Astronomical Spectroscopy: Where most of the Real Science Gets Done
Presentation Outline

• Review of EM Radiation and Atomic Physics
• Three Types of Spectra
• Spectrographic Instrumentation
• History and Nomenclature of Astronomical Spectroscopy
• Spectroscopic Observations in Astronomy
• Conclusions
Electromagnetic Radiation

• Particle nature of light
  – Photons
    • Energy & momentum
    • Absorption and emission

• Wave nature of light
  – Oscillating electric and magnetic fields
  – Wavelength, frequency, velocity & energy
  – Amplitude & intensity
  – Diffraction & interference
Wavelength is the distance between adjacent peaks of the electric field.

Frequency is the number of waves passing any point each second.

All light travels with speed $c = 300,000 \text{ km/s}$. 

Wavelength

Crest

Amplitude

Undisturbed state

Trough

Direction of wave motion
Electromagnetic Radiation

• Spectral regions
  – Visible light is tiny portion of entire EM spectrum
  – Shorter wavelengths: UV; X-ray; γ ray
  – Longer wavelengths: IR; μ-wave; radio
Electromagnetic Radiation

• Spectral regions
  – Visible light is tiny portion of entire EM spectrum
  – Shorter wavelengths: UV; X-ray; γ ray
  – Longer wavelengths: IR; μ-wave; radio

• Atmospheric windows
  – Optical and radio reach ground unhindered
  – UV and higher energies are blocked
  – IR is mostly blocked
    • Few narrow windows reaching some mountaintops
The bozone layer: shielding the rest of the solar system from the Earth's harmful effects.
Atomic Physics

• Quantum Mechanics
  – Atomic constituents
    • Nuclei of protons and neutrons
    • Cloud of electrons
Ten million atoms could fit end-to-end across this dot.

The nucleus is nearly 100,000 times smaller than the atom but contains nearly all of its mass.

Atom: Electrons are “smeared out” in a cloud around the nucleus.

Nucleus: Contains positively charged protons (red) and neutral neutrons (gray).
Atomic Physics

• Quantum Mechanics
  – Atomic constituents
    • Nuclei of protons and neutrons
    • Cloud of electrons
  – Electrons limited to specific energy levels in atoms
    • Prefer ground state unless energy is absorbed
Atomic Physics

• Quantum Mechanics
  – Atomic constituents
    • Nuclei of protons and neutrons
    • Cloud of electrons
  – Electrons limited to specific energy levels in atoms
    • Prefer ground state unless energy is absorbed
  – Transitions between levels are “quantized”
    • Collisions due to thermal motions
Longer arrows mean higher speed.
Atomic Physics

- Quantum Mechanics
  - Atomic constituents
    - Nuclei of protons and neutrons
    - Cloud of electrons
  - Electrons limited to specific energy levels in atoms
    - Prefer ground state unless energy is absorbed
  - Transitions between levels are “quantized”
    - Collisions due to thermal motions
    - Photon absorption/emission
No thanks. Wrong energy.

Aha!

Ahh.

Oops.
Electron jumps involved in light emission
Various possibilities as electron changes orbits

(a)

(b)
Atomic Physics

• Hydrogen atom
  – Simplest: one proton and one electron
    • Also most abundant in universe – 90% of all atoms
  – Energy levels follow $1/n^2$ relationship
ionization level 13.6 eV
level 4 12.8 eV
level 3 12.1 eV
level 2 10.2 eV
level 1 (ground state) 0 eV
Atomic Physics

• Hydrogen atom
  – Simplest: one proton and one electron
    • Also most abundant in universe – 90% of all atoms
  – Energy levels follow $1/n^2$ relationship
  – Transitions to given level are named
    • Lyman (n=1); Balmer (n=2); Paschen (n=3); etc.
Atomic Physics

- **Hydrogen atom**
  - Simplest: one proton and one electron
  - Also most abundant in universe – 90% of all atoms
  - Energy levels follow $1/n^2$ relationship
  - Transitions to given level are named
    - Lyman ($n=1$); Balmer ($n=2$); Paschen ($n=3$); etc.

