Light

- Light (electromagnetic radiation) is the medium through which we have learned most of what we know about the astronomical universe.
- For example, this is the visible spectrum of the Sun:

From it, we can learn a lot about the Sun without having to go there.
- But to do that, we have to understand how light and matter interact.
Light
Ways light and matter interact

Emission

Absorption

Transmission

Reflection and Scattering

- Reflection and scattering are related a bit like kinetic and thermal energy are
- Scattering from a projection screen is *randomized* reflection

- Scattering can also occur when light is transmitted through a substance
- That’s what makes our sky blue
- Now let’s find out more about light itself…
The Nature of Light

- Light is a wave
- Like all waves it has a wavelength $\lambda$, a frequency $f$, and a wave speed $V$
- Like all waves, if we know the wavelength and the frequency, we can calculate the speed of the wave
  \[ v = \lambda \times f \]
- Like all waves, light comes in many wavelengths and frequencies
- But unlike most other waves, it always travels with the same speed (in vacuum)
  \[ c = 300,000 \text{ km/s} \]
The Nature of Light

- Light is also a particle
- It depends on how you observe it
- The particles are called “photons”
- The energy of each photon is:

\[ E = hf \]

where \( f \) = frequency
and \( h \) = Planck’s constant
\( (6.626 \times 10^{-34} \text{ J} \cdot \text{s}) \)
How is Light Produced?

- Vibrating electric charges produce light
- Electric charges generate electric fields
- When a charge vibrates, so does its field
- This generates an electric field wave
How is Light Produced?

- The changing electric field in the wave generates a changing magnetic field
How is Light Produced?

• The changing electric field in the wave generates a changing magnetic field
• And then the changing magnetic field generates a changing electric field
• And you have an *electromagnetic (EM)* wave traveling through space
• These EM waves are called *electromagnetic radiation*

• Our textbook refers to all electromagnetic radiation as “light”
• What we refer to as light in our everyday lives is only a small range of electromagnetic radiation, called “visible light”, because we can see it with our eyes
The Electromagnetic Spectrum

- The frequency (or wavelength) of visible light determines its color
- The visible range covers a little less than one octave of frequency…
  (Musical notes one octave apart differ in frequency by a factor of 2)
The Electromagnetic Spectrum

- There are more than 70 octaves of frequency in the electromagnetic spectrum.
- Wavelengths range from the size of mountains to the size of atomic nuclei.
Spectral Analysis

- There is a lot of information in the light coming from a celestial object
- All you have to do is break it into its component wavelengths – into a spectrum

[Diagram showing a spectrum with intensity on the y-axis and wavelength on the x-axis, with peaks and troughs indicating different wavelengths]

- To interpret a spectrum, you need to know how light-matter interactions affect it
- Let’s look at how this spectrum would be made, and why it looks this way
Spectral Analysis

- This is a **spectrograph**, an instrument used to record a spectrum
- It has a lens to make the incident light rays parallel
- A vertical aperture slit to let only a sliver of light into the instrument
- A prism to break the light into its component wavelengths
- Another lens to focus the spectrum on a screen or detector to record it
Spectral Analysis

• If the spectrograph looks directly at a source of light, as it is here, it will see and record a continuous *thermal radiation* spectrum
• Let’s talk about thermal radiation…
Thermal Radiation

- Thermal radiation is emitted by all objects with T > absolute zero
- Particles in such objects are in constant thermal motion…
  …randomly vibrating and moving around
- The vibrations of charged particles (e\(^-\) and p\(^+\)) cause them to emit light…
  …no matter where they are in the object
- Thermal radiation is the light emitted by those on the object’s surface
Thermal Radiation

- The energy corresponding to thermal motion depends on temperature...

\[ KE_{\text{avg}} = \frac{3}{2} kT \quad \text{where} \quad k = 1.38 \times 10^{-23} \frac{\text{J}}{\text{K}} \]

- Thermal radiation depends on the amount of thermal motion...
- ...so the nature of thermal radiation depends on the temperature too
- This causes it to follow two important physical laws
- They are the Stefan-Boltzmann Law and Wien’s Law
The Laws of Thermal Radiation

- **Stefan-Boltzmann Law**: Hotter objects emit more total thermal energy
  - Total energy emitted per square meter of surface area per second is proportional to $T^4$

