100\,\mu m} \sim F_\nu(100\,\mu m) \cdot T^{-6}$

Hard part: from $\tau_{100\mu m}$ to τ_V, τ_B

- Actually really easy *if you assume dust is spatially uniform*
- Recent efforts to do better using standard crayons:
  - Stars: Schlafly et al. (2010)
  - Passive galaxies: Peek & Graves (2010)

Correcting for Extinction

Universal Method:

- Assume Schlegel et al. (1998)'s map of $\tau_{100\,\mu\mathrm{m}}$ to be the word of God
- Assume $\tau_{100\,\mu\mathrm{m}} \propto \tau_V$ (uniform dust)
- Assume a Cardelli et al. (1989) or Fitzpatrick (1999) extinction curve with $R_V = 3.1$
- Divide by exp $\left[-\tau(\lambda)\right]$
- Cite each of the above papers

And you have corrected for interstellar extinction.

Uncertainties in extinction plague studies of large-scale structure

- Density change due to structure or Milky Way dust?

$\Rightarrow$ Big surveys done near galactic poles

ISM Emission

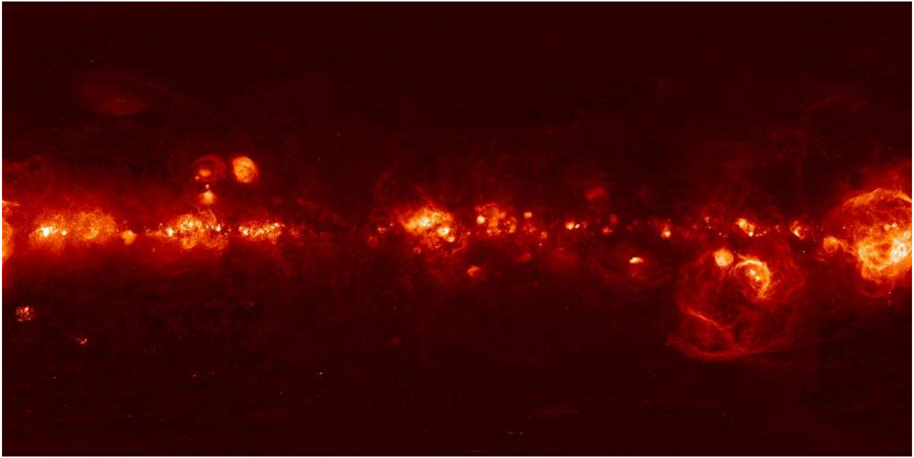
Emission by dust, warm ISM, coronal gas contribute to the sky background:

- ~20 K dust radiates at ~100 μm
- H II synchrotron radiation in radio
- Spinning dust in the microwave?
- Balmer lines, forbidden lines from H II
- X-rays from coronal gas

Generally unimportant backgrounds (except for cosmology!)

ISM Emission

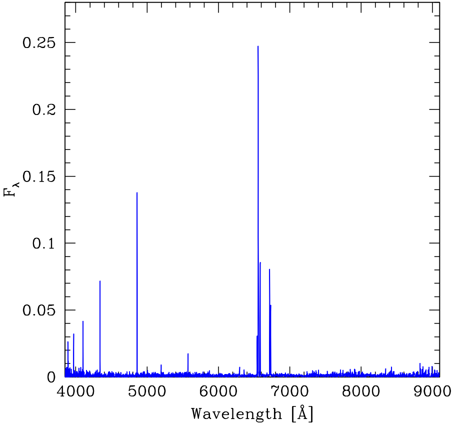
Hα map:



Finkbeiner (2003), compilation of WHAM, SHASSA, VTSS

ISM Emission

Average diffuse H-alpha emission spectrum:



Typical Hα surface brightness:

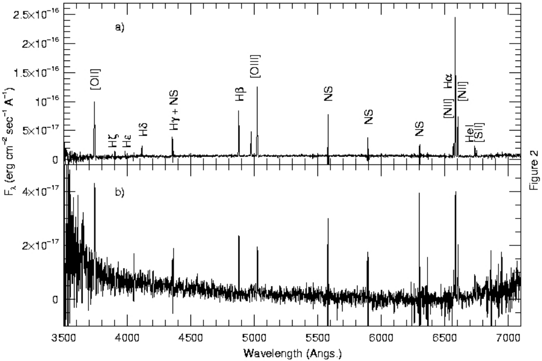
1 Rayleigh

$\sim$ 0.4 photons s^{-1} cm^{-2} arcsec^{-2}

$\sim 2 \times 10^{-16}$ erg s^{-1} cm^{-2} arcsec^{-2}

ISM Emission

Classical H II spectrum

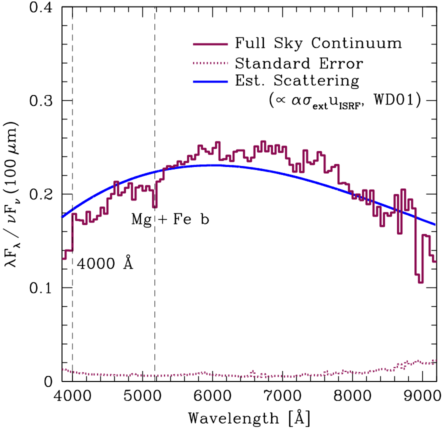


Diffuse Galactic Light

Diffuse ~20 K dust scatters starlight

⇒ Very low surface brightness diffuse light

- Only a few percent of airglow, ~25–26 mag arcsec^{-2}
- Intensity is strongly dependent on galactic latitude
- Comparable to very faint, unresolved stars, galaxies



Summary

Observers deal with atmospheric and extraterrestrial extinction, emission

- Terrestrial extinction severe in IR
- Extraterrestrial extinction can be severe in optical

Background/foreground emission varies immensely, and limits most observations

- Moonlight: up to ~18 mag arcsec^{-2} in V, worse in U, B
- Airglow: up to ~21 mag arcsec^{-2} in V, much worse in IR
- Zodiacal light: up to ~21 mag arcsec^{-2} in V, worse near ecliptic
- Diffuse galactic light: up to ~24 mag arcsec^{-2} in V along dusty lines of sight

Ideal observing conditions: zenith, solar minimum, new moon, Mauna Kea or Atacama desert

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