Near-Infrared Observations of Planets

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Plan for Today

• physics of radiation generation
• techniques (imaging (AO?), spectroscopy)
• challenges in observing planets
• examples:
  • terrestrial planets
  • gas giants
Energy Generation

- what are we seeing when we observe solar system objects in the NIR?
  - reflected sunlight
  - blackbody radiation
- relative amount of each depends on target (temperature)
Molecular Spectroscopy

• 3 types of transitions:
  • rotational, vibrational, electronic

In molecular spectroscopy it is common to report energies in wavenumbers, $\tilde{E}$ cm$^{-1}$, rather than Joules ($E$). The two are related through

$$\tilde{E} = E/\hbar c$$

where the Planck constant, $\hbar = 6.626 \times 10^{-34}$ J s and the speed of light must be taken in cm s$^{-1}$:

$c = 2.998 \times 10^{10}$ cm s$^{-1}$, of course.

The reason for this convention is that the resonance condition for a photon of frequency $\nu$ s$^{-1}$ to bring about a transition between two states separated by an energy $\Delta E$ J is $h\nu = \Delta E$, so the photon's wavenumber, $\tilde{\nu} = \nu/c = \Delta E/\hbar c$ is proportional to the energy difference and has convenient orders of magnitude for most spectroscopic applications.
Rotational Spectroscopy

The energy levels of a diatomic molecule A-B, treated as a rigid rotor are given in terms of a quantum number, \( J \):

\[
\tilde{E}_J = BJ(J + 1), \quad J = 0, 1, 2, \ldots
\]

where the rotational constant (in \( \text{cm}^{-1} \)) is

\[
B = \frac{\hbar}{8\pi^2 I}, \quad I = \mu r^2, \quad \mu = \frac{m_A m_B}{m_A + m_B}
\]

and \( I \) is the moment of inertia of the molecule in terms of its reduced mass, \( \mu \), and bond length, \( r \).

There is no zero-point energy (\( \tilde{E}_0 = 0 \)), and each energy level has degeneracy

\[
g_J = 2J + 1
\]

For a molecule to show a pure rotation spectrum it must have a permanent electric dipole moment. The selection rule on \( J \) is then \( \Delta J = \pm 1 \), and the absorption spectrum is observed as lines (equally spaced by \( 2B \)) in the microwave region of the electromagnetic spectrum:
Vibrational Spectroscopy

The energy levels of a diatomic molecule treated as a harmonic oscillator are given in terms of a quantum number, \( v \) :

\[
\hat{E}_v = \tilde{\nu}(v + \frac{1}{2}), \quad v = 0, 1, 2, \ldots
\]

where the fundamental vibrational wavenumber, \( \tilde{\nu} \), is given (in \( \text{cm}^{-1} \)) by

\[
\tilde{\nu} = \frac{1}{2\pi c} \sqrt{\frac{k}{\mu}}
\]

where \( k \) is the bond force constant. There is zero-point energy (\( \hat{E}_0 = \frac{1}{2} \tilde{\nu} \)), and the energy levels are non-degenerate (\( g_v = 1 \)).

To show an infrared vibrational spectrum, there must be a change in the molecule's dipole moment on vibration. The selection rule on \( v \) is then \( \Delta v = \pm 1 \), so the absorption spectrum consists of a single line at a wavenumber

\[
\tilde{\nu}_{v+1-v} = \hat{E}_{v+1} - \hat{E}_v = \tilde{\nu}
\]

transitions seen in IR
Ro-vibrational Transitions

At high-resolution, vibrational transitions appear in spectra as bands of lines due to rotational transitions \((J' \leftarrow J'')\) occurring simultaneously with the change in vibrational quantum number \((v' \leftarrow v'')\).

