Kitt Peak Condition Report

- It is dark. Flashlights are not always provided. Recommend something you can carry at all times in your pocket.
- Temperature: Freezing to 70°F
- Low humidity common, high humidity occasional
- Can do laundry while you are there (powdered detergent provided)
- Food, bedding, towels provided
- “Night lunch” sign up recommended
Interferometric Observations of Comets

Jeff Morgenthaler

Outline

• How does interference work?
  – Wave nature of light
  – Derive Bragg reflection/Fabry-Pérot/grating equation
• What is interferometry? What is not interferometry?
  – Dispersive spectroscopy vs. Interferometry
• Why is interferometry better for comets?
  – High etendue, high spectroscopic resolving power
• Interferometric instruments
  – Fabry-Pérot
  – Michelson
  – Spatial Heterodyne Spectrometer
• How we use interferometers to study comets
  – Fabry-Pérot spectra
Fig. 1.— Derivation of the basic interference equation for Bragg reflection (figure: Morgenthalmé 1998). The “scattering surfaces” could also be the mirrored plates in a Fabry-Pérot. The derivation is similar for a transmission grating oriented vertically along the heavy dashed line. Assuming $\beta$ is the output angle, the general equation for the diffraction grating is: $\sin \alpha + \sin \beta = n\lambda / D$. 

\[
\frac{n \lambda}{2D} = \sin \alpha
\]

Path difference $= n \lambda$

Side of triangle $= n \lambda / 2$
What is interferometry?

- What it is not
  - Prism (refraction)
  - Grating spectrometer – reflective or transmissive (diffraction)
  - Bragg crystal spectrometer (reflection)
  - General: Translate wavelength into an angle

- Interferometers
  - Fabry-Pérot
  - Michelson
  - Weird ones (e.g. Spatial Heterodyne Spectrometer)
  - General: Use the principle of interference to achieve an interferometric null or reenforcement over a wide range of angles
The Fabry-Pérot

- Two parallel plates of glass, distance $D$ apart
- Reflective surfaces facing each other
- Consider normal incident light
- Some light bounces off first surface, some penetrates
- Light bounces around inside, constructively interfering if $n\lambda = D$
- Some light escapes second surface for detection
Fig. 2.—Fabry-Pérot ring pattern of hydrogen-deuterium lamp.
Fig. 3.— Spectrum of a hydrogen-deuterium lamp.
Fig. 4.— Transmission grating spectrometer. Figure: S. Dodds, Rice U.
Fig. 5.— Output of a grating spectrograph (Figure: S. Shah et al., J Phys. B, 1973). Top are lines of Fe, bottom is the band structure of SrI.
Key difference between Fabry-Pérot and grating techniques

- Etendue: Effective area solid-angle product: $A\Omega$

- Concentrate on $\Omega$, which is how much $\alpha$ can change before spectrometer gets fooled into thinking it is looking at a different wavelength

- Fabry-Pérot: $\sin \alpha, \sin \beta \rightarrow 1$

- Gratings: $\sin \alpha = \sin \alpha, \sin \beta = \sin \beta$

  - $\sin \alpha + \sin \beta = n\lambda$

- For a grating, a small change of input $\alpha$ shows up immediately as an apparent change in wavelength $\lambda$

  - This is why high-resolution grating spectrographs need narrow slits

- For a Fabry-Pérot, $\alpha$ can change more before $\lambda$ appears to change

Fabry-Pérot spectroscopy (really any interferometric technique) is better for extended objects
Resolving Power

- Resolving power: \( R = \frac{\lambda}{\Delta \lambda} \)
- For one \( \lambda \), Doppler shift \( R = \frac{c}{\Delta v} \)
- Prism: Michelson’s 1907 Nobel Prize lecture credits Lord Rayleigh with a prism with \( R = 40,000 \). \( R < 4,000 \) typical
- Gratings:
  - \( R = \frac{nL}{D} \), where \( L \) is the length of the grating
  - Typical \( R \sim 3,000 – 30,000 \) (\( \Delta v \sim 100 \text{ km s}^{-1} – 10 \text{ km s}^{-1} \))
  - Monster, finely grooved, high order gratings can get \( R > 100,000 \)
- Fabry-Pérot:
  - \( R = \frac{2N_R D}{\lambda} \), where \( N_R \) is related to the reflectivity of the glass plates (typical value = 20)
  - A monster Fabry-Pérot is 6 inches in diameter
  - Comet studies: \( R = 30,000 – 100,000 \) (\( \Delta v \sim 10 \text{ km s}^{-1} – 3 \text{ km s}^{-1} \))
  - Gonzalo Hernandez mesospheric winds \( R = 10^6 \)
Michelson Interferometer: Fourier transform device

- Like an opened-up Fabry-Pérot
- Input light is split by a half-slivered mirror
- Resulting beams directed towards two mirrors which reflect the light back toward the beam splitter
- Light recombines
- If path is precisely the same, there is a maximum in output
- One mirror is moved and the output monitored
- As the path difference moves through integer multiples of a particular wavelength present in the source, interference will occur
- That interference fringe will repeat every time the mirror moves by one wavelength
- Fourier transform of fringe signal vs. path difference plot gives source spectrum
- Resolving power depends on how far the mirror moves. S/N is built up by multiple passes
Fig. 6.— Michelson interferometer.  (Figure credit Leonardo Motta, http://scienceworld.wolfram.com)
Spatial Heterodyne Spectrometer (SHS)

- Michelson on steroids and ludes
- Mirrors are replaced by gratings
  - Wavefront angles depend on wavelength: light is spraying everywhere
  - One wavelength ("the tune") will follow the Michelson path around both arms
  - Slightly different wavelength will be angled and cross in an ‘X’ pattern
  - Constructive interference of crossing wavefronts makes fringes
- No moving parts
- High etendue, like Fabry-Pérot
Fig. 7.— Spatial Heterodyne Spectrometer (Harlander et al. 2003).
Fig. 8.— SHS fringe pattern. Photo credit Yunlong Lin and the SHOW project.
Real Fabry-Pérot data and science

- Spectral mode (rings)
  - Get total flux coming from source (e.g. comet, atmosphere)

- Image mode
  - Narrow-band filter imaging
  - Only way to isolate some emission lines (e.g., [O I] 6300 Å)

- Data cubes (see Walt’s movies of H₂O⁺)
  - Find projected velocity distribution
Fig. 9.— Fabry-Pérot observations of Hydrogen Balmer-α in comet Hale-Bopp (Morgen théaler et al. 2002).
Fig. 10.— Fabry-Pérot observations of Hydrogen Balmer-α in comet Hale-Bopp, converted to spectrum (Morgenthaler et al. 2002).
Fig. 11.— Fabry-Pérot observations of [O I] 6300 Å in comet Hale-Bopp, showing band-passes used for image-mode observations (Morgenthaler et al. 2001).
Fig. 12.—Fabry-Pérot image-mode observations of [O I] 6300 Å and nearby continuum in comet Hale-Bopp (Morgenthaler et al. 2001).
Fig. 13.—Narrow-band image in the OH molecular band at 3080 Å (Harris et al. 2002).
Fig. 14.—Radial profiles of narrow-band images of comet Hale-Bopp (Morgenthaler et al. 2001).
Comet Hale-Bopp

Fig. 15.—Hale-Bopp H$_2$O$^+$ velocity map.
REFERENCES


