Extrasolar Planets
Are you here today?
(a) yes
(b) no
(c) Captain, the sensors indicate a class M planet orbiting this star
Exam #2 (again)

- The second midterm exam is **next Tuesday, 5/10**, during the first half of class - please come on time (or better yet, early)
- It will be multiple choice, and you will take it using a 50-question scantron, so make sure to bring one to class!
- It will cover the material in Chapters 6, S2, 13, 14, 15, 16 of the optional textbook (what we covered in class since the last midterm through today)
- The format will be the same as the first midterm
- Most questions will look something like the in-class “Conceptual Questions” or the Lecture Tutorial and Ranking Task questions - your LT book is your textbook to study from
- Cell phones **must** be off and put away during the exam (as they should be in every class). If I see or hear a cell phone that is grounds to **fail the exam**!
- There will be no second half of class, so once you are done you will have the afternoon off. Don’t have too much fun! :)
Today’s Topics

- Extrasolar Planets - the problem
- Formation of our Solar System
- Doppler Detection of Extrasolar Planets
- Properties of Extrasolar Planets
- Effect on Models of Solar System Formation
- Other Techniques of Extrasolar Planet Detection
The Problem

- Until 1995, we only knew of one Solar System - our own
- We had suspected for hundreds of years, and had confirmed as long ago as the 1800s (by stellar parallax) that the stars were extremely distant Suns
- Only their extreme intrinsic brightness makes them visible over such vast distances
- Planets shine by reflected light and are much smaller than stars, so direct detection of planets around other stars is extremely difficult (Jupiter would be 1 billionth as bright as the Sun from outside the Solar System)
- As we will see, the first detections of extrasolar planets came indirectly
Before we consider extrasolar planets, let’s first discuss our own Solar System.

Two main features of our Solar System that any theory of formation must explain:

1. Organized, nearly circular orbits of the planets
2. 2 major categories of planets
   a) Inner, small, rocky, *terrestrial* planets (Mercury, Venus, Earth, Mars)
   b) Outer, large, gaseous (H, He) *jovian* planets (Jupiter, Saturn, Uranus, Neptune)
Formation of our Solar System

- As we saw in our discussion of star formation, stars form from spinning clouds of hydrogen gas that contract by gravity.
- As the cloud contracts, it spins faster, much as a spinning skater spins faster as she draws in her arms. **Spinning Platform Demo**
- The disk will be densest (and hottest) in the center; the temperature drops as one moves further from the star.
Formation of our Solar System

- Let’s focus on the second of our features of the Solar System, namely the 2 major categories of planets
  a) Inner, small, rocky, *terrestrial* planets
  b) Outer, large, gaseous (H, He) *jovian* planets
- This feature can be explained by considering the temperature gradient in the solar nebula and the condensation temperature of common materials in the solar nebula
- In the inner solar system (inside the “ice line”), minerals and metals can condense but water and other hydrogen compounds (CH$_4$, NH$_3$) cannot, so the planets formed are rocky and small (minerals and metals make up ~ 0.6% of the nebula)
Formation of our Solar System

- In the outer solar system, outside the “ice line”, hydrogen compounds can condense (freeze) so there is ~3x as much material to form solid (icy) planetesimals.
- These planetesimals become large enough to gravitationally capture hydrogen and helium gas, growing into gas giants, which have icy-rocky cores.
- Models show that a core of 3-20 $M_{\text{earth}}$ will lead to planets like Uranus (14 $M_{\text{earth}}$) and Jupiter (318 $M_{\text{earth}}$).
Lecture Tutorial: *Temperature and Formation of the Solar System*, pp. 111-112

- Work with one or more partners - not alone!
- Get right to work - you have **10 minutes**
- Read the instructions and questions carefully.
- Discuss the concepts and your answers with one another. **Take time to understand it now!!!!**
- Come to a consensus answer you all agree on.
- Write clear explanations for your answers.
- If you get stuck or are not sure of your answer, ask another group.
- If you get really stuck or don’t understand what the Lecture Tutorial is asking, ask me for help.
Planet Formation Quiz

Which of the following types of planets would form in the early solar system at locations hot enough for liquid water to boil into a gas?

a) rocky terrestrial planets
b) jovian gas giant planets
Detection of Extrasolar Planets

- In 1995, the first planet around a main sequence star was detected.
- Since direct detection is currently impossible, how was it found?
- To answer this, consider the Sun and Jupiter:
  - Although Kepler considered the planets to be orbiting a stationary Sun, Newton showed that all pairs of bodies orbit a common center-of-mass (COM).
  - In the case of the Sun and Jupiter, the COM is near the edge of the Sun.
  - Thus, every 12 years, as Jupiter orbits at an average distance of 5 AU, the Sun conducts a small loop of radius equal to the Sun’s radius with the same period.
  - The speed of the Sun in this orbit is much smaller than $v_{\text{jupiter}} = 412 \text{ m/s}$, about 13 m/s.
Detection of Extrasolar Planets

