Light and Atoms

ASTR 170 • 2010 S1 • Daniel Zucker • E7A 317
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Overview

We’ve looked at telescopes, spectrographs and spectra – now let’s find out how they can tell us what we want to know:

• What is an atom?

• How do atoms interact with light?

• What kinds of spectra do you see when you look at objects in the sky?

• What can you learn from a star’s spectrum?
The Power of Starlight

Just by analyzing the light received from a star, astronomers can retrieve information about a star’s

1. Total energy output
2. Surface temperature
3. Radius
4. Chemical composition
5. Velocity relative to Earth
6. Rotation period
In astronomy, we cannot perform experiments with our objects (stars, galaxies, ...).

The only way to investigate them is by analyzing the light (= radiation) which we observe from them.
Light as a Wave (1)

- Light waves are characterized by a wavelength $\lambda$ and a frequency $f$.
- $f$ and $\lambda$ are related through $f = \frac{c}{\lambda}$

\[ c = 3 \times 10^8 \text{ m/s} \]
Light as a Wave (2)

- Wavelengths of light are measured in units of nanometers (nm) or Ångströms (Å):

  \[ 1 \text{ nm} = 10^{-9} \text{ m} \]

  \[ 1 \text{ Å} = 10^{-10} \text{ m} = 0.1 \text{ nm} \]

*Visible light* has wavelengths between 4000 Å and 7000 Å (= 400 – 700 nm).
Different colours of visible light correspond to different wavelengths.
Light as Particles

• Light can also appear as particles, called photons (explains, e.g., photoelectric effect).

• A photon has a specific energy $E$, proportional to the frequency $f$:

$$E = hf$$

$h = 6.626 \times 10^{-34} \text{ J*s}$ is the Planck constant.

The energy of a photon does not depend on the intensity of the light!
The Electromagnetic Spectrum

Wavelength

Frequency

Need satellites to observe

High flying air planes or satellites
Atomic Structure

- An atom consists of an *atomic nucleus* (protons and neutrons) and a cloud of electrons surrounding it.

- Almost all of the mass is contained in the nucleus, while almost all of the space is occupied by the electron cloud.
Nuclear Density

If you could fill just a teaspoon with material as dense as the matter in an atomic nucleus, it would weigh ~ 2 billion tonnes.
Different Kinds of Atoms

- The kind of atom depends on the number of protons in the nucleus.

- Most abundant: Hydrogen (H), with one proton (+1 electron)

- Next: Helium (He), with 2 protons (and 2 neutrons + 2 el.)

Different numbers of neutrons ↔ different isotopes
Electron Orbits

- *Electron orbits* in the electron cloud are restricted to very specific radii and energies.

\[ r_1, E_1, r_2, E_2, r_3, E_3 \]

- These characteristic electron energies are different for each individual element.
Atomic Transitions

• An electron can be kicked into a higher orbit when it absorbs a photon with exactly the right energy.

• The photon is absorbed, and the electron is in an excited state.

• All other photons pass by the atom unabsobered.

(Remember that $E_{ph} = h*f$)
Colour and Temperature

Stars appear in different colours,
from blue (like Rigel)
via green / yellow (like our sun)
to red (like Betelgeuse).

These colours tell us about the star’s temperature.
Black Body Radiation (1)

The light from a star is usually concentrated in a rather narrow range of wavelengths. The spectrum of a star’s light is approximately a thermal spectrum called a **black body spectrum**.

A perfect black body emitter would not reflect any radiation. Thus the name “black body”.
Two Laws of Black Body Radiation

1. The *hotter* an object is, the *more energy* it emits:

\[ F = \sigma T^4 \]

where

- \( F \) = Energy Flux =

\[ = \text{Energy given off in the form of radiation, per unit time and per unit surface area [J/s/m}^2\text{];} \]

- \( \sigma \) = Stefan-Boltzmann constant
Two Laws of Black Body Radiation

2. The peak of the black body spectrum shifts towards shorter wavelengths when the temperature increases.

→ Wien’s displacement law:

\[ \lambda_{\text{max}} \approx \frac{3,000,000 \text{ nm}}{T_{\text{K}}} \]

(where \( T_{\text{K}} \) is the temperature in Kelvin)
Stellar Spectra

The spectra of stars are more complicated than pure blackbody spectra. They contain characteristic lines, called absorption lines.

With what we have learned about atomic structure, we can now understand how those lines are formed.
Kirchhoff’s Laws of Radiation (1)

1. A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a continuous spectrum.
Kirchhoff’s Laws of Radiation (2)

2. A low-density gas excited to emit light will do so at specific wavelengths and thus produce an emission spectrum.

- Light excites electrons in atoms to higher energy states.
- Transition back to lower states emits light at specific frequencies.
- Emission spectrum.
Kirchhoff’s Laws of Radiation (3)

3. If light comprising a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum. Light excites electrons in atoms to higher energy states. Frequencies corresponding to the transition energies are absorbed from the continuous spectrum.
The Spectra of Stars

The inner, dense layers of a star produce a continuous (blackbody) spectrum.

Cooler surface layers absorb light at specific frequencies.

