Next week: Study Week

Optional attendance; bring any questions.
Will review Test 1, 2, 3.

Final Exam

- May 7 or 9, 10:10am, BPB 102 (the usual classroom)
- Covers the entire semester
- With some (~1/2) overlap with Test 1, 2, 3
Chapter 13
Other Planetary Systems
The New Science of Distant Worlds
“Extrasolar Planets”
13.1 Detecting Extrasolar Planets

Our goals for learning:

• Why is it so difficult to detect planets around other stars?
• How do we detect planets around other stars?
Why is it so difficult to detect planets around other stars?

**Brightness Difference!**

- A Sun-like star is about a billion times brighter than the sunlight reflected from its planets.
- Like being in San Francisco, and trying to see a pinhead (~Earth) in Washington DC, placed at 15 meters from a grapefruit (~Sun).
How do we detect planets around other stars?

Two Main Methods

- **Direct:** Pictures or spectra of the planets themselves -- *this is very difficult*...

- **Indirect:** Measurements of stellar properties revealing the effects of orbiting planets
Gravitational Tugs

- Sun and Jupiter orbit around their common **center of mass**
- Sun therefore wobbles around that center of mass with same period as Jupiter
Gravitational Tugs

• Sun’s motion around solar system’s center of mass depends on tugs from all the planets

• Astronomers around other stars that measured this motion could determine masses and orbits of all the planets
1. Astrometric Technique

- We can detect planets by measuring the change in a star’s position on sky.

- However, these tiny motions are very difficult to measure (~0.001 arcsecond: You’ll need more than 100 times better resolution than the HST).

- This method works best for massive planets.

- Only one extrasolar planet detected by this method thru 2007.
2. Doppler Technique

- Measuring a star’s Doppler shift can tell us its motion toward and away from us.

- Current techniques can measure motions as small as 1 m/s (walking speed!)
First Extrasolar Planet

- First extrasolar planet (around a regular star) to be discovered in 1995
- Doppler shifts of star 51 Pegasi indirectly reveal a planet with 4-day orbital period
- Short period means small orbital distance -- only 1/8 of Mercury’s orbital distance from the Sun
- The surface temperature of 51 Pegasi is probably >1000K, making it a “hot jupiter”

- Planet around 51 Pegasi has a mass similar to Jupiter’s, despite its small orbital distance.
How Orbital Properties of a Star Depend on a Planet's Mass and Orbital Radius

To Earth

Orbital Radius (AU)
5.0
20.0

Planet Mass (M_Jupiter)
0.5
0.5

1.48 AU
9.28 MJupiter

Star's Speed (towards Earth) (m/s)
400
300
200
100
0
-100
-200
-300
-400

Time (days)
500
1000
1500
2000

How To Use
Credits
Other Extrasolar Planets

- Doppler data curve tells us about a planet’s mass and the shape of its orbit

- Large planet mass

- Highly eccentric orbit
Quiz

To detect an extrasolar planet by means of the Doppler shift, you look for a periodic shift of the spectrum lines

A. of the star the planet is orbiting
B. of the planet
C. of the star and the planet
3. Transits and Eclipses

• A **transit** is when a planet crosses in front of a star
• The resulting eclipse reduces the star’s **apparent brightness** and tells us planet’s **radius**
• **No orbital tilt**: accurate measurement of planet **mass**
Spectrum during Transit

• Change in **spectrum** during **transit** tells us about **composition** of planet’s **atmosphere**

the planet’s upper atmosphere absorbs additional light at wavelength that depend on its composition

Absorption line depths are exaggerated for clarity.
Direct Detection

- Special techniques can eliminate light from brighter objects
- These techniques are enabling direct planet detection
Directly imaged planets being discovered!

Fall 2008

Fomalhaut b
~25 lyr from Earth

~8 M\text{Jupiter}
IR image

~130 lyr from Earth

HR 8799

Fomalhaut b
~3 M\text{Jupiter}, visible wavelength
Other Planet-Hunting Strategies

• **Gravitational Lensing**: Mass bends light in a special way when a star with planets passes in front of another star.

• **Features in Dust Disks**: Gaps, waves, or ripples in disks of dusty gas around stars can indicate presence of planets.
What have we learned?

• Why is it so difficult to detect planets around other stars?
  – Direct starlight is billions of times brighter than starlight reflected from planets

• How do we detect planets around other stars?
  – A star’s periodic motion (detected through Doppler shifts) tells us about its planets
  – Transiting planets periodically reduce a star’s brightness
  – Direct detection is possible if we can block the star’s bright light
13.2 The Nature of Extrasolar Planets

Our goals for learning:

• What have we learned about extrasolar planets?
• How do extrasolar planets compare with planets in our solar system?
What have we learned about extrasolar planets?
Measurable Properties

- Orbital Period, Distance, and Shape
- Planet Mass, Size, and Density
- Composition
Orbits of Extrasolar Planets

- Most of the detected planets have orbits smaller than Jupiter’s.
- Planets at greater distances are harder to detect with Doppler technique -- observational bias.
Orbits of Extrasolar Planets

- Orbits of some extrasolar planets are much more elongated (greater eccentricity) than those in our solar system.
Multiple-Planet Systems

- Many stars have more than one detected planet.
- Not so surprising based on Nebular theory of solar system formation and our solar system.
Orbits of Extrasolar Planets

