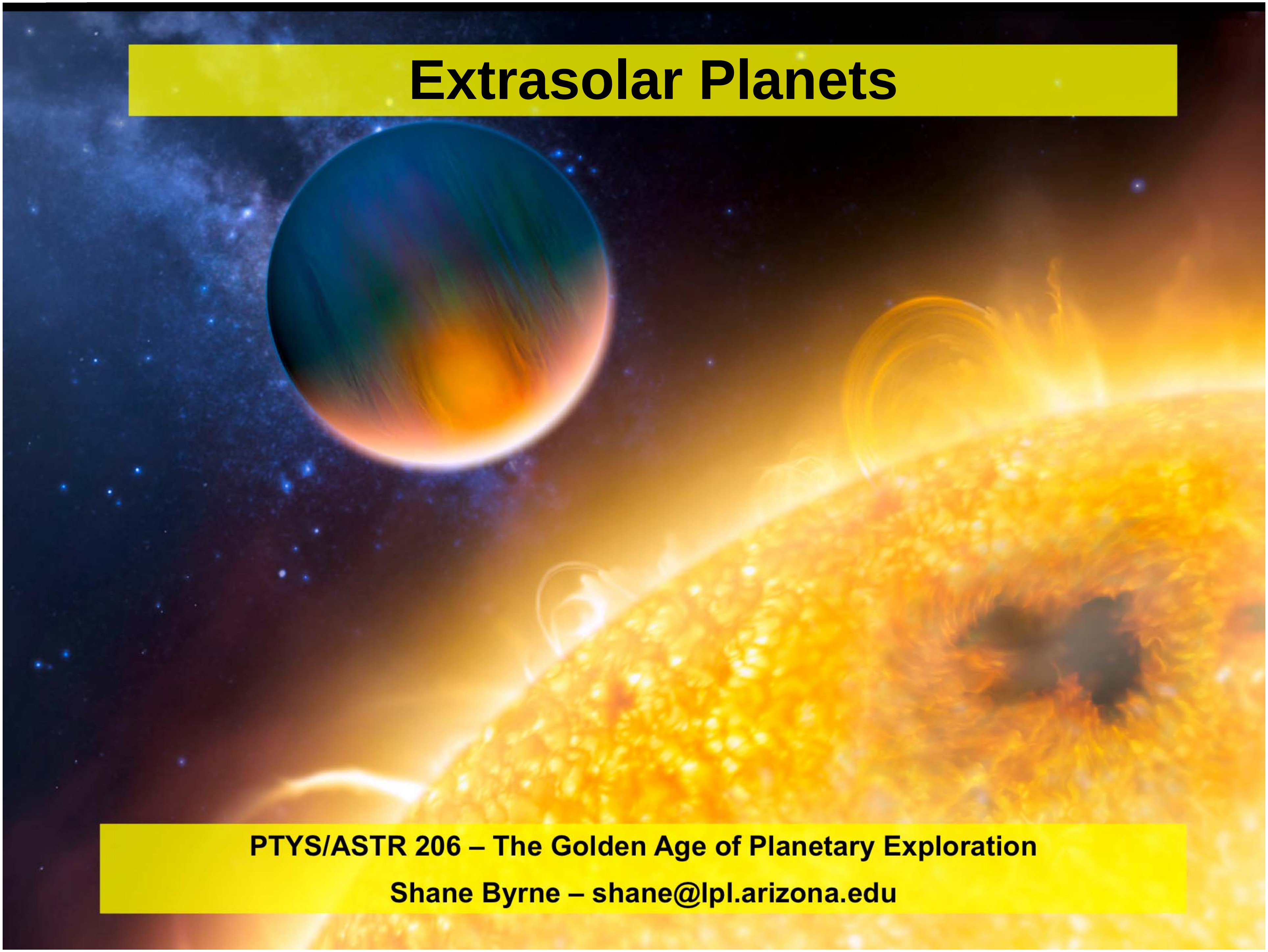
- **Announcements**
  - **HW6 due now**
    - **Or next Tuesday for partial credit**
  - **Course Evaluations**
    - **2 forms**
    - **One for the course, one for the instructor**
    - **We’ll finish early so you can fill these out**
  - **TA award nominations**
    - **Optional – if you think one of the TAs should get special recognition**
    - **Don’t just check the boxes, you need to write a few words about what the TA did that you liked.**
    - **Forms and submission box are on the table outside**

