IR Techniques & Adaptive Optics

Astronomy 671

Feb 6 2006

Motivation

- The Giant Segmented Mirror Telescope (GSMT), the committee’s top ground-based recommendation and second priority overall, is a 30-m-class ground-based telescope that will be a powerful complement to NGST in tracing the evolution of galaxies and the formation of stars and planets. It will have unique capabilities in studying the evolution of the intergalactic medium and the history of star formation in our galaxy and its nearest neighbors. GSMT will use adaptive optics to achieve diffraction-limited imaging in the atmospheric windows between 1 and 25 μm and unprecedented light-gathering power between 0.3 and 1 μm. The committee recommends that the technology development for GSMT begin immediately and that construction start within the decade. Half the total cost should come from private and/or international partners. Open access to GSMT by the U.S. astronomical community should be directly proportional to the investment by the NSF.
Outline

- Telescopes
  - Diffraction-limited performance
- Radiation, detection & sensitivity
- Photometry
- Backgrounds
- Seeing & Adaptive Optics

Schematics of Telescopes

- Keplerian
- Herschelian
- Newtonian
- Gregorian
- Mersenne
- Schmidt
- Bouwers-Maksutov
- Cassegrain, Ritchey-Chrétien, Dall-Kirkham
The Perfect Telescope

- Collects photons with 100% transmission
  - No obscurations
  - Zero thermal emission and zero scattered light
- No geometrical aberrations
  - Diffraction-limited performance

\[ FWHM = \frac{1.2\lambda}{D} \]
\[ \theta_D = \frac{1.2\lambda}{D} \]

Radiation Transport: Terminology

- \( I_v \) = specific intensity
  - energy from a given direction
  \[ I_v = h\nu c \frac{dn_v}{d\Omega} \]
  - number density of photons per unit frequency interval (#/cm²/Hz)

- \( F_v \) = Flux density
  \[ F_v = \int d\Omega I_v \cos\theta \]
  \[ \int d(\cos\theta) 2\pi I_v \cos\theta \quad \text{(az. sym.)} \]
  \[ \pi I_v \quad (I_v \text{ = const.)} \]

\[ d\Omega = 2\pi\sin\theta \, d\theta \]
\[ dA_{\text{proj}} = dA \cos\theta \]
Flux from a star

\[ f_v = \int d\Omega I_v \quad (\cos \theta \approx 1) \]

\[ d\Omega = \frac{dA_{\text{proj}}}{d^2} = \frac{2\pi r dr}{d^2} = -\frac{2\pi R^2 \cos \phi d(\cos \phi)}{d^2} \]

\[ \Rightarrow f_v = \frac{2\pi R^2}{d^2} \int_0^1 I_v(0, \mu) \mu d\mu \quad (\mu = \cos \phi) \]

\[ = \frac{R^2}{d^2} F_v \quad \Rightarrow f_v = \frac{R^2}{d^2} \pi B_v \quad (\text{if } I_v = B_v) \]

- \( f_v \) = monochromatic flux seen by an observer
- \( f \) = observed flux density
- \( f \) = flux seen by an observer

Signal-Limited Detection

Suppose \( P_s \) is the signal power falling onto an ideal detector of quantum efficiency, \( \eta \), the signal current is:

\[ i_s = \frac{\eta P_s}{h\nu} \quad \text{w/ noise} \quad i_N = \sqrt{2e i_s \Delta f} = \sqrt{\frac{2\eta e^2 P_s \Delta f}{h\nu}} \]

The signal-to-noise ratio is then

\[ \frac{S}{N} = \frac{i_s}{i_N} = \sqrt{\frac{\eta P_s}{2h\nu \Delta f}} \quad \Rightarrow \text{NEP} \equiv P_s \bigg|_{S/N=1} \frac{2h\nu \Delta f}{\eta} \]

\[ \Rightarrow \text{NEP} = \frac{h\nu}{\eta T} \]

Minimum detectable power (or NEP) will produce on average one photodetection per measurement time \( T \).
Background Limited Instrument Performance (BLIP)

- In addition to $P_S$ there may be an unwanted background power, $P_B$. The signal and noise currents are now

$$i_S = \frac{\eta e P_S}{h\nu} \quad i_N = \sqrt{\frac{2\eta e^2 (P_S + P_B) \Delta f}{h\nu}}$$