The energy levels can be written

\[
\tilde{E}_{v,J} = \tilde{\nu}(v + \frac{1}{2}) + BJ(J + 1)
\]

and the selection rule \(\Delta J = \pm 1\) (for closed-shell diatomics) gives rise to two branches of lines: R \((\Delta J = +1\) ) and P \((\Delta J = -1\) ). So the band structure of a vibrational transition \((v + 1 \leftarrow v\) ) shows lines at:

\[
\tilde{\nu}_{P(J)} = \tilde{\nu} - 2BJ \quad \text{and} \quad \tilde{\nu}_{R(J)} = \tilde{\nu} + 2B(J + 1)
\]

In the notation \(P(J)\) and \(R(J)\), the quantum number \(J\) refers to the lower state of the transition.
Techniques: Imaging

• need to observe in Earth’s atmospheric windows (e.g. J, H, K)

• possibly also convolve this with target’s own atmospheric windows
Commonly Used Facilities

- IRTF/NSFCAM2 (Mauna Kea)
- Keck/NIRC (Mauna Kea)
- HST/NICMOS
- APO/GRIM, NICFPS
Adaptive Optics

• basic idea: correct wavefront distortions using a deformable secondary mirror

• can achieve better correction in NIR (why?)

http://www.ctio.noao.edu/~atokovin/tutorial/intro.html
AO Lingo

• PSF = point spread function

• Strehl ratio $S = P/P_0 = \text{central intensity of PSF}/\text{central intensity of Airy function}$

• $r_0 =$ Fried’s parameter (atmospheric coherence length) - scales as $\lambda^{\frac{6}{5}}$

• seeing: $\beta = 0.98\lambda/r_o$ so $S = (r_0/D)^2$

• isoplanatic angle: $\theta_0 = 0.31 \frac{r_0}{h}$ h=characteristic turbulence altitude (~ 5 km)
AO Observations of Planets

Titan

- 1st night 2/26/99
  - H band

- 1st night 2/26/99
  - ? band

- 2nd night 2/27/99
  - H band

- 2nd night 2/27/99
  - ? band

Haumea (2003 EL₆₁)

762 Pulcova (CFHT)
NIR Spectroscopy

- for atmospheres, sensing reflected sunlight and/or atmospheric absorptions
- for surfaces, sensitive to mineralogy (e.g. hydrated minerals on Mars)
Figure 3. Saturn effective pressure levels from 1—2.5 μm. The depth at which atmospheric gas opacity reaches unity for a two-way nadir path is depicted as a function of wavelength. The depths of cloud and haze layers can be effectively constrained over four orders of magnitude of pressures in this spectral region. Here, the correlated-K approach (Goody et al. 1989; Lacis and Oinas 1991) is used to determine the effective CH₄ gas opacity, using CH₄ absorption coefficients of Baines et al. (1993) interpolated for the temperature/pressure structure of Saturn given a CH₄ mixing ratio of 0.0045 after Courtin et al. (1984). The pressure-induced
Cassini/VIMS
Atmospheric Absorptions in Saturn and Titan

(a)

Saturn

Titan

Wavelength (µm)

This and previous slide from Baines et al. (2005)
Challenges

- telluric vs. target features in spectra
- AO doesn’t work well for very extended objects (although recently improved)
- target may completely fill slit; need to offset to get sky spectra
Venus Imaging

Venus Night Side: GSFC AOTF at APO 3.5 m Telescope, 16 Dec. 1997

looking in different atmospheric “windows” probes different depths in Venus’ cloud decks

Thursday, April 9, 2009
Venus Spectroscopy

CO variation with latitude

Marcq et al. (2005)

CO variation with latitude
Methane on Mars

Mumma et al. (2009)
Mars Imaging

looking for spatial variations in CO$_2$ and H$_2$O frosts

Thursday, April 9, 2009
Jupiter’s NIR Spectrum

Taylor et al. (2004)
Optical + NIR + IR
Jupiter’s Cloud Structure

West et al. (2004)
Observing at IRTF
IRTF Telescope

[Images of the IRTF Telescope and its surroundings]
CSHELL spectra of Jupiter IRTF, 2004
Saturn

SpeX Day Side Spectra at 3 Southern Latitudes, 17 January 2006

Wavelength (microns)

Flux (Jy)

-37.85
-26.67
-12.42
Uranus

- remember Jim’s Pizza Lunch?
- using NIR spectroscopy to improve understanding of ice giants’...
  - cloud structure
  - methane abundance