- **Textbook**
  - **Was reading the book useful for the lectures?**
  - **Was the book useful for the homework?**
- **Clickers**
  - **How many of you have purchased a clicker for use in a UA class?**
  - **How many of you have had to purchase more than one type of clicker?**
  - **Could you find cheaper 2nd hand clickers?**
  - **How many of you feel that the expenditure was worthwhile and added to your educational experience?**

Extrasolar Planets



PTYS/ASTR 206 – The Golden Age of Planetary Exploration

Shane Byrne – shane@lpl.arizona.edu

In this lecture…

- Review how planets form
- Other types of stars
- How we detect extrasolar planets
  - Radial velocity
  - Astrometry
  - Transits
  - Direct imaging!
- Characteristics of extrasolar planets
  - Orbits
  - Atmospheres
  - Densities
- Future missions

The raw material

- **Solar systems form from large clouds of gas and dust**
  - **Giant Molecular clouds**

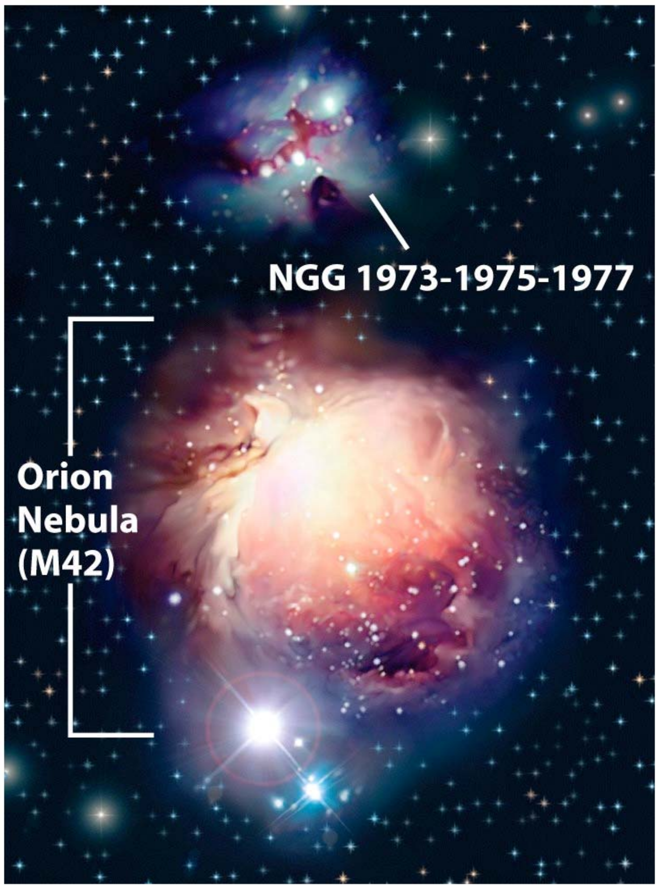


Figure 8-8a
Universe, Eighth Edition

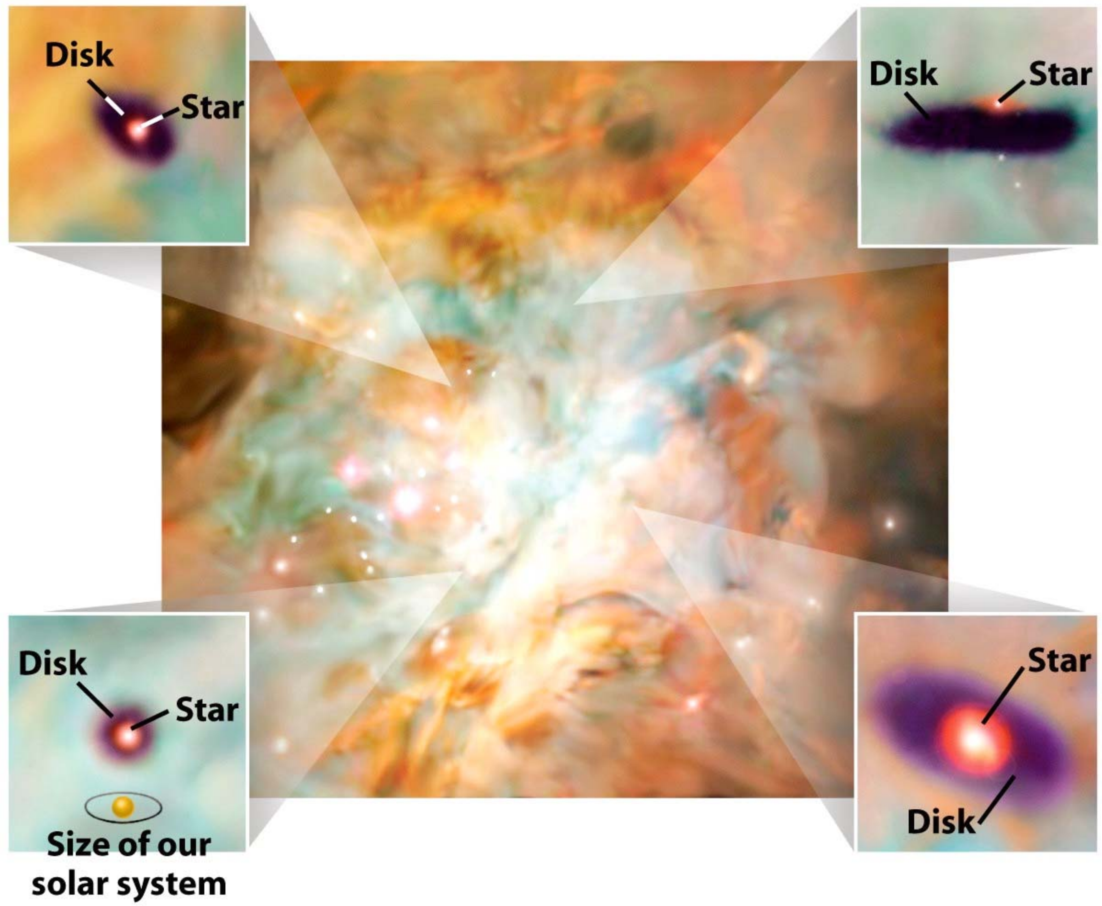
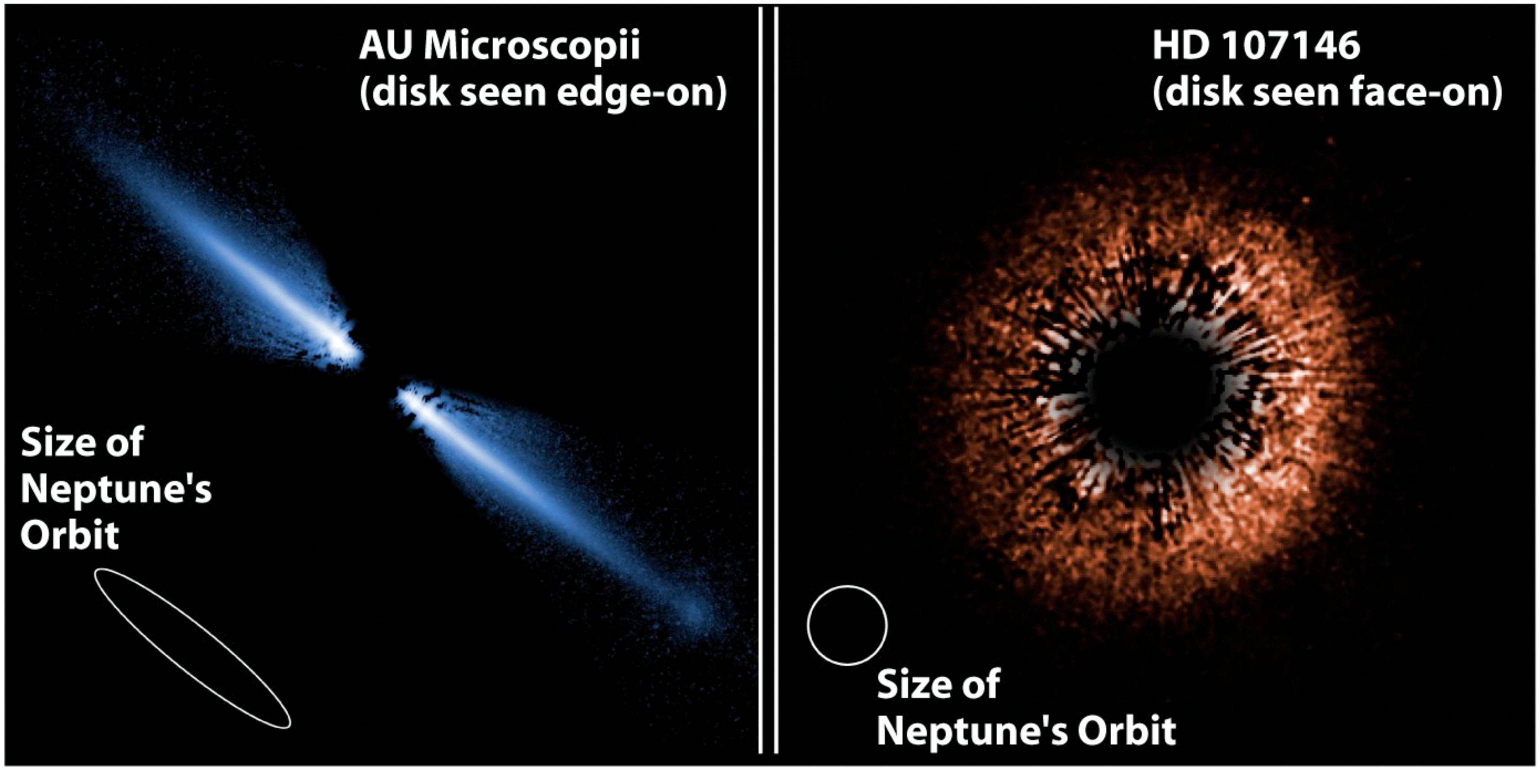