- **Other elements**
  - Differ in number of protons (Atomic Number)
  - Isotopes: same # of protons, different # of neutrons
  - Ions have excessive positive or negative charge
atomic number = number of protons
atomic weight = number of protons + neutrons

Hydrogen ($^1\text{H}$)
- atomic number = 1
- atomic weight = 1
  (1 electron)

Helium ($^4\text{He}$)
- atomic number = 2
- atomic weight = 4
  (2 electrons)

Carbon ($^{12}\text{C}$)
- atomic number = 6
- atomic weight = 12
  (6 electrons)

The number of electrons in a neutral atom equals its atomic number.

Isotopes of Hydrogen
- hydrogen
- deuterium
  - $^1\text{H}$ (1 proton)
  - $^2\text{H}$ (1 proton + 1 neutron)

Isotopes of Carbon
- carbon-12
- carbon-14
  - $^{12}\text{C}$ (6 protons + 6 neutrons)
  - $^{14}\text{C}$ (6 protons + 8 neutrons)
Three Types of Spectra

• Continuous Spectra
  – Formed by thermal emission from solid or liquid
  – Kirchhoff’s First Law of Radiation:
    • A luminous solid or liquid emits light of all wavelengths, thus producing a continuous spectrum
Three Types of Spectra

• Continuous Spectra
  – Formed by thermal emission from solid or liquid
  – Kirchhoff’s First Law of Radiation:
    • A luminous solid or liquid emits light of all wavelengths, thus producing a continuous spectrum
  – Known as black-body radiation
    • Depends only on temperature of source
    • Hotter objects emit more radiation at all wavelengths
    • Hotter objects have peak emission at shorter wavelengths
Wavelength (nanometers)

Ultraviolet  Visual  Infrared

Object at 7000 K

$I_{\max}$

7000 K
A diagram showing the intensity versus wavelength of an object at 6000 K and 5000 K. The graph indicates that at higher temperatures, the peak intensity (I_max) shifts to shorter wavelengths. The x-axis represents wavelength in nanometers, and the y-axis represents intensity. The curve for the object at 6000 K is positioned to the right of the curve for the object at 5000 K.
Three Types of Spectra

• Emission Spectra
  – Emission of light at specific wavelengths
    • Formed by photoemission from an excited gas
  – Kirchhoff’s Second Law of Radiation:
    • A rarefied luminous gas emits light whose spectrum shows bright lines, and sometimes a faint superimposed continuous spectrum
Three Types of Spectra

• Emission Spectra
  – Emission of light at specific wavelengths
    • Formed by photoemission from an excited gas
  – Kirchhoff’s Second Law of Radiation:
    • A rarefied luminous gas emits light whose spectrum shows bright lines, and sometimes a faint superimposed continuous spectrum
  – Different elements, molecules and ions have different spectra
    • Can “fingerprint” specific species
Three Types of Spectra

• Absorption Spectra
  – Absence of light at specific wavelengths
    • Due to photoexcitation by atoms in cool gas
  – Kirchhoff’s Third Law of Radiation:
    • If the white light from a luminous source is passed through a gas, the gas may absorb certain wavelengths from the continuous spectrum so that those wavelengths will be missing or diminished in its spectrum, thus producing dark lines
Continuous spectrum

Absorption spectrum of hydrogen

Emission spectrum of hydrogen
Light from the Sun

Visible surface of Sun

Continuous spectrum

Atmosphere of Sun

Phocons emitted in all directions (emission spectrum)

To Earth

Unabsorbed light (absorption spectrum)
Spectrographic Instrumentation

- Elements of modern spectrograph
  - Entrance aperture
    - slit or pinhole
  - Collimating lens/mirror
    - Designed to match f/ratio of telescope
  - Dispersive element
    - prism or grating
  - Camera lens/mirror
  - Detector
    - Photographic plate or solid state device
  - Comparison lamps for wavelength calibration
Spectrographic Instrumentation

• Dispersive elements
  – Glass prism
    • Index of refraction wavelength dependent
    • Pass light through a narrow slit
    • Resolution (ability to separate adjacent wavelengths) depends on:
      – Type of glass
      – Width of slit
      – Angle of prism
Spectrographic Instrumentation

