The Effect of Atmospheric Extinction on LSST Photometry

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The Large Synoptic Survey Telescope (LSST)

- Study dark energy by characterizing expansion of universe → need many accurate redshifts
- 3-gigapixel CCD camera takes images of entire night sky in three days
- Broadband photometric system: collect photon flux from distant objects in six wavelength bands
- Measure relative photon flux through each band to determine the redshift of a distant object
Photometric Filter Bands

- - - Filters Only  --- Filters + CCD Quantum Efficiency

Transmittance [%]

Wavelength [nm]

U  G  R  I  Z  Y

300 400 500 600 700 800 900 1000 1100
The Problem

Accuracy of instruments is hindered by fluctuating atmospheric conditions.

How well do we need to know the parameters governing atmospheric behavior in order to minimize uncertainty in the data?
Atmospheric Extinction

- Light entering atmosphere is scattered or absorbed
- Three extinction coefficients characterize wavelength-dependent extinction distribution:

\[ A(\lambda; \alpha_R, \alpha_M, \alpha_A, \alpha_P) = \exp[-(k_R + k_M + k_A)] \]

- Rayleigh scattering by particles with radius \( \ll \lambda \):

\[ k_R(\lambda) = \alpha_R \lambda^{-4.05} \]

- Molecular absorption by water vapors (humidity-dependent), oxygen, ozone, etc:

\[ k_M(\lambda) = \alpha_M f(\lambda) \]

- Aerosol scattering by particles with radius \( \gg \lambda \) governed by spectral index \( \alpha_P \):

\[ k_A(\lambda) = \alpha_A \lambda^{-\alpha_P}, \quad \text{where} \quad 0.5 < \alpha_P < 1.5 \]

- Coefficients depend on volume density of particles.
- New distributions: variations in each \( \alpha \) up to \( \Delta \alpha = \pm 100\% \)
Extinction Distribution

- Sample Atmosphere
- Approximation

Transmittance [%]

Wavelength [nm]

- Rayleigh Scattering
- Aerosol Scattering
- Molecular Absorption

O₂
H₂O

U G R I Z Y
Quantifying Atmospheric Effects

- Set of spectral energy distributions (SEDs) for standard stars
- Dwarf stars as control group, giants and supergiants as “unknowns”
- For each star $S$:
  - $\Phi_{True}(f, S)$ – True flux through each filter band $f$:
  - $\Phi_{Meas}(f, S, A)$ – Measured flux through each filter band, with camera efficiency and atmospheric extinction $A$

- Correction factor for unknown SEDs:

$$C(f, A) = \frac{1}{N} \sum_{Dwarfs} \frac{\Phi_{True}(f, S)}{\Phi_{Meas}(f, S, A)}$$
Differential Flux

![Differential Flux Graph]

- SED
- SED + Filters
- SED + Filters + CCD QE + Atmosphere

\[\Delta \alpha_R = 0\%
\]
\[\Delta \alpha_M = 0\%
\]
\[\Delta \alpha_A = 0\%
\]
\[\Delta \alpha_P = 0\%
\]
Quantifying Atmospheric Effects II

- Compared $\Phi_{corr} = C \Phi_{Meas}$ with $\Phi_{True}$ for the unknown stars
- Least-squares fit $\Phi_{corr}$ distribution to 3rd order polynomial
- Measured bias and width of data about ideal line ($\Phi_{corr} = \Phi_{True}$)

![Graph showing corrected versus true flux with best fit line and chi-squared value]
Measured trends in mean fit bias and width with respect to ideal line, $\Phi_{Corr} = \Phi_{True}$

What percent uncertainty in atmospheric parameters will give < 0.1% uncertainty in bias and width?
Trends in Bias and Width (w.r.t. Ideal)

Changing $\alpha_R$, $\alpha_M$, $\alpha_A$:

Changing $\alpha_A$, $\alpha_P$:
Conclusions

- Rayleigh scattering parameter has a negligible effect on the signal.

- Molecular absorption parameter affects higher wavelength bands, but still allows for 33% or greater uncertainty in $\alpha_M$.

- Aerosol scattering parameter affects all wavelength bands, most significantly for small $\lambda \rightarrow$ need to measure atmospheric aerosol content with as small as 1.6% uncertainty.

- Further work (next week): measure effect of atmospheric extinction on redshifted galactic SEDs.
Acknowledgments

- Prof. David Burke for his mentorship and guidance
- Alessondra Springmann for her help with my presentation and general well-being
- SULI program coordinators
- Department of Energy
- The rest of the SULI clan for making this summer fantastic!
Backup Slides
The Nature of Dark Energy

- Some unknown form of energy that causes the expansion of the universe to accelerate
- “Size” of universe characterized by Lorentz-invariant line element:
  \[ ds^2 = -c^2 dt^2 + a^2(t) d\vec{x}^2 \]
- Scale factor \( a(t) \) was smaller in the past than it is today \((t = 0)\), measured as a function of redshift:
  \[ 1 + z = \frac{a(0)}{a(t)} \]
- Hubble parameter \( H(t) = (\dot{a}/a)^2 \) determines rate of expansion over time.
- Need accurate redshift measurements → LSST!
Changing Atmospheric Parameters

![Graph showing changes in atmospheric parameters](image)

- **Δα_R = 0%**
- **Δα_R = -80%**
- **Δα_R = 100%**
- **Δα_M = 0%**
- **Δα_M = -80%**
- **Δα_M = 100%**

**Transmittance [%]**

**Wavelength [nm]**
Accuracy in Atmospheric Parameters

for $\sigma_{Bias,\alpha} < 0.1$ [% True Flux]

<table>
<thead>
<tr>
<th>Band</th>
<th>$\sigma_R$</th>
<th>$\sigma_M$</th>
<th>$\sigma_A$</th>
<th>$\sigma_P$</th>
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<td>530</td>
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<td>122</td>
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<td>z</td>
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<td>880</td>
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<td>Y</td>
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<td>61.6</td>
<td>834</td>
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for $\sigma_{Width,\alpha} < 0.1$ [% True Flux]

<table>
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<th>Band</th>
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<th>$\sigma_M$</th>
<th>$\sigma_A$</th>
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Maximum percent uncertainty in $\alpha$ for 0.1% contribution to uncertainty in data.

Small $\sigma$ means corresponding $\alpha$ must be well understood.