Absolute surface spectrophotometry of Zodiacal Light:
measurement of optical diffuse backgrounds

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Outline

1. Zodiacal light: basics
   - Scattering geometry
   - Brightness (ballpark)
   - Variation (spatial, temporal)
   - Spectrum

2. Separation of Diffuse Galactic Light (DGL) from Zodiacal Light (ZL)
   - Source & scattering geometry
   - Spectrum

3. Calibration of diffuse background measurements
   - Instrumental backgrounds
   - Absolute,
   - ... surface,
   - ... ... spectrophotometry,
   - ... ... with multiple instruments

4. Complications near Earth
   - Airglow
   - Tropospheric & ground scattering
   - Earth-orbiting telescopes

5. Summary: recipes for happiness (happier-ness)

Based on: coordinated HST-/Ground-based program to measure the EBL (Bernstein, Freedman, & Madore 2002a,b,c, 2005; Bernstein 2007)
Zodiacal light — basics

- Geometry:
Zodiacal light — basics

- Geometry:

  \[ \lambda \leq 3 \, \mu m \quad \text{scattered sunlight} \]

  \[ \lambda > 2 \, \mu m \quad \text{thermal emission} \]

Galactic Coordinates
Zodiacal light — basics ($\lambda \sim 0.5 \, \mu m$)

- Relative flux of backgrounds:

  - note: $ZL \sim 100 \times EBL$
  - $ZL \sim 10-100 \times DGL$
  - $ZL \sim$ Airglow (from ground)
Zodiacal light — basics

- Relative flux of backgrounds:

Optical = scattered sunlight
Infrared = thermal emission

*Scattered flux at $\lambda \sim 0.5$ µm does not accurately predict thermal flux at $\lambda > 2$ µm*
Zodiacal light — basics  \((\lambda \sim 0.5 \, \mu m)\)

- Flux:
  - Stable w/ solar cycle \((\varepsilon \geq 30^\circ)\)
  - Seasonal variation: view w/r/t mid-plane of dust (e.g. Helios probe)
  - Structure: dust bands, cometary trails, earth trailing structures, etc, etc

**Must be measured contemporaneously for accurate removal.**
Zodiacal light — basics ($\lambda \sim 0.5 \mu m$)

- **Flux:**
  - Stable w/ solar cycle (at $\varepsilon \geq 30^\circ$)
  - Seasonal variation: view w/r/t mid-plane of dust (e.g. Helios probe)
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$\varepsilon = \text{elongation angle}$

$\beta = \text{latitude}$

$\lambda - \lambda_0 = \text{heliocentric longitude}$

$\sim 100 \times \text{optical EBL}$

$\sim 50-100 \times \text{optical DGL near poles}$
Zodiacal light — basics \((\lambda \sim 0.5 \, \mu m)\)

- Spectrum:
  - solar
  - slightly reddened, depending on \(\varepsilon\) angle

\[ I_{6000} / I_{5000} \sim 1.07 \]

\[ 10\% \text{ per } 1000\AA \]

HST/FOS, \(\lambda - \lambda_0 \sim 130^\circ, 150^\circ, \beta = 31^\circ, 35^\circ \) (\(\Delta\text{time } \sim 3\text{ weeks}\))
Zodiacal light — basics \((\lambda \sim 0.5 \, \mu m)\)

- Spectrum:
  - solar
  - slightly reddened, depending on \(\varepsilon\) angle
  - spectral features are well preserved

  » flux can be measured from Fraunhoffer line strength (correlation, EW measurement, etc)
  » better resolution is better (limited only by sensitivity)
Diffuse Galactic Light

- **Source**: Integrated Star Light (ISL), known stellar types
Diffuse Galactic Light

- **Source:** Integrated Star Light (ISL), known stellar types
- **Scattering:** dust is spatially variable (on very small scales, 10’s of arcsec)
  
  Mean DGL flux can be estimated from simple scattering models using:
  