The signal-to-noise ratio is then

$$\frac{S}{N} = \frac{\eta P_S^2}{2 h\nu \Delta f (P_S + P_B)}$$

BLIP occurs for $P_B >> P_S$, such as looking through the atmosphere in the infrared.

$$\Rightarrow NEP = \sqrt{\frac{2 h\nu P_B \Delta f}{\eta}}$$

Point Source Sensitivity

- Letting $t = 1/(2\Delta f)$ = integration time and $\tau_a, \tau_i =$ atmospheric, instrument transmission. For BLIP

$$P_S = \frac{S}{N} \sqrt{\frac{h\nu P_B}{\eta t}}$$

Now for a point source

$$P_S = f_\lambda \Delta \lambda A_T \tau_a \tau_i \quad f_\lambda = \text{ergs/cm}^2/\text{s}/\mu\text{m}$$

$$A_T = \text{area of telescope.}$$

$$\Rightarrow f_\lambda = \frac{S}{N} \frac{1}{\Delta \lambda A_T \tau_a \tau_i} \sqrt{\frac{h\nu P_B}{\eta t}}$$

Flux density to achieve a given S/N ratio in time $t$ for BLIP.
Point Source Extraction

- How do we extract the photo-electrons for a point source?

**Options**

- Add-up signal in pixels that contain the source.
- Fit point spread function (PSF) to source (better)
- Optimizing extraction radius to get best S/N ratio (if not using PSF).
- Don’t have to get “all” the flux - but must account for this in calibration and S/N calculations.

Point Source Sensitivity (cont’d)

- Assume background emission is extended and “thermal”:
  
  \[ P_B = \varepsilon \lambda B_\lambda (T) \Delta \lambda A_T \Omega \tau_i \]

  - \( \varepsilon = \) emissivity
  - \( A_T = \) telescope area
  - \( \Omega = \) solid angle for extracting source
- If there are more sources of background, add them to get \( P_B \).
- Putting the above in for \( P_B \) gives
  
  \[
  f_\lambda = \frac{S}{N} \frac{1}{\tau_a} \sqrt{\frac{h\nu \varepsilon \lambda B_\lambda}{\eta \tau_i t \Delta \lambda A_T}} \cdot \Omega
  \]
Point Source Sensitivity (cont’d)

- Assume background emission is extended and “thermal”:

\[ P_B = \varepsilon \lambda B_\lambda (T) \Delta \lambda A_T \Omega \tau_i \]

\( \varepsilon = \) emissivity

\( A_T = \) telescope area

\( \Omega = \) solid angle for extracting source

- If there are more sources of background, add them to get \( P_B \).

- Putting the above in for \( P_B \) gives

\[
\lambda f = \frac{S}{N} \frac{1}{\tau_a} \sqrt{\frac{h \nu \varepsilon \lambda B_\lambda \Omega}{\eta \tau_i t \Delta \lambda A_T}}
\]

Scaling Laws for Point Sources

- For diffraction limited performance:

\[ A_T \Omega = 0.92 \lambda^2 \quad \Rightarrow \quad \lambda f \propto \frac{1}{D^2 \sqrt{t}} \]

- For a fixed beam size (e.g. seeing limited):

\[ \Omega = \frac{\pi}{4} \theta_B^2 \quad \Rightarrow \quad \lambda f \propto \frac{\theta_B}{D \sqrt{t}} \]
Extended Source Sensitivity

For an extended source on the sky. Let

\[ f_\lambda = I_\lambda \Omega \quad \text{I}_\lambda = \text{specific intensity} \quad \text{(ergs/cm}^2\text{/sec/sr)} \]

Then

\[ I_\lambda = \frac{S}{N \tau_a} \sqrt{\frac{h \nu \varepsilon_\lambda B_\lambda}{\eta \tau_i t}} \frac{1}{\Delta \lambda A_\Omega \Omega} \]

Scaling Laws for Extended Sources

For diffraction limited performance:

\[ A_\Omega \Omega = 0.92 \lambda^2 \quad \Rightarrow \]

\[ I_\lambda \propto \frac{1}{\sqrt{t}} \quad \text{Diffraction limited beam size} \]

\[ t \propto \left[ \frac{S}{N} \right]^2 \frac{1}{I_\lambda^2} \]

\[ \left(1.22 \frac{\pi}{4}\right)^2 = 0.92 \]