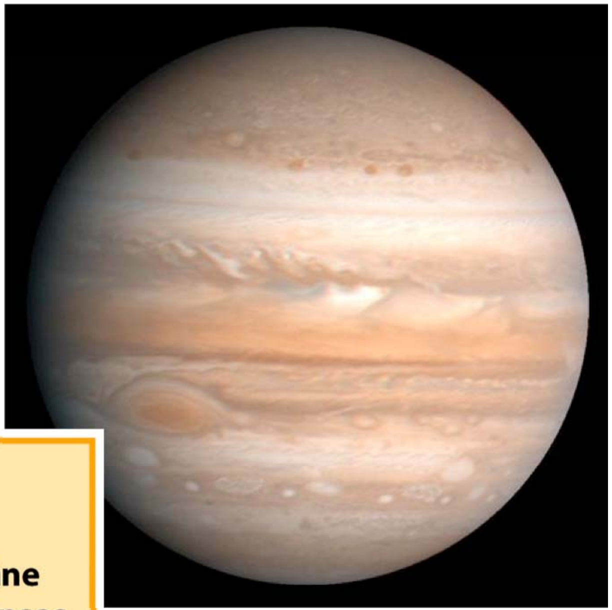
Figure 8-8b
Universe, Eighth Edition

- These disks are a common occurrence
  - Disk material is much hotter and denser than the giant molecular cloud
- Proto-star at center
  - Contraction generates heat
  - Heat and pressure allow nuclear fusion
  - Star switches on and generates its own energy



Chapter 8 Opener
Universe, Eighth Edition

- **Large gas giants (like Jupiter) form far from the sun**
- **Small rocky planets (like Earth) form close to the sun**