  - dust (or H) column density,
  - ISL intensity along L.o.S, and
  - observed extinction properties of galactic dust

$\sim (1-10) \times \text{EBL}$

Schlegel, Finkbeiner, & Davis 1998
Diffuse Galactic Light

- **Source:** Integrated Star Light (ISL), known stellar types
- **Scattering:** dust is spatially variable (on very small scales)
  - Mean DGL flux can be estimated from simple scattering models
- **If poor spatial resolution, ISL is a direct contribution.**
  - Any solar-type spectrum will be removed as ZL if spectral features are used
Diffuse Galactic Light

- **Source**: Integrated Star Light (ISL), known stellar types
- **Scattering**: dust is spatially variable (on very small scales)
  - Mean DGL flux can be estimated from simple scattering models
- **If poor spatial resolution, ISL is a direct contribution.**
  - Any solar-type spectrum will be removed as ZL if spectral features are used
  - Other stellar mix can be identified by line ratios and correlated/removed simultaneously.

![Graph](image_url)

Compared to solar.
Calibration of measurement of diffuse backgrounds

- Case study: EBL measured with HST

\[ \text{[(Observed flux) - ZL - DGL - Inst]} \] \text{DN/s/pix} = \text{EBL} \text{ DN/s/pix}
Calibration of measurement of diffuse backgrounds

- Case study: EBL measured with HST+ LCO in an HST field of view

* HST/FOS turned out not to be sensitive enough to allow a ZL measurement

* \[(\text{Observed flux}) - \text{ZL} - \text{DGL} - \text{Inst}\] \(\text{ergs/s/cm}^2/\text{sr/Å} = \text{EBL} \text{ ergs/s/cm}^2/\text{sr/Å}\)
Calibration of measurement of diffuse backgrounds

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Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds: unpredictable!
  - Absolute ...
  - Absolute surface ....
  - Absolute surface spectrophotometry

Unknown unknowns:** Dark “glow” from the MgF₂ (A/R coating) of window over CCDs

<table>
<thead>
<tr>
<th>Step</th>
<th>Statistical Uncertainty (%)</th>
<th>Systematic Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias level removal (§ 3.2)</td>
<td>&lt;0.01</td>
<td>...</td>
</tr>
<tr>
<td>Dark current removal (§ 3.3)</td>
<td>&lt;0.01</td>
<td>...</td>
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<tr>
<td>Pixel-to-pixel flat-fielding (§ 3.4)</td>
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<td>...</td>
</tr>
<tr>
<td>Slit illumination (§ 3.4)</td>
<td>...</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Point-source flux calibration (§ 3.6.1)</td>
<td>...</td>
<td>0.6</td>
</tr>
<tr>
<td>Aperture correction (§ 3.6.2)</td>
<td>...</td>
<td>0.2</td>
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** - e⁻ traps at low light levels
- charge diffusion
- flux calibration drift
- uncertain psf corrections
- uncertain scattering properties in instrument
- radioactive glasses (BK7)
- etc etc etc
Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute [flux of a star vs uniform source]
  - Absolute surface ....
  - Absolute surface spectrophotometry

DN/s/pix $\Rightarrow$ ergs/s/cm²/sr/A

DN/s/ STAR $\Rightarrow$ ergs/s/cm²/A

10" slit

How much flux/star...

... got into the slit? ~94-96%

... got to the CCD once in? ~97%

ALL of the flux/area will get in from a uniform background source.
Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute ...
  - Absolute surface ....
  - Absolute surface spectrophotometry

How wide WAS that slit?

Matters you need to know flux/area.

**Related questions:**

- What is the telescope plate scale?
- What is the spectrograph plate scale?
- Is the grating tilted (x-y plate distortion)
- Is there optical distortion?
- Are the slit jaws parallel? uniform?
  - etc etc etc
Calibration of measurement of diffuse backgrounds

• Case study:
  – Instrumental backgrounds
  – Absolute ...
  – Absolute surface ....
  – Absolute surface spectrophotometry

Sensitivity function
Extinction function

... atmospheric stability
... instrumental stability
... charge transfer, conservation, diffusion ...