For a fixed beam size:

\[ \Omega = \frac{\pi}{4} \theta_B^2 \quad \Rightarrow \]

\[ I_\lambda \propto \frac{1}{\theta_B D \sqrt{t}} \quad \text{Fixed beam size} \]

\[ t \propto \left[ \frac{S}{N} \right]^2 \frac{1}{\theta_B^2 \lambda^2 D^2} \]

\[ \text{Independent of D!} \]
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Spectral Lines

\[ f = \frac{S}{N \tau_a} \sqrt{\frac{h \nu \epsilon_\lambda B_\lambda \Delta \lambda \Omega}{\eta \tau_t A_T}} \]

The integrated flux will be roughly: \( f = f_\lambda \Delta \lambda \) so that the sensitivity is now:

- Narrow spectral bandpass to remove extraneous flux without reducing line flux
- For best sensitivity

Techniques

Broadband Photometric Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Bands</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Johnson-Morgan-Cousins</td>
<td>UBV RI JHKLM</td>
<td>UV through IR</td>
</tr>
<tr>
<td>Hipparcos-Tycho</td>
<td>( H_p, B_p, V_T )</td>
<td>Space-based</td>
</tr>
<tr>
<td>Thuan-Gunn</td>
<td>( g, r, i, z )</td>
<td>Avoid airglow lines</td>
</tr>
<tr>
<td>SDSS</td>
<td>( u', g', r', i', z' )</td>
<td>Wide bands for faint source detection</td>
</tr>
<tr>
<td>HST</td>
<td>WFPC2, NICMOS</td>
<td>See HST website</td>
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</table>

Intermediate-band Photometric Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Bands</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strömgren</td>
<td>( uvby\beta_n \beta_n )</td>
<td>Stellar properties</td>
</tr>
<tr>
<td>DDO</td>
<td>45,42,41,38,35</td>
<td>Stellar properties</td>
</tr>
</tbody>
</table>
Example: UBV Filter System

- Defined by Johnson & Morgan in 1953
- A precise definition of these filters requires:
  - reflecting telescope with aluminized mirrors
  - an IP21 photomultiplier
  - filters for:
    - V Corning 3384
    - B Corning 5030 plus Schott GG 13
    - U Corning 9863
- Note: The shorter wavelength edge of the U band is cutoff by atmospheric absorption

UBV Filter set

- UBV filter bandpass excluding atmospheric effects
- Atmospheric effects on U filter bandpass
**Thuan and Gunn**

Thuan and Gunn filter set:

Transmission function is shown at right.

Thuan and Gunn, 1976, PASP, 88 543

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**SDSS Filters**

SDSS filter set:

Top: Filter transmissions and CCD response (thin line)

Bottom: System passbands including filter, CCD response and atmosphere

IR Filters and the Atmosphere

- Atmospheric transmission from 0.9 to 30 µm for altitude = 4.2 km, zenith angle = 30°, H₂O = 1 mm. \( \lambda/\Delta \lambda = 300 \) for 1-6 and 150 for 6-30 µm. IR filter band passes are shown. From Tokanaga.

UBVRI Filter Characteristics

<table>
<thead>
<tr>
<th>Band</th>
<th>( \lambda_{\text{eff}} ) (µm)</th>
<th>FWHM (µm)</th>
<th>( f_{\nu}^0 ) (Jy)</th>
<th>( F_{\lambda}^0 ) (W m⁻² µm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>0.365</td>
<td>0.066</td>
<td>1780</td>
<td>4.01x10⁻⁸</td>
</tr>
<tr>
<td>B</td>
<td>0.445</td>
<td>0.094</td>
<td>4000</td>
<td>6.06x10⁻⁸</td>
</tr>
<tr>
<td>V</td>
<td>0.551</td>
<td>0.088</td>
<td>3600</td>
<td>3.56x10⁻⁸</td>
</tr>
<tr>
<td>R</td>
<td>0.658</td>
<td>0.138</td>
<td>3060</td>
<td>2.12x10⁻⁸</td>
</tr>
<tr>
<td>I</td>
<td>0.806</td>
<td>0.146</td>
<td>2420</td>
<td>1.12x10⁻⁸</td>
</tr>
<tr>
<td>J</td>
<td>1.22</td>
<td>0.213</td>
<td>1570</td>
<td>3.16x10⁻⁹</td>
</tr>
<tr>
<td>H</td>
<td>1.63</td>
<td>0.307</td>
<td>1020</td>
<td>1.15x10⁻⁹</td>
</tr>
<tr>
<td>K</td>
<td>2.19</td>
<td>0.390</td>
<td>636</td>
<td>3.98x10⁻¹⁰</td>
</tr>
<tr>
<td>L</td>
<td>3.45</td>
<td>0.472</td>
<td>281</td>
<td>7.08x10⁻¹¹</td>
</tr>
<tr>
<td>M</td>
<td>4.75</td>
<td>0.46</td>
<td>154</td>
<td>2.05x10⁻¹¹</td>
</tr>
</tbody>
</table>

