Prospects for ground-based submillimeter spectroscopy:

New capabilities and challenges

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Astronomical capability of a ground-based single-aperture telescope

Background-limited sensitivity:

$$\text{NEFD} \sim \frac{h \nu (n(n+1))^{1/2}}{\eta_{\text{inst}} \eta_{\text{tel}} \eta_{\text{atm}} A_{\text{tel}} (\Delta \nu)^{1/2}}$$

$$n = \epsilon_{\text{load}} \eta_{\text{inst}} (e^{h \nu / kT} - 1)^{-1}$$

Telescope size, surface quality, site are important

→ ALMA will have large $A$

→ Single apertures can have large $\eta$’s (sky and surface)

→ Broad bandwidth and multiple spatial beams provide further capability advantage
Quantum noise not important from the ground-based mm, submm.

Ground-based mm, submm

SOFIA

Herschel

Cold space telescope
Submm Spectroscopy Platforms

5σ, 1 Hour Line Sensitivity, [W/m^2]

(Wavelength (μm))

(Raw point-source sensitivity, 5σ, 1 h)

Herschel SPIRE
Herschel PACS
SOFIA
ZEUS / JCMT
A25
Z-Spec / LMT
ALMA Bands
Submm Spectroscopy Platforms

5σ, 1 Hour Line Sensitivity, [W / m²]

Wavelength (μm)

Arrows account for time to survey full telluric window or 10%

Herschel SPIRE
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Challenges for far-IR through mm spectrometers for ground-based telescopes

*Best use of good weather depends on scientific goals*

- Spectral mapping of galactic regions, nearby galaxies:
  - Optimize number of spatial elements with sufficient spectral coverage

- Galactic nuclei, point sources w/ known redshifts:
  - Optimize sensitivity w/ a few spectral elements → maximize throughput

- Follow up of point sources w/ unknown redshifts:
  - Maximize number of simultaneous spectral resolution elements
    (Width of telluric bands presents the fundamental limit) \( \delta \nu / \nu \sim 0.1 \)

- The future → multi-object submm spectroscopy?
  - \( \delta \nu / \nu \sim 0.1--0.4 \) AND \( N_{\text{sources}} \sim 10-100 \)
Spectrometer Architectures

- **Heterodyne receivers** provide the highest spectral
  - But suffer from quantum noise: $\text{NEP}_{\text{QN}} = h \nu [\delta \nu]^{1/2}$ vs. $\text{NEP}_{\text{BG}} \sim h \nu [n(n+1)\delta \nu]^{1/2}$
  - Also offer limited bandwidth:
    - 10 GHz IF bandwidth at 1 THz gives $\nu / \Delta \nu \sim 100$

- **Fourier transform spectrometer (FTS)** couples the full
  - Sensitivity penalty

- **Fabry-Perot naturally accommodates spectral mapping**
  - But scanning time results in sensitivity penalty, esp for searching

- **Grating spectrometer is the best choice for point sources**
  - 1st order \rightarrow octave of instantaneous bandwidth
  - Good efficiency
  - But only moderate resolution
Instrument size an issue for long $\lambda$ grating systems

Conventional broadband grating systems are huge when scaled to $\lambda \sim 100 \, \mu m$

For example: SIRTF IRS Long-Hi module: 40 x 15 x 20 cm for R=600 at 37 $\mu m$.

→ For 200 $\mu m$, this module would be over 2 meters in size.

→ Much larger than required by fundamental limit: $L \sim R \times \lambda$.

*SIRTF IRS long-high module--Roellig et al. 1999*

Figure 5. The IRS long-high module optical layout.
A solution – curved grating in waveguide

Each facet positioned to provide perfect performance at two frequencies.

✈ System is diffraction-limited over the full band.
New work in submillimeter-wave broadband systems:
Z-Spec for CSO / 30 m / LMT

- Propagation confined in parallel-plate waveguide
- 2-D Geometry
- Stray light eliminated
- Curved grating diffracts and focuses
- Efficient use of space
- No additional optical elements

Bradford et al, 2003
K.A. McGreer, 1996
H.A. Rowland, 1883
Summary -- toward the future

- A very large single-aperture telescope at the world’s best site can provide a spectroscopy platform with raw sensitivity approaching that of ALMA in the short submillimeter windows
  - And large bandwidth and / or many spatial beams can provide a substantial advantage for spatial / spectral surveying
  - 200 µm window is completely unique to Atacama (or South Pole)

- Such a platform will allow probing of the dense atomic / ionized ISM at redshifts of up to 2 – near the peak of the star-formation activity.

- The submillimeter is the final technical frontier and spectrometer and detector technology will continue to improve and adapt to new scientific questions
  - Not all the photons focused in the field of the telescope are yet detected with $\delta \nu / \nu = 1000$!