• Dispersive elements (continued)
  – Diffraction grating
    • Parallel lines ruled on glass substrate
    • Uses diffraction and interference properties of light
    • Resolution depends on number of lines $N$
Diffraction Grating

- White light strikes grating from left
- Line spacing is $d$
- Constructive interference
  - Angle $\theta$ depends on wavelength $\lambda$
    - $n$ is an integer
  - Light spread out into spectrum

$$d \sin \theta = n\lambda$$
Spectrographic Instrumentation

• Echelle Spectrographs
  – Very high resolution
  • Cross-dispersive prism or grating
Figure 1: Side and bottom views of 4m echelle spectrograph
Spectrographic Instrumentation

• Echelle Spectrographs
  – Very high resolution
    • Cross-dispersive prism or grating
  – Source must be bright, point-like
    • Stars or Bright galactic nuclei
  – Measure profile of absorption/emission lines
Spectrographic Instrumentation

- Echelle Spectrographs
  - Very high resolution
    - Cross-dispersive prism or grating
  - Source must be bright, point-like
    - Stars or Bright galactic nuclei
  - Measure profile of absorption/emission lines

- Multi-object Spectrographs
  - Observe more than one source at a time
    - More efficient use of telescope time
  - Optical fibers and plug-plate
History and Nomenclature

- Isaac Newton
  - Used prism to observe spectrum of Sun
    - Insufficient resolution to observe absorption lines
- Joseph von Fraunhofer
  - Observed solar spectrum at higher resolution
History and Nomenclature

• Isaac Newton
  – Used prism to observe spectrum of Sun
    • Insufficient resolution to observe absorption lines

• Joseph von Fraunhofer
  – Observed solar spectrum at higher resolution
  – Identified numerous absorption lines
    • Origin of spectroscopic nomenclature
      – Ca II H + K (singly-ionized Calcium)
      – Na I D (neutral Sodium)
Stellar Observations

• Temperature
  – Balmer Thermometer
    • Assumes thermodynamic equilibrium
      – Hotter stars excite more electrons to upper levels
    • Based on “strength” of absorption lines
Stellar Observations

• Temperature
  – Balmer Thermometer
    • Assumes thermodynamic equilibrium
      – Hotter stars excite more electrons to upper levels
    • Based on “strength” of absorption lines
      – Uses more than just Balmer lines for measurement
Stellar Observations

• Temperature
  – Balmer Thermometer
    • Assumes thermodynamic equilibrium
      – Hotter stars excite more electrons to upper levels
    • Based on “strength” of absorption lines
      – Uses more than just Balmer lines for measurement
    • Accurate stellar temperatures
      – Much more precise than photometric colors

• Composition
  – Observe absorption lines of various species
    • Fit to computer models of stellar atmospheres
Stellar Observations

• Spectral Classification
  – Based on:
    • Temperature (OBAFGKM)
      – Ten subclasses in each class from 0 (hottest) to 9 (coolest)
Spectral classification
Stars of different temperatures show different absorption lines with different strengths