*Bands for Johnson-Cousins-Glass system from Binney and Merrifield, 1998. Flux is band-average for V=0 A0V star.
Stellar Colors

U-B vs. B-V color of stars

From Glass 1999

IR Filter Characteristics

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_{\text{eff}}$ (µm)</th>
<th>FWHM (µm)</th>
<th>$f_{\nu}^0$ (Jy)</th>
<th>$F_{\nu}^0$ (W m$^{-2}$ µm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>0.5556</td>
<td>…</td>
<td>3540</td>
<td>3.44×10$^{-8}$</td>
</tr>
<tr>
<td>J</td>
<td>1.215</td>
<td>0.26</td>
<td>1630</td>
<td>3.31×10$^{-9}$</td>
</tr>
<tr>
<td>H</td>
<td>1.654</td>
<td>0.29</td>
<td>1050</td>
<td>1.15×10$^{-9}$</td>
</tr>
<tr>
<td>$K_S$</td>
<td>2.157</td>
<td>0.32</td>
<td>667</td>
<td>4.30×10$^{-10}$</td>
</tr>
<tr>
<td>K</td>
<td>2.179</td>
<td>0.41</td>
<td>655</td>
<td>4.14×10$^{-10}$</td>
</tr>
<tr>
<td>L</td>
<td>3.547</td>
<td>0.57</td>
<td>276</td>
<td>6.59×10$^{-11}$</td>
</tr>
<tr>
<td>L'</td>
<td>3.761</td>
<td>0.65</td>
<td>248</td>
<td>5.26×10$^{-11}$</td>
</tr>
<tr>
<td>M</td>
<td>4.769</td>
<td>0.45</td>
<td>160</td>
<td>2.11×10$^{-11}$</td>
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<tr>
<td>8.7</td>
<td>8.756</td>
<td>1.2</td>
<td>50.0</td>
<td>1.96×10$^{-12}$</td>
</tr>
<tr>
<td>N</td>
<td>10.472</td>
<td>5.19</td>
<td>35.2</td>
<td>9.63×10$^{-13}$</td>
</tr>
<tr>
<td>11.7</td>
<td>11.653</td>
<td>1.2</td>
<td>28.6</td>
<td>6.31×10$^{-13}$</td>
</tr>
<tr>
<td>Q</td>
<td>20.130</td>
<td>7.8</td>
<td>9.70</td>
<td>7.18×10$^{-13}$</td>
</tr>
</tbody>
</table>

*From Tokonaga in Astrophysical Quantities, V-band is monochromatic $\lambda$. 

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Filters and Calibration

- The signal from a calibrator and source are compared to get the flux density of the source.
- If $R$ is the total system response the the source signal is

$$S_{cal} = R(v_0) f^c_{v}(v_0) \int \frac{R(v) f^c_{v}(v)}{R(v_0) f^c_{v}(v_0)} dv$$

- We have the equivalent equation for source.
- Define a relative response and flux with carets and dividing these we have the source flux at $v_0$:

$$f_v(v_0) = f^c_{v}(v_0) \frac{S}{S_{cal}} \int \hat{R}(v) \hat{f}^c_{v}(v) dv$$

Calibration

- Thus to calibrate a source we must know (or assume) a spectral shape and pick a wavelength.
- For instance the IRAS Point Source Catalog (PSC) assumes an underlying flux density that goes as

$$f_v \propto \nu^{-1}$$

Or equivalently

$$f_{\lambda} \propto \lambda^{-1}$$
Flux & Magnitudes

- 1 Jansky (Jy) = $10^{-26}$ W m$^{-2}$ Hz$^{-1}$ = $10^{-23}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$
- Magnitude = 2.5 log ($I/I_0$)
- AB magnitude system defines the flux for a flat-spectrum source (in $f_\nu$ space)
  - $m(\text{AB})$ is defined for a monochromatic flux, $f_\nu$ (ergs sec$^{-1}$ cm$^{-2}$ Hz$^{-1}$) as
    $$m(\text{AB}) = -2.5 \log(f_\nu) - 48.60$$
- In this system, an object with constant flux per unit frequency interval has zero color.