- Most of the detected planets have greater mass than Jupiter
- Planets with smaller masses are harder to detect with Doppler technique -- selection effect (bias towards more massive planets)
Surprising Characteristics

- Some extrasolar planets have **highly elliptical orbits**

- Some massive planets orbit **very close to their stars**: “hot Jupiters”
Hot Jupiters

Jupiter
Composed primarily of hydrogen and helium
5 AU from the Sun
Orbit takes 12 Earth years
Cloud top temperatures ≈ 130 K
Clouds of various hydrogen compounds
Radius = 1 Jupiter radius
Mass = 1 Jupiter mass
Average density = 1.33 g/cm³
Moons, rings, magnetosphere

“Hot Jupiters” orbiting other stars
Composed primarily of hydrogen and helium
As close as 0.03 AU to their stars
Orbit as short as 1.2 Earth days
Cloud top temperatures up to 1,300 K
Clouds of “rock dust”
Radius up to 1.3 Jupiter radii
Mass from 0.2 to 2 Jupiter masses
Average density as low as 0.2 g/cm³
Moons, rings, magnetospheres: unknown
Quiz

Most of the extrasolar planets discovered so far are

A. Small planets like Earth with very circular orbits
B. Small planets like Earth with eccentric orbits
C. Large planets like Jupiter with circular orbits
D. Large planets like Jupiter with eccentric orbits
What have we learned?

• What have we learned about extrasolar planets?
  – Detected planets are generally much more massive than Earth
  – They tend to have orbital distances smaller than Jupiter’s
  – Some have highly elliptical orbits

• How do extrasolar planets compare with planets in our solar system?
  – Some “hot Jupiters” have been found
13.3 The Formation of Other Solar Systems

Our goals for learning:

- Can we explain the surprising orbits of many extrasolar planets?
- Do we need to modify our theory of solar system formation?
Revisiting the Nebular Theory

- **Nebular theory** predicts that massive Jupiter-like planets should not form inside the **frost line** (at $\ll 5$ AU)
- Discovery of “hot Jupiters” has forced re-examination of nebular theory
- “Planetary migration” or gravitational **encounters** may explain “hot Jupiters”
Planetary Migration

- A young planet’s motion can create waves in a planet-forming disk

- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward
Gravitational Encounters

• Close gravitational encounters between two massive planets can eject one planet while flinging the other into a highly elliptical orbit

• Multiple close encounters with smaller planetesimals can also cause inward migration
Orbital Resonances

- Resonances between planets can also cause their orbits to become more elliptical
Do we need to modify our theory of solar system formation?
Modifying the *Nebular Theory*

- Observations of extrasolar planets have shown that *nebular theory* was *incomplete* (the bottom line was OK)

- Effects like *planet migration* and *gravitational encounters* might be more important than previously thought
Planets: Common or Rare?

- One in ten stars examined so far have turned out to have planets
- The others may still have smaller (Earth-sized) planets that current techniques cannot detect
What have we learned?

• Can we explain the surprising orbits of many extrasolar planets?
  – Original nebular theory cannot account for “hot Jupiters”
  – Planetary migration or gravitational encounters may explain how Jupiter-like planets moved inward

• Do we need to modify our theory of solar system formation?
  – Migration and encounters may play a larger role than previously thought
13.4 Finding New Worlds

Our goals for learning:

• How will we search for Earth-like planets?
How will we search for Earth-like planets?

Transit Missions

• NASA’s *Kepler* mission began to look for transiting planets in 2009

• Will stare the stars in constellation Cygnus continuously for 4 yrs, measuring their brightness every 15min (extended to 2016)

• It is designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star
Kepler’s Transiting Planet Systems

The artist’s rendering depicts the multiple planet systems discovered by NASA’s Kepler mission. Out of hundreds of candidate planetary systems, scientists had previously verified six systems with multiple transiting planets (denoted here in red). Now, Kepler observations have verified planets (shown here in green) in 11 new planetary systems. Many of these systems contain additional planet candidates that are yet to be verified (shown here in dark purple). For reference, the eight planets of the solar system are shown in blue.

Credit: NASA Ames/Jason Steffen, Fermilab Center for Particle Astrophysics
Kepler Candidates as of February 1, 2011
Using NASA's planet-hunting Kepler spacecraft, astronomers have discovered 2,326 candidate planets orbiting other suns since the Kepler mission’s search for Earth-like worlds began in 2009. To find them, Kepler monitors a rich star field to identify planetary transits by the slight dimming of starlight caused by a planet crossing the face of its parent star. In this remarkable illustration, "Kepler's Planet Candidates," all of Kepler's planet candidates are shown in transit with their parent stars ordered by size from top left to bottom right. Simulated stellar disks and the silhouettes of transiting planets are all shown at the same relative scale, with saturated star colors. Of course, some stars show more than one planet in transit, but you may have to examine the picture at high resolution to spot them all. The star's color represents its temperature as shown in the lower scale, and the letter (A,F,G,K,M) are how astronomers classify star types. Look carefully: some systems have multiple planets. For reference, Jupiter is shown transiting the sun.

Credit: Jason Rowe, NASA Ames Research Center and SETI Institute
What have we learned?

• How will we search for Earth-like planets?
  – Transit missions like *Kepler* will find Earth-like planets that cross in front of their stars.
  – Astrometric missions will be capable of measuring the “wobble” of a star caused by an orbiting Earth-like planet
  – Missions for direct detection of an Earth-like planet will need to use special techniques (like interferometry) for blocking starlight