## Spectroscopy: The Study of Squiggly Lines

[Astronomical Distances] [Basics of Light] [Tools for Light Analysis] [Measuring Light] [Electromagnetic Spectrum] [Fun with Units] [Atmospheric Transmission] [Space Links]

#### What are Those Squiggly Lines?

Using Light to Learn About the Universe



## Spectroscopy in Curiosity's site selection



### **Electron Orbital Transitions**



 In the visible/near-infrared, spectra are dominated by transitions between *d* orbitals in transition metals

#### **Electron Orbits**



# **Periodic Table of the Elements**



Atomic masses in parentheses are those of the most stable or common isotope.

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57 28 La 18 Lanthanum 2 138.9055	58 Ce 1 Cerium 140.116	2 8 18 19 2	59 28 Pr 18 Praseodymium 2 140.90765	60 28 Nd 18 Neodymium 2 144.24	61 28 Pm 18 Promethium 2 (145)	62 28 Sm 18 Samarium 2 150.36	63 28 Eu 18 Europium 2 151.964	64 28 Gd 18 Gadolinium 2 157.25	65 28 Tb 18 7erbium 2 158.92534	66 28 Dy 18 Dysprosium 2 162.500	67 28 Ho 18 Holmium 29 164.93032	68 28 Er 18 Erbium 2 167.259	69 28 Tm 18 311 Thulium 2 168.93421	70 28 Yb 18 Ytterbium 2 173.04	71 Lu Lutetium 174.967	
89 2 Actinium 9 (227) 2	90 Th <sup>1</sup> <sup>3</sup> <sup>1</sup> <sup>1</sup> <sup>1</sup> <sup>2</sup> <sup>2</sup> <sup>2</sup> <sup>2</sup> <sup>2</sup> <sup>2</sup> <sup>1</sup>	2 8 18 32 18 10 2	91 28 Pa 18 Protactinium 9 231.03588 2	92 28 U 18 Uranium 9 238 02891 2	93 28 Np 18 Neptunium 9 (237) 2	94 28 Pu 18 22 24 Plutonium 2	95 28 Am 18 Americium 8 (243) 2	96 28 Cm 18 32 25 Curium 9 (247) 2	97 28 Bk 32 Berkelium 8 (247) 2	98 28 Cf 32 Californium 8 (251) 2	99 2 Es 32 Einsteinium 8 (252) 2	100 28 Fm 18 Fermium 20 (257) 2	101 28 Mc 18 Mendelevium 8 (258) 2	102 28 No 18 Nobelium 8 (259) 2	103 Lr Lawrenciu (262)	un

Note: The subgroup numbers 1-8 were adopted in 1984 by the tremational Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those umbers.

## Energy Level Splitting in Solids: Part 1



In a free atom these have equal energy, but not in a crystal...

## Energy Level Splitting in Solids: Part 2



Distortion of some "sites" in a crystal  $\rightarrow$  further energy splitting  $\rightarrow$  diagnostic of mineralogy

#### Fe electronic transitions in olivine, pyroxene



#### Spectroscopy: linking meteorites to asteroids





## **Electron Orbital Transitions**



• In the visible/near-infrared, spectra are dominated by transitions between *d* orbitals in transition metals

 Electrons can also be transferred from one atom to another one nearby

## Electron charge transfer: why Mars is red!



## Semiconductor physics



## Band gap transition absorptions



Yellow color of sulfur (e.g., on Io) due to band gap transitions

### Molecular vibrations



### Water vibrations: ice vs. hydrated minerals

- A D are Europa,
- E is Ganymede,
- F is model ice spectrum



# Europa spectral variations



## Europa's hydrates: acid or salts?



#### Hydrated salt spectra



#### Hydrated salts on Mars: e.g., bassanite



# Spectroscopy-guided roving



# Peroxide, CO<sub>2</sub> and more on Europa (and Ganymede, Callisto)



# Kuiper belt objects: spectrally diverse



# Organic molecules

Identified on Callisto, Ganymede, Iapetus, Phoebe, ...



# Amides: Spectral biomarkers?

- Link amino acids in proteins, with distinct IR signature → biomarker
- NIR bands ambiguous; stronger fundamental bands at ~6 µm





# **Methane on Mars?**

Krasnopolsk y et al. (2004)

#### Methane release: Northern summer



Mumma et al. (2009)

#### **Methane on Earth – mainly biogenic**



Atreya et al. (2007)

#### **History of CH<sub>4</sub> observations**

- All based on IR absorption lines near 3.3 or 7.7 µm
- Upper limits 20–50 ppbv from Viking, ground-based pre-2003 (Maguire 1977; Krasnopolsky et al. 1997; Lellouch et al. 2000)
- Mumma et al. ground-based (reported 2003, published 2009): 0–50 ppb range
- Krasnopolsky et al. ground-based (2004): 10 ppb global avg.
- Formisano et al. MEx-PFS (2004): 0–30 ppb range
- Fonti & Marzo TES (2010): 0–70 ppb range

#### The challenge of ground-based observing



- Terrestrial CH<sub>4</sub> ~1750 ppb, ~10<sup>4</sup> x Martian abundance!
- Doppler shifts up to 18 km/s
  → line offsets up to 0.2 nm

#### Mumma et al. (2009) ground-based



Three lines resolved; no unidentified spectral features

Discovered new CO<sub>2</sub> band system (Villanueva et al. 2008) overlapping lines analyzed by Krasnopolsky and PFS team

#### Mumma et al. (2009): seasonal, spatial variations



West Longitude

#### **Curiosity's SAM Tunable Laser Spectrometer**



#### **Curiosity's SAM Tunable Laser Spectrometer**



Transmission