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>ERROR BUDGET FOR ZODIACAL LIGHT FLUX</th>
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<td></td>
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Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute ...
  - Absolute surface ....
  - Absolute surface spectrophotometry
  - *With multiple instruments — measurements must be calibrated on an absolute scale.*

If backgrounds (100x EBL) are subtracted *after* calibration, a ~5% calibration error becomes a ~500% uncertainty in the EBL.
Calibration of measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute …
  - Absolute surface ….  
  - Absolute surface spectrophotometry
  - *With one instrument — measurement becomes relative, not absolute.*

If backgrounds (100x EBL) are subtracted *before* calibration, a ~5% calibration error becomes a ~5% uncertainty in the EBL.*

*(Unknown instrumental backgrounds are still a problem)*
Measurements from/near the Earth

- **Airglow in the optical**
  - Particularly variable within ~2 hrs sunset/sunrise
  - Variability also due to scattering (see next slides)
Measurements from/near the Earth

- **Airglow in the near IR**
  - Particularly variable
  - Bright
Measurements from/near the Earth

- Airglow in the near IR
  - Particularly variable
  - Bright
Measurments from/near the Earth

- Airglow in the near IR
  - Particularly variable
  - Bright
Measurements from/near the Earth

- Shuttle “glow” — emission from atmosphere in direction of line of sight
- “Earth shine”

- These sources further complicated by
  - Radioactive windows (MgF$_2$, BK7, etc), which respond to radiation
  - Scattering in the telescope
  - Extended PSF of off-axis sources due to mirrors (micro-ripple, dust, etc)
  - etc etc etc
Measurements from/near the Earth

- Tropospheric scattering:
  - sources include [ZL, DGL, EBL] + [Moonlight, Integrated star light]
  - Can be modeled, but not at the 1% level.

![Graph showing extinction vs. wavelength]

![Diagram of atmospheric layers and scattering]

Rebecca Bernstein
Irvine, CA — View from 5 AU

2010 March 25
Measurements from/near the Earth

- Tropospheric scattering:
  - sources include [ZL, DGL, EBL] + [Moonlight, Integrated star light]
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Measurements from/near the Earth

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  - sources include [ZL, DGL, EBL] + [Moonlight, Integrated star light]
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Measurements from/near the Earth

- **Tropospheric scattering:**
  - sources include [ZL, DGL, EBL] + [Moonlight, Integrated star light]
  - Can be modeled, but not at the 1% level.

- **Ground scattering:**
  - Albedo of soil, vegetation, etc within 100 km can contribute ~5%
  - Sources: [ZL, DGL, EBL] + [Moonlight, Integrated star light]
  - Can be modeled, but not at the 1% level.
Recipe for happier-ness includes*

- Minimize backgrounds (line of sight, location of telescope)
- Above the Earth’s atmosphere (or 5 AU, or possibly in the IR where atmospheric scattering is low)
- Use 1 instrument (for all diffuse and resolved backgrounds)
- Minimize in-instrument scatter (minimal # of optics)
- High spatial resolution (remove point source stars at ~22 AB mag V?)
- High spectral resolution (≤ 1Å)
- Avoid polarization-dependent instrumental effects (multiple mirrors)
- Include surface brightness tests prior to launch (charge transfer, trapping, instrument glow, etc)

* in measurement of diffuse backgrounds, only.
This slide intentionally left blank
Reality and measurement of diffuse backgrounds

- Case study:
  - Instrumental backgrounds
  - Absolute [flux calibration]
  - Absolute surface ....
  - Absolute surface spectrophotometry

How much light...

1. Got into the slit?
2. Got to the CCD once in?

from the (point source) standard star vs your uniform background source