- **Wien's Law**: Hotter objects emit photons with higher energies
  - Frequency emitted at peak of thermal radiation is proportional to $T$

- This leads to a very characteristic shape for a thermal radiation spectrum
Thermal Radiation

- How Temperature Affects Thermal Radiation
  - Thermal radiation spectra have a characteristic shape:

![Thermal Radiation Spectrum Diagram](image-url)
Thermal Radiation

- How Temperature Affects Thermal Radiation
  - Thermal radiation spectra have a characteristic shape:

The “Rock of Gibraltar”
Thermal Radiation

- **How Temperature Affects Thermal Radiation**
  - Thermal radiation spectra have a characteristic shape:
  - Hotter objects emit more total thermal radiation overall
  - Hotter objects emit photons with higher average energies
Thermal Radiation

- **How Temperature Affects Thermal Radiation**
  - Thermal radiation spectra have a characteristic shape:
  
    ![Thermal Radiation Spectra Diagram](image)

    - Thermal radiation spectra also explain the colors of stars...
Spectral Analysis

• So, if the spectrograph looks directly at a source of light…
  …it will see and record a continuous *thermal radiation* spectrum…
  …whose intensity and peak frequency depend on the surface temperature.
Absorption Line Spectrum

- But if it looks at a source of light through a cooler cloud of gas,
- It records an *absorption line spectrum*
Absorption Line Spectrum

- The Sun's spectrum is an example of an absorption line spectrum.
- From the pattern of lines, absorption spectra can be used to determine the chemical identity of any gases present.
Emission Line Spectrum

- If the spectrograph looks at a heated cloud of gas…
- It records an emission line spectrum
These are emission line spectra of some elemental gases

The pattern is unique for each element...

...so the chemical identity of gases...

...can be determined from emission (and absorption) spectra
Kirchoff’s Laws

- Kirchoff’s Laws summarize this behavior:
  - Looking directly at a source of light gives a continuous thermal emission spectrum
  - Looking at a source of light through a cloud of cooler gas gives an absorption spectrum
  - Looking at a cloud of gas hotter than the background gives an emission spectrum
Kirchoff’s Laws

- But why do light and matter interact this way?
- Because light interacts with the electrons in atoms
Formation of Spectra

- This is the “classical atom”
  - Also called the “Bohr atom”
  - Also called the “solar system model of the atom”
  - Useful and easy to understand, but not very realistic

![Diagram of ground state and excited state with electron and proton](image-url)
The “quantum theory atom” is more realistic
- In this conception, the electrons are not discrete particles orbiting the nucleus
- Instead, they are located in clouds of “electron density” around the nucleus
- The highest electron density occurs at the location of the classical orbits
- The shape of the electron density changes with electron energy
The “quantum theory atom” is more realistic
- In this conception, the electrons are not discrete particles orbiting the nucleus
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- The shape of the electron density changes with electron energy
- Some of the shapes can be rather odd (according to quantum mechanics)
Formation of Spectra

- In order to move from a lower energy state to a higher energy state, the electron must absorb an exact amount of additional energy.
- And when the electron falls back down to a lower energy state, it must release that excess energy.
- All three of Kirchoff’s Laws are explained by this.
- Let’s see how...
Absorption, Emission, and Transmission of Photons
Production of Absorption and Emission Lines
Production of Thermal Radiation
Production of Thermal Radiation
Summary of Kirchoff’s Laws

- Look directly at a source of light and see a continuous thermal radiation spectrum.

- Look at a gas cloud which is hotter than the background and see an emission line spectrum.

- Look at a source of light through a gas cloud and see an absorption line spectrum.
Kirchoff's laws allow us to interpret a spectrum like this.
The characteristic shape of a thermal radiation spectrum is there.
Two of them, in fact.
Spectral Analysis

- There are absorption lines
Spectral Analysis

- There are emission lines
• The thermal, absorption, and emission spectra tell us about the object
• Consider the thermal emission curves
• One peaks at an infrared wavelength…
• …and one at a visible wavelength
• These indicate the surface temperature of the object
• But wait, the object has only one surface…
  …it cannot have two surface temperatures!
• So what gives?
Spectral Analysis