<table>
<thead>
<tr>
<th>Spectral Class</th>
<th>Approximate Temp (K)</th>
<th>Balmer Lines</th>
<th>Other Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>40,000</td>
<td>Weak</td>
<td>Ionized helium</td>
</tr>
<tr>
<td>B</td>
<td>20,000</td>
<td>Medium</td>
<td>Neutral helium</td>
</tr>
<tr>
<td>A</td>
<td>10,000</td>
<td>Strong</td>
<td>Weak ionized calcium</td>
</tr>
<tr>
<td>F</td>
<td>7500</td>
<td>Medium</td>
<td>Weak ionized calcium</td>
</tr>
<tr>
<td>G</td>
<td>5500</td>
<td>Weak</td>
<td>Medium ionized calcium</td>
</tr>
<tr>
<td>K</td>
<td>4500</td>
<td>Very weak</td>
<td>Strong ionized calcium</td>
</tr>
<tr>
<td>M</td>
<td>3000</td>
<td>Very weak</td>
<td>Strong Titanium Oxide</td>
</tr>
<tr>
<td>Spectral type</td>
<td>Example(s)</td>
<td>Temperature Range</td>
<td>Key Absorption Line Features</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------</td>
<td>-------------------</td>
<td>-------------------------------------------------------------------</td>
</tr>
<tr>
<td>O</td>
<td>Stars of Orion's Belt</td>
<td>&gt;30,000 K</td>
<td>Lines of ionized helium, weak hydrogen lines</td>
</tr>
<tr>
<td>B</td>
<td>Rigel</td>
<td>30,000 K−10,000 K</td>
<td>Lines of neutral helium, moderate hydrogen lines</td>
</tr>
<tr>
<td>A</td>
<td>Sirius</td>
<td>10,000 K−7,500 K</td>
<td>Very strong hydrogen lines</td>
</tr>
<tr>
<td>F</td>
<td>Polaris</td>
<td>7,500 K−6,000 K</td>
<td>Moderate hydrogen lines, moderate lines of ionized calcium</td>
</tr>
<tr>
<td>G</td>
<td>Sun, Alpha Centauri A</td>
<td>6,000 K−5,000 K</td>
<td>Weak hydrogen lines, strong lines of ionized calcium</td>
</tr>
<tr>
<td>K</td>
<td>Arcturus</td>
<td>5,000 K−3,500 K</td>
<td>Lines of neutral and singly ionized metals, some molecules</td>
</tr>
<tr>
<td>M</td>
<td>Betelgeuse, Proxima Centauri</td>
<td>&lt;3,500 K</td>
<td>Molecular lines strong</td>
</tr>
</tbody>
</table>

*All stars above 6,000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.
Stellar Observations

• Spectral Classification
  – Based on:
    • Temperature (OBAFGKM)
      – Ten subclasses in each class from 0 (hottest) to 9 (coolest)
    • Size (luminosity classes)
      – Supergiant (Ia or Ib or II)/Giant (III or IV)/Main Sequence (V)
Stellar Observations

• Spectral Classification
  – Based on:
    • Temperature (OBAFGKM)
      – Ten subclasses in each class from 0 (hottest) to 9 (coolest)
    • Size (luminosity classes)
      – Supergiant (Ia or Ib or II)/Giant (III or IV)/Main Sequence (V)
  • Ex: Sun is G2 V
  – Related to H-R diagram
Stellar Observations

• Spectral Classification
  – Based on:
    • Temperature (OBAFGKM)
      – Ten subclasses in each class from 0 (hottest) to 9 (coolest)
    • Size (luminosity classes)
      – Supergiant (Ia or Ib or II)/Giant (III or IV)/Main Sequence (V)
    • Ex: Sun is G2 V
  – Related to H-R diagram
  – Some stars fall outside scheme
    • Need new classes
      – Carbon stars
      – L stars (cooler than M stars)
M8 star spectrum

L3 star spectrum

Intensity

Wavelength (nm)

700  800  900

TiO

TiO

CrH  FeH

TiO
Stellar Observations

- Radial velocity (line-of-sight)
Radial versus tangential motion
True velocity

Velocity measured by Doppler shift

Star

Earth
Stellar Observations

- Radial velocity (line-of-sight)
  - Doppler effect
    - Approaching objects are blue-shifted
    - Receding objects are red-shifted
Stellar Observations

• Radial velocity (line-of-sight)
  – Doppler effect
    • Approaching objects are blue-shifted
    • Receding objects are red-shifted
    • Magnitude of shift directly related to velocity
  – Observe wavelength shifts in absorption lines
Laboratory spectrum
Lines at rest wavelengths.

Object 1
Lines redshifted: Object is moving away from us.

Object 2
Greater redshift: Object is moving away faster than Object 1.

Object 3
Lines blueshifted: Object is moving toward us.

Object 4
Greater blueshift: Object is moving toward us faster than Object 3.