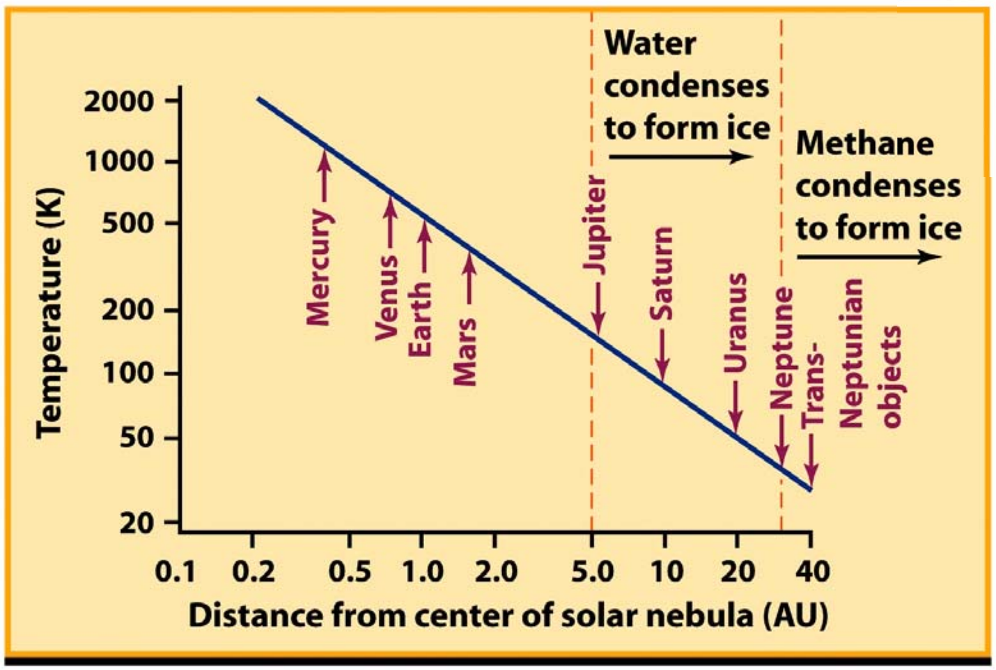
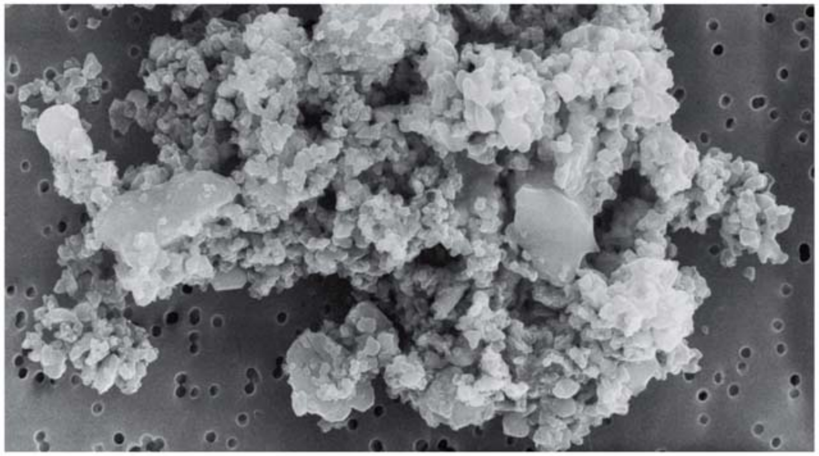


Figure 8-10
Universe, Eighth Edition

- **Particles suspended in gas**
  - **Collide and join together to form clumps**
  - **Grow to 1cm in size**