- The astronomer who made the spectrum knows what she’s looking at.
- And she knows the visible thermal spectrum is from reflected sunlight…
- …but the object’s surface has absorbed some of it and distorted the spectrum…
- …some blue and green are missing, so the object will look red.
- The infrared thermal radiation spectrum is from the surface of the object itself.
- And it is cold.
• Now the absorption lines
• They are characteristic of CO$_2$
• So a cool CO$_2$ gas is between the observer and the object’s surface
• A CO$_2$ atmosphere!
• Now the emission lines
• They are the spikes in ultraviolet
• They are high-energy UV spikes, so they indicate a hot gas
• A hot upper atmosphere!
Spectral Analysis

- And now putting it all together, it makes sense…
• And now putting it all together, it makes sense…
• The object is the red planet, Mars
• We got all of this information…without having to actually go to Mars
• Understanding Kirchoff’s Laws makes it possible
• And that’s the power of spectroscopy in astronomy
• Spectroscopy is an important tool in astronomy
• It provides information that’s difficult and expensive to get any other way
• It can tell us about the composition and temperature of a celestial object…
  …without even going there
• It can also tell us about its motion…
The Doppler Effect
The Doppler Effect

- The pitch of a sound is due to its frequency.
- When a source of sound is not moving...
- ...sound waves have their normal pitch for all observers.
The Doppler Effect

- The pitch of a sound is due to its frequency
- When a source of sound is not moving...
- ...sound waves have their normal pitch for all observers

- But when the source moves...
- ...sound waves traveling in the direction of motion get compressed to a higher pitch...
- ...and sound waves traveling opposite the direction of motion get stretched to a lower pitch
The Doppler Effect

- The same thing happens to light waves
- Light waves traveling in the direction of motion are “compressed” to shorter wavelengths, higher frequencies, higher energies...
- ...they are “blue-shifted”
The Doppler Effect

- The same thing happens to light waves
- Light waves traveling in the direction of motion are “compressed” to shorter wavelengths, higher frequencies, higher energies…
  - …they are “blue-shifted”
- Light waves traveling opposite are “stretched” to longer wavelengths, lower frequencies, lower energies…
  - …they are “red-shifted”
The Doppler Effect

- These are what Doppler-shifted spectra actually look like
- The middle one is the “rest spectrum”
- The direction of the shift shows whether the object is receding or approaching
- The amount of shift provides information about how fast it’s moving
- This makes sense because faster motion will compress or stretch the waves more

$$\text{speed} = \left( \frac{\text{observed wavelength}}{\text{rest wavelength}} - 1 \right) c = \left( \frac{655.0 \times 10^{-9} \text{ m}}{656.3 \times 10^{-9} \text{ m}} - 1 \right) \left( 3 \times 10^8 \frac{\text{m}}{\text{s}} \right) = -6 \times 10^5 \frac{\text{m}}{\text{s}} = -0.002c$$

- The negative sign means the object is approaching
The Doppler Effect

- Doppler shifts of the center of a spectral line indicate whether and how fast an object is moving toward us or away from us.
- Doppler shifts due to rotation increase the width of the line.
The Doppler Effect

• Most extrasolar planets are confirmed with Doppler shifts:

• Telescopes gather light from celestial objects for this and other techniques…
• …and that’s the topic we turn to now…
Telescopes

What two properties of telescopes are most important to astronomers?

- Light-collecting area
  - Gives brighter images

- Angular resolution
  - Gives more detail
  - Human eye: 1'
  - Hubble Space Telescope: 0.05"
  - A factor of 1200 better

For more on Telescopes, refer to Dr Brian Uzpen’s 1/27 lecture (available on Meeting Links), as well as the textbook.
Most of the information we have about the astronomical universe came from telescopes. But some of it came from space probes. They can provide images and information that telescopes on or near Earth cannot.
Space Probes

- Mercury – Mariner 10 flyby – March 1974
  - These are mosaics

approaching

retreating
Space Probes

- **Mercury – Messenger**

  - Crashed onto Mercury on 30-Apr-2015 at ~14000 kph (8800 mph)
  - Probably left crater ~16 m (52 ft) wide
Space Probes

• Venus – Pioneer orbiter – Feb 1979
  – Ultraviolet
Space Probes

- Venus – Magellan orbiter – early 1990s
  - Radar
Space Probes

- Venus – Venera 13 lander – Mar 1982
  - Optical

- Spacecraft only survived for a little over 2 hours
  - 457°C (855°F)
  - 84 atm pressure
Space Probes