© Addison Wesley Longman, Inc.
Stellar Observations

• Radial velocity (line-of-sight)
  – Doppler effect
    • Approaching objects are blue-shifted
    • Receding objects are red-shifted
    • Magnitude of shift directly related to velocity
  – Observe wavelength shifts in absorption lines

• Spectroscopic Binary Stars
  – Periodic Doppler shifts due to orbital motions
  – Can measure mass of stars using Kepler’s Laws
Approaching A

Receding B

Blue shift

A

B

Red shift
Spectral lines of stars split by Doppler effect

Merged spectral lines
Mizar is a visual binary. Spectroscopy shows that each of the visual stars is itself a binary.
Stellar Observations

- Line broadening
  - Rotational broadening
Rotational broadening

Star Rotation

This side blue shifted

Observer sees:

This side red shifted

Intensity

"Natural line"

Frequency

Receding side

Approaching side

Line center
Stellar Observations

• Line broadening
  – Rotational broadening
  – Thermal broadening
TM 5-3  Thermal broadening

(a) Diagram showing various shifts (blue shift, red shift) with arrows pointing in different directions.

(b) Graph showing intensity on the y-axis and frequency on the x-axis. The graph illustrates large red shift and large blue shift away from the centroid ("natural" frequency).
Stellar Observations

• Line broadening
  – Rotational broadening
  – Thermal broadening
  – Interstellar medium absorption lines
Stellar Observations

• Line broadening
  – Rotational broadening
  – Thermal broadening
  – Interstellar medium absorption lines

• Reddening and Extinction
  – scattering of shorter wavelengths by dust
Stellar Observations

• Line broadening
  – Rotational broadening
  – Thermal broadening
  – Interstellar medium absorption lines

• Reddening and Extinction
  – scattering of shorter wavelengths by dust

• Stellar Populations in our Galaxy
  – Population I stars in galactic disk (metal rich)
  – Population II stars in halo (metal poor)
Stellar Observations

• Extra-solar planets
  – Observe Doppler shift in stellar absorption lines
    • Indirect means of detecting Jupiter-mass objects
    • Periodicities range from days to years
    • Much smaller velocities than in binary systems
      – Requires very high resolution Echelle spectrographs
stellar motion caused by tug of planet

orbit of unseen planet

starlight redshifted to Earth

starlight blueshifted

© Addison Wesley Longman, Inc.
Stellar Observations

• Extra-solar planets
  – Observe Doppler shift in stellar absorption lines
    • Indirect means of detecting Jupiter-mass objects
    • Periodicities range from days to years
    • Much smaller velocities than in binary systems
      – Requires very high resolution Echelle spectrographs
  • About 200 “Jupiters” discovered to date
    – Selection effects make these objects easier to find
    – Many with unusual orbital properties
Stellar Observations

• Extra-solar planets
  – Observe Doppler shift in stellar absorption lines
    • Indirect means of detecting Jupiter-mass objects
    • Periodicities range from days to years
    • Much smaller velocities than in binary systems
      – Requires very high resolution Echelle spectrographs
    • About 200 “Jupiters” discovered to date
      – Selection effects make these objects easier to find
      – Many with unusual orbital properties
  – Other detection schemes (non-spectroscopic)
    • Microlensing
    • Eclipses/transits in front of primary
Galaxy Observations

• Rotation Curves
  – Spiral galaxies rotate around center
    • One side approaches us, one side recedes from us
Galaxy Observations

• Rotation Curves
  – Spiral galaxies rotate around center
    • One side approaches us, one side recedes from us
    • Observe rotational broadening if galaxy unresolved
Observer sees combined beam:

- **Blueshifted**
- **Unshifted**
- **Redshifted**

Spiral galaxy

Approaching

Galactic rotation

Receding
Galaxy Observations

• Rotation Curves
  – Spiral galaxies rotate around center
    • One side approaches us, one side recedes from us
    • Observe rotational broadening if galaxy unresolved
    • Observe “flattened s-shape” in resolved spirals
Galaxy Observations

• **Rotation Curves**
  – Spiral galaxies rotate around center
    • One side approaches us, one side recedes from us
    • Observe rotational broadening if galaxy unresolved
    • Observe “flattened s-shape” in resolved spirals
  – Expect *Keplerian rotation* outside visible extent
    • Observe flat rotation curve – missing mass
    • Origin of dark matter
Velocity (km/sec)

Distance from center

Right-body rotation

Limit of visible galaxy

Observed curve
Galaxy Observations

• Cluster Masses and Dark Matter
  – Velocity dispersion of galaxy clusters
(a) Binary galaxy