10 μm = 0.01 mm

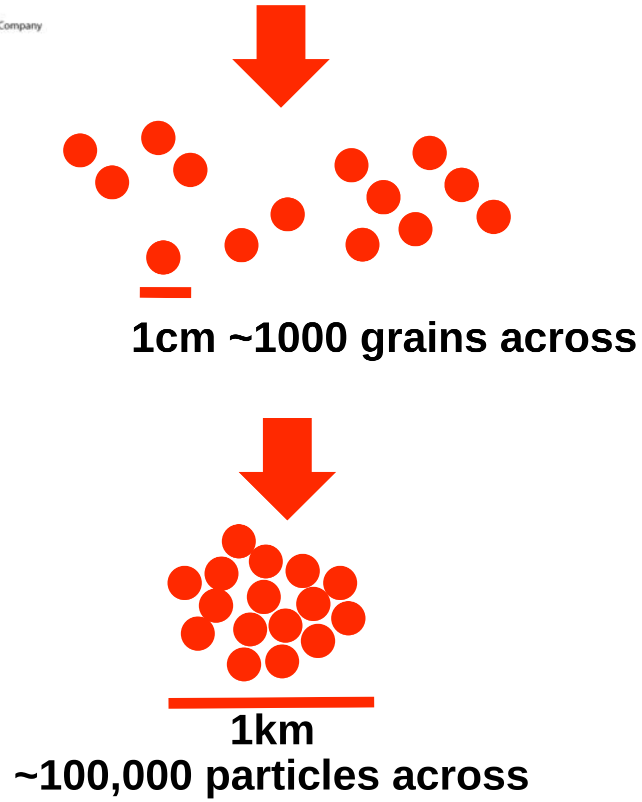
Figure 8-9
Universe, Eighth Edition

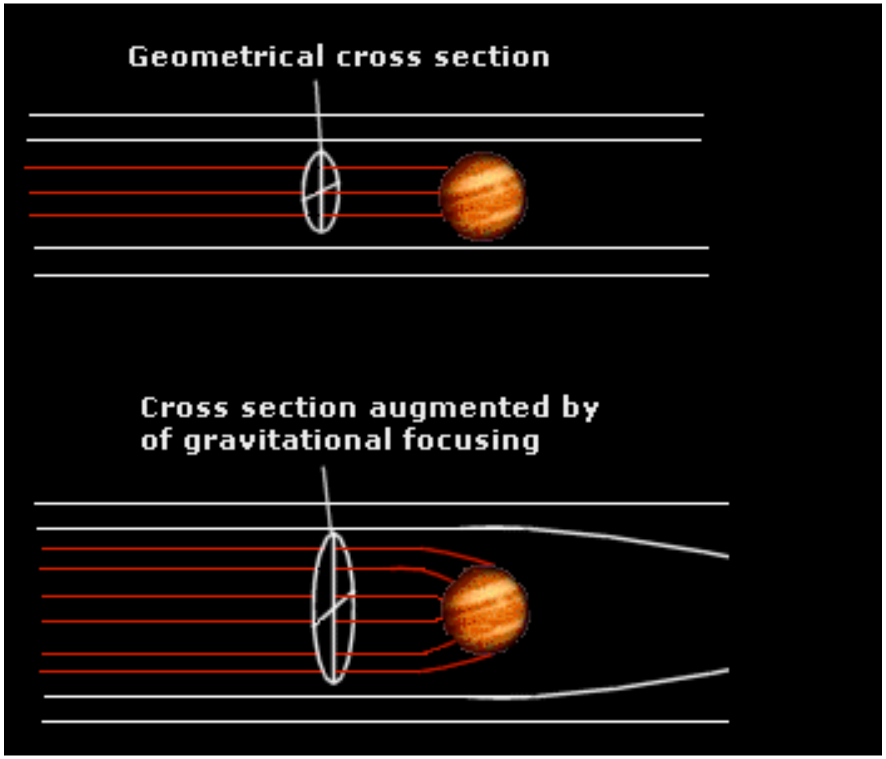
- **Particles >1cm in size grow by collisions**
  - **Decoupled from the gas motions**
  - **Suffer gas drag**
  - **Start spiraling into the sun**

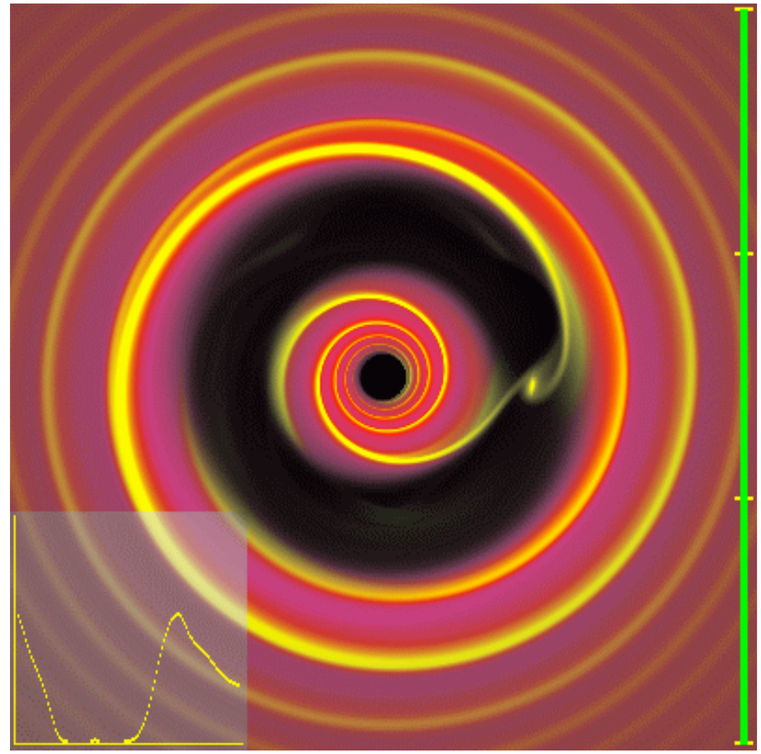
The weak link in the story goes here.