Infrared Backgrounds

- On earth the backgrounds come from
  - Atmosphere (OH airglow and Thermal emission)
  - Telescope emission
  - Instrument and coupling optics emission
- In space, other backgrounds are important
  - Scattered solar light
  - Zodiacal dust emission
  - Galactic dust emission
  - Distant galaxy confusion
Fig. 2.3: Left: Day sky background. A–E, scattered sunlight for various altitudes and conditions; F is a blackbody at 283 K; G is emission of water vapor and CO₂; H = bright aurora; I = haze radiance + scatter of Earth flux under different conditions. Right: Night sky background. J, city lights; A, blackbody at 283 K; B, emission of water vapor and CO₂; C, aurora; D, airglow; E, F, haze and scatter of Earth flux under different conditions; G–K, scattered moonlight for various conditions; from Stewart and Hopfield (1965).

From Glass 1999

Groundbased IR Backgrounds

From Gillett, 1987
Groundbased IR Backgrounds

From Tokanaga, 2001

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J, H, and K band backgrounds

- J, H, and K-band backgrounds as measured from Mauna Kea (Ramsay et al. 1992)
- Airglow is present with thermal emission becoming important in the K-band
- OH emission dominates airglow

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**OH Airglow**

- Due to mainly to radiation from excited levels of OH\(^-\) (hydroxyl radical)
- Excitation via: \( \text{H} + \text{O}_3 \rightarrow \text{OH}^* + \text{O}_2 \)
- Occurs at altitudes from 85-100 km
- Spatially and temporally variable
  - Spatial periods of tens of kilometers
  - Varies by \( \sim 10\% \) over periods of 5-15 minutes
  - Varies \( \sim 2 \) or more over a night
- OH suppression image systems are difficult
  - Need high spectral resolution to suppress lines

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**Space Backgrounds**

*Fig. 2.7. Specific intensity (\( \times v \)) of diffuse emission from the night sky, observed away from the galactic and ecliptic planes, from high in the Earth’s atmosphere; from Leinert et al. (1998). Mainly derived from COBE data.*

From Glass 1999
The 10µm Background Problem

✓ We can compute the number of photoelectrons generated per second by the background in a pixel:

\[ N_e = -\frac{\varepsilon_\lambda B_\lambda(T)\Delta\lambda A\Omega}{h\nu} \eta_\lambda \tau_\lambda \]

\( \eta = \text{QE} \)
\( \tau = \text{transmission} \)
\( \Omega = \text{pixel solid angle} \)
\( A = \text{telescope area} \)
\( \varepsilon = \text{emissivity} \)

At 10 µm:
\( B_\lambda(290) = 8.39 \times 10^{-4} \text{ W/cm}^2/\text{µm/sr} \)
\( h\nu = 1.99 \times 10^{-19}/\lambda(\text{µm}) \text{ joules} \)

For diffraction limited performance
\( A\Omega = \left[ (\pi/4)D (1.2/\lambda) \right]^2 = 8.88 \times 10^{-9} \lambda^2(\text{µm}) \text{ cm}^2\text{sr} \)

Take \( \varepsilon = 0.3, \Delta\lambda = 1 \text{ µm}, \eta = 0.2, \text{ and } \tau = 0.1 \)

The 10µm Problem (cont’d)

✓ Plugging in gives

\[ N_e = \frac{0.3 \times 8.39 \times 10^{-4} \times 1 \times 8.88 \times 10^{-9} \times 10^2}{1.99 \times 10^{-19}/10} \times 0.2 \times 0.1 \]
\[ = 2.25 \times 10^8 \text{ e-/sec/pixel} \]

✓ If a detector has a unit cell that can handle \( \sim 2 \times 10^5 \text{ e-/pix} \)

⇒ must read out the array at a rate of 1100 Hz to avoid saturation.

✓ Typically well size is deeper and we sample many pixels across the diffraction disk ⇒ \( \sim 50-200 \text{ Hz may be okay.} \)