(b) Galaxy cluster

Redshift

Blueshift

Elliptical

Irregular

Spiral

Observer

Observer

Blueshift

Redshift

No shift
Galaxy Observations

• Cluster Masses and Dark Matter
  – Velocity dispersion of galaxy clusters
    • Dynamical gravitational mass of cluster
    • Visible cluster mass in stars
    • Hot intracluster gas between galaxies
    • Universe consists mainly of dark matter
      – Scientists still don’t know what this stuff is made of
Galaxy Observations

• Cosmic Redshift
  – General Theory of Relativity (1915)
    • Predicted dynamic (non-static) universe
Galaxy Observations

• Cosmic Redshift
  – General Theory of Relativity (1915)
    • Predicted dynamic (non-static) universe
    • Einstein’s Cosmological constant
  – Mt. Wilson Observatory (1920s)
    • Humason & Hubble show most galaxies redshifted
<table>
<thead>
<tr>
<th>Galaxy, part of cluster in</th>
<th>Distance (megaparsecs)</th>
<th>Red shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgo</td>
<td>24</td>
<td>1,200 km/sec</td>
</tr>
<tr>
<td>Ursa Major</td>
<td>300</td>
<td>15,000 km/sec</td>
</tr>
<tr>
<td>Corona Borealis</td>
<td>430</td>
<td>22,000 km/sec</td>
</tr>
<tr>
<td>Boötes</td>
<td>770</td>
<td>39,000 km/sec</td>
</tr>
<tr>
<td>Hydra</td>
<td>1,200</td>
<td>61,000 km/sec</td>
</tr>
</tbody>
</table>
Galaxy Observations

• Cosmic Redshift
  – General Theory of Relativity (1915)
    • Predicted dynamic (non-static) universe
    • Einstein’s Cosmological constant
  – Mt. Wilson Observatory (1920s)
    • Humason & Hubble show most galaxies redshifted
      – Recession velocity proportional to galaxy distance
Galaxy Observations

• Cosmic Redshift
  – General Theory of Relativity (1915)
    • Predicted dynamic (non-static) universe
    • Einstein’s Cosmological constant
  – Mt. Wilson Observatory (1920s)
    • Humason & Hubble show most galaxies redshifted
      – Recession velocity proportional to galaxy distance
    • Expansion of Universe
  – Quasars
    • Most distant observed objects in universe
    • Powered by supermassive black holes
HYDROGEN SPECTRUM OF 3C-273

Red shifted

Hydrogen emission lines

H\text{\textalpha}

4000
4800
5600
6400
7200
8000

Wavelength (Å)

Intensity
Conclusions

• Science from Spectroscopy
  – Stellar physics
  – Doppler velocities
  – Interstellar medium

• Science from other techniques
  – Imaging
  – Photometry
  – Polarimetry
  – Timing measurements
emission lines (UV): hot upper atmosphere

object reflects red sunlight: rust-colored surface

thermal emission from Sun

object absorbs blue light from Sun

CO₂ absorption bands: carbon dioxide atmosphere

thermal emission peak in infrared indicates surface temperature about 225 K
A Sampling of what Spectroscopy Tells Us: Solar System

- **Sun**
  - Temperature, pressure, composition of photosphere
  - Velocities of convective cells
  - Solar wind velocity and composition
- **Planets and Moons (pre-Landers)**
  - Atmospheric composition and temperature
  - Surface mineralogy of Terrestrial worlds
- **Asteroids/Comets and other small bodies**
  - Composition of these bodies
A Sampling of what Spectroscopy Tells Us: Stars

• Intrinsic Properties
  – Temperature/Spectral Type
  – Size/Luminosity Class
  – Metallicity
  – Rotation rate

• Extrinsic Properties
  – Radial velocity
    • Multi-star systems and planetary companions
A Sampling of what Spectroscopy Tells Us: Galaxies and the Universe

• Expansion of the Universe
• Supermassive Black Holes in Galactic cores
• Existence of Dark Matter and Dark Energy
  – Rotation curves of spiral galaxies
  – Velocity dispersion of elliptical galaxies
  – Acceleration of distant supernovae
• Galaxy Evolution
• Large Scale Structure of the Universe