Getting to kilometer-size before falling into the sun is still an unsolved problem…

- **Particles eventually grow to 1km**
  - **Gas drag becomes irrelevant**







- Gravity starts to take over
  - Objects grow quickly
- Giant rocky/ice cores can form where water ice is stable
  - Giant cores can capture large gas envelopes
  - Must do this before the disk dissapates

- **We already see plenty of forming stars with gas disks….**
- **We already see plenty of debris disks**
  - **What’s left after the gas gets stripped away**
- **But do any of them have planets like ours?**

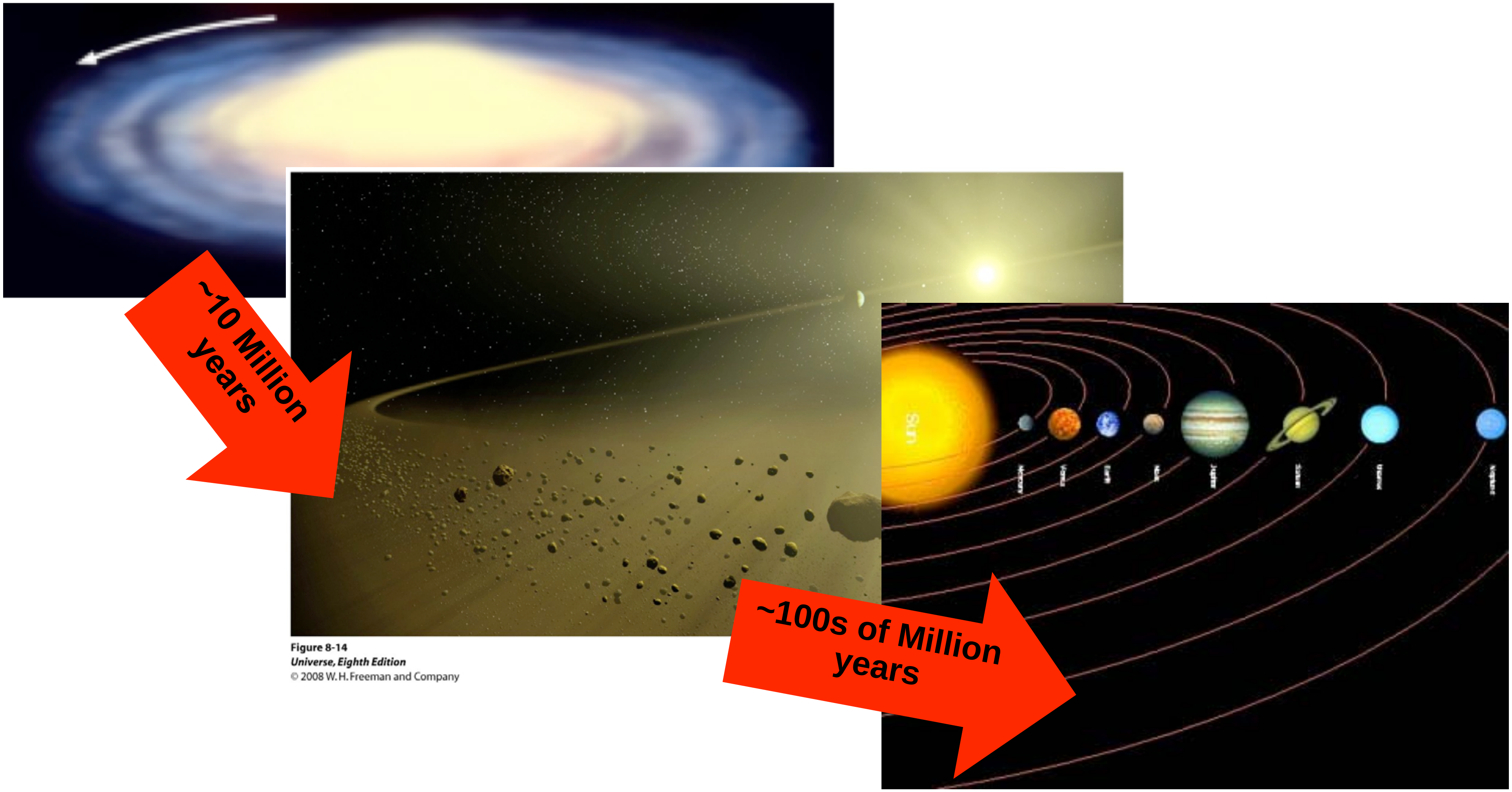


Figure 8-14
Universe, Eighth Edition
© 2008 W. H. Freeman and Company

- **We have big telescopes…. So what's the problem?**
  - **Why don't we just take pictures of these planets?**
  - **Planets aren't dim, we should be able to see them easily…**

- **It's not the planet that's the problem…**
  - **It's the nearby star that's blinding us.**

Comparing the sun to other stars

- **Pretty mediocre – fortunately for us