- Earth and Moon – Galileo orbiter – December 1992
  - Optical
Space Probes

- Mars – Viking I lander – 1976
  - Optical
Space Probes

- Mars – Pathfinder – 1997
  - Optical
Space Probes

- Cassini – Saturn
Space Probes

- Titan – Huygens lander – Jan 2005
  - Optical
Space Probes

- Titan – Huygens lander – Jan 2005
  - Optical

- Video of descent (Titan Touchdown)
Space Probes

- Hubble Space Telescope – Pluto

Pluto Faces
*Hubble Space Telescope* • ACS/HRC

NASA, ESA, and M. Buie (Southwest Research Institute)
Space Probes

- New Horizons – Pluto

Pluto and Charon

Border of the heart

Pluto’s Atmosphere
Space Probes

• **Breakthrough Starshot**
  – **Video**
  – 20% speed of light…
  – How long will it take?
Crewed Space Flight

- Mercury, Gemini, Apollo, STS (Space Shuttle), ISS
- SpaceX to (or around) the Moon
- SpaceX or NASA or ESA or China or Russia or ideally, a global consortium, to Mars…
  …and beyond
- This will have to happen eventually…
  …if we humans, or perhaps more likely our technologically enhanced descendants, want to survive…
  …that is, if we don’t become extinct at our own hands…
  …or those of the cosmos
Space Probes

- Voyager – 1977-present

Voyager 2
Space Probes

- Voyager – 1977-present
Space Probes

- Voyager – 1977-present
Space Probes

- Voyager – 1977-present

The Golden Record
Space Probes

• Voyager – 1977-present

The Golden Record

• It almost didn’t fly…
  …Timothy Ferris, the producer, etched “To the makers of music – all worlds, all times” in the take-out grooves
• This violated NASA specs
• But Carl Sagan convinced NASA to let it fly anyway
Space Probes

- Voyager – 1977-present

The Golden Record

- What about those diagrams?
Space Probes

- Voyager – 1977-present
Space Probes

- Voyager – 1977-present

Select images on the Voyager Golden Record

A woman in a supermarket

A photo of Jupiter with its diameter indicated

This image depicts humans drinking, licking and eating as modes of feeding.

This is a photograph of the Arecibo observatory marked with an indication of scale.

This image is a photograph of page 6 from Isaac Newton's *Philosophiae Naturalis Principia Mathematica* Volume 3, *De mundi systemate* (On the system of the world).

This is a photograph of Egypt, Red Sea, Sinai Peninsula and the Nile from Earth orbit annotated with chemical composition of Earth's atmosphere.
Space Probes

- Voyager – 1977-present
Space Probes

- Voyager – 1977-present
Space Probes

• Voyager – 1977-present

"This Voyager spacecraft was constructed by the United States of America. We are a community of 240 million human beings among the more than 4 billion who inhabit the planet Earth. We human beings are still divided into nation states, but these states are rapidly becoming a single global civilization.

We cast this message into the cosmos. It is likely to survive a billion years into our future, when our civilization is profoundly altered and the surface of the Earth may be vastly changed. Of the 200 billion stars in the Milky Way galaxy, some – perhaps many – may have inhabited planets and space faring civilizations. If one such civilization intercepts Voyager and can understand these recorded contents, here is our message:

This is a present from a small distant world, a token of our sounds, our science, our images, our music, our thoughts and our feelings. We are attempting to survive our time so we may live into yours. We hope someday, having solved the problems we face, to join a community of galactic civilizations. This record represents our hope and our determination, and our good will in a vast and awesome universe."

Jimmy Carter, President, USA
Space Probes

• Voyager – 1977-present

"As the Secretary General of the United Nations, an organization of the 147 member states who represent almost all of the human inhabitants of the planet Earth, I send greetings on behalf of the people of our planet. We step out of our solar system into the universe seeking only peace and friendship, to teach if we are called upon, to be taught if we are fortunate. We know full well that our planet and all its inhabitants are but a small part of this immense universe that surrounds us and it is with humility and hope that we take this step."

Kurt Waldheim, Secretary General, United Nations