Detection of Extrasolar Planets

- Although this speed is small, if one looked carefully at the absorption line spectrum of the Sun, one would see the lines redshifted and blueshifted as the Sun executed its (near-circular) orbit.
- The size of this Doppler shift would be tiny (about 40 parts per billion) about $20 \times 10^{-6}$ nm shift in wavelength at 500 nm.
- Since the Doppler shift is due to the tug of gravity by the planet on the star, the size of the shift grows as:
  1. the planet mass gets larger relative to the star’s mass
  2. the planet’s orbit is closer to the star

\[
F_{\text{grav}} \propto \frac{M_{\text{star}} m_{\text{planet}}}{r_{s-p}^2} \quad \text{so} \quad a_{\text{star}} = \frac{F_{\text{grav}}}{M_{\text{star}}} \propto \frac{m_{\text{planet}}}{r_{s-p}^2}
\]
Detection of Extrasolar Planets

• In 1995, a planet was discovered orbiting the star 51 Pegasi
• As the planet orbited the star, the star was tugged back and forth (like the Sun), leading to a Doppler shift in the star’s absorption lines which, when converted to velocities looked like the figure
• Notice the scale (≈ 57 m/s), about 4 times the shift of the Sun, but still very small
• Also note the time-scale (4 day period!)
• The planet must be very close to the star (a ~ 0.05 AU < 0.39 AU for Mercury)

**Kepler’s 3rd Law**

• From the size of the Doppler shift, the mass of the planet is ~ 0.5 \( M_{\text{jupiter} \.} \)
Detection of Extrasolar Planets

- This assumes we are viewing the orbit edge-on
- If the orbit is tilted, the velocity *along the line-of-sight* (which is what causes the Doppler shift) is smaller, so the mass estimate is a **lower limit**
- Most of the first detections of extrasolar planets have been discovered by the “Doppler” technique
- Note that of these early detections
  - most of them have masses more similar to Jupiter than Earth,
  - are at distances closer than Jupiter, and
  - many are in highly eccentric orbits
- Why? \( a_{\text{star}} \propto \frac{m_{\text{planet}}}{r_{\text{s-p}}^2} \)
- Recall
- The method is biased towards large, close planets
Summary of Doppler Technique

1. The star and planet are orbiting the COM with the same period
   • Thus, the observed period of the star is equal to the period of the planet

2. The period of the orbit gives the size of the orbit (Kepler’s 3rd Law)

3. At every moment, the star and planet are moving in opposite directions
   • Thus, when the planet is moving away from the Earth, the star is moving towards the Earth, and vice versa

4. We observe the star’s spectrum
   • Thus, when we see a redshift (positive velocity), the star is moving away from the Earth, and the planet is moving towards the Earth, and vice versa

5. The mass of the planet relative to the star and the distance between the star and planet determine the size of the Doppler shift
   • Higher planet mass ⇒ larger Doppler shift
   • Closer distance ⇒ larger Doppler shift
Attendance Quiz

Are you here today?

(a) yes
(b) no
(c) Captain, the sensors indicate a class M planet orbiting this star
To detect an extrasolar planet by means of the Doppler shift, you look for a periodic shift of the spectrum lines

a) of the planet
b) of the star the planet is orbiting
c) of the star and the planet
Lecture Tutorial: *Motion of Extrasolar Planets*, pp. 125-131

- Work with one or more partners - not alone!
- Get right to work - you have **20 minutes**
- Read the instructions and questions carefully.
- Discuss the concepts and your answers with one another. Take time to understand it now!!!!
- Come to a consensus answer you all agree on.
- Write clear explanations for your answers.
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- If you get really stuck or don’t understand what the Lecture Tutorial is asking, ask me for help.
Extrasolar Planets Quiz II

The orbital period of an unseen planet

a) will be the same as period of the star’s Doppler shift
b) will be much larger than the star’s
c) will be much smaller than the star’s
Extrasolar Planets Quiz III

The shorter the period of the Doppler curve

a) the farther the unseen planet is from the star
b) the closer the unseen planet is to the star
c) the greater the mass of the planet
d) the smaller the mass of the planet
e) (b) and (c)
The larger the mass of the unseen planet

a) The larger the Doppler shift of the star
b) The smaller the Doppler shift of the star
c) The faster the period of the star’s Doppler shift
d) The slower the period of the star’s shift
e) (a) and (c)
Given the location marked with the dot on the star’s radial velocity curve, at what position (1-4) would you expect the planet to be located at this time?

- a) 1
- b) 2
- c) 3
- d) 4
Transit-Eclipse Detection of Extrasolar Planets

- The other main technique of detecting extrasolar planets is transits or eclipses.
  Note: Mercury transited the Sun in November 2006 – next one is on Monday!
  Venus transited the Sun in 2004 and 2012 – next one in 2217!
Transit-Eclipse Detection of Extrasolar Planets

- Recall that in eclipsing binary stars, one star occults the other, causing a dip in the combined amount of light from both stars.
- When a planet transits a star, it blocks a small amount (less than 1%) of the star’s light; when the planet is behind the star, its thermal (infrared) radiation is blocked.
- Note: this technique only works when we view the planetary orbit nearly edge-on.
The NASA Kepler Mission

Launched in 2009

Using the transit method of planet discovery

Monitored 200,000 stars for 4 years
Inching closer to Earth’s twin…

KEPLER-20e
DECEMBER 2011

KEPLER-22b
DECEMBER 2011

KEPLER-186f
APRIL 2014

KEPLER-452b
JULY 2015

ARTISTIC CONCEPT
95 Planet Candidates Orbiting Red Dwarfs

![Graph showing the size of planets relative to Earth against the light received by the planet relative to Earth.](image)