=> Spectra of stars are absorption spectra.
Analyzing Absorption Spectra

- Each element produces a specific set of absorption (and emission) lines.
- Comparing the relative strengths of these sets of lines, we can study the composition of gases.

### TABLE 7-2
The Most Abundant Elements in the Sun

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage by Number of Atoms</th>
<th>Percentage by Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>91.0</td>
<td>70.9</td>
</tr>
<tr>
<td>Helium</td>
<td>8.9</td>
<td>27.4</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.008</td>
<td>0.1</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.07</td>
<td>0.8</td>
</tr>
<tr>
<td>Neon</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.003</td>
<td>0.06</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.003</td>
<td>0.07</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.002</td>
<td>0.04</td>
</tr>
<tr>
<td>Iron</td>
<td>0.003</td>
<td>0.1</td>
</tr>
</tbody>
</table>

By far the most abundant elements in the Universe
Lines of Hydrogen

Most prominent lines in many astronomical objects: **Balmer lines of hydrogen**
The Balmer Lines

Transitions from 2nd to higher levels of hydrogen

The only hydrogen lines in the visible wavelength range

2nd to 3rd level = H_α (Balmer alpha line)
2nd to 4th level = H_β (Balmer beta line)
...

n = 1
n = 2
n = 3
n = 4
n = 5
Observations of the H-Alpha Line

Emission nebula, dominated by the red $H\alpha$ line
Absorption Spectrum Dominated by Balmer Lines

Modern spectra are usually recorded digitally and represented as plots of intensity vs. wavelength.

![Absorption Spectrum Diagram]

- $H_{\gamma}$
- $H_{\beta}$
- $H_{\alpha}$

Wavelength (nm)
The Balmer Thermometer

Balmer line strength is sensitive to temperature:

Most hydrogen atoms are ionized => weak Balmer lines

Almost all hydrogen atoms in the ground state (electrons in the \( n = 1 \) orbit) => few transitions from \( n = 2 \) => weak Balmer lines

Hydrogen Balmer lines are strongest for medium-temperature stars.
Measuring the Temperatures of Stars

Comparing line strengths, we can measure a star’s surface temperature!

The lines of each atom or molecule are strongest at a particular temperature.
Spectral Classification of Stars (1)

Different types of stars show different characteristic sets of absorption lines.
### Spectral Classification of Stars (2)

#### Mnemonics to remember the spectral sequence:

<table>
<thead>
<tr>
<th>Spectral Class</th>
<th>Approximate Temperature (K)</th>
<th>Hydrogen Balmer Lines</th>
<th>Other Spectral Features</th>
<th>Naked-Eye Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>40,000</td>
<td>Weak</td>
<td>Ionized helium</td>
<td>Meissa (O8)</td>
</tr>
<tr>
<td>B</td>
<td>20,000</td>
<td>Medium</td>
<td>Neutral helium</td>
<td>Achernar (B3)</td>
</tr>
<tr>
<td>A</td>
<td>10,000</td>
<td>Strong</td>
<td>Ionized calcium weak</td>
<td>Sirius (A1)</td>
</tr>
<tr>
<td>F</td>
<td>7500</td>
<td>Medium</td>
<td>Ionized calcium weak</td>
<td>Canopus (F0)</td>
</tr>
<tr>
<td>G</td>
<td>5500</td>
<td>Weak</td>
<td>Ionized calcium medium</td>
<td>Sun (G2)</td>
</tr>
<tr>
<td>K</td>
<td>4500</td>
<td>Very weak</td>
<td>Ionized calcium strong</td>
<td>Arcturus (K2)</td>
</tr>
<tr>
<td>M</td>
<td>3000</td>
<td>Very weak</td>
<td>TiO strong</td>
<td>Betelgeuse (M2)</td>
</tr>
</tbody>
</table>

- Oh
- Be
- A
- Fine
- Girl/Guy
- Kiss
- Me
- Only
- Bad
- Astronomers
- Forget
- Generally
- Known
- Mnemonics
Stellar Spectra

Surface temperature
The Composition of Stars

From the relative strength of absorption lines (carefully accounting for their temperature dependence), one can infer the composition of stars.
Class Announcements

• Assignment #1 given out today (Wednesday, 3 March), due Friday, 12 March
• Lecture PDFs and other materials available from: web.science.mq.edu.au/~zucker/Astronomy_170.html
• First practicals today (immediately after lecture, E7B 213/217, 11:00 – 2:00)
• Sign up sheets for Observatory practicals will be available next week
• Physics/Astronomy & Astrophysics/Photonics BBQ next Thursday (11 March) 12:30 – 2:00
PHYSICS, ASTRONOMY & ASTROPHYSICS AND PHOTONICS

BBQ

Who: ALL Physics, Astronomy & Astrophysics and Optical Technology students, postgrads and staff.

When: Thursday 11th March (Week 3), 12.30 pm – 2pm

Where: Adjacent to the North balcony of E7B, near the First Year Physics Labs

Why: An opportunity for students of these degrees to meet informally with each other & staff, and to ask questions, pass on views and experience etc.

Did we mention that:

FOOD AND BEVERAGES ARE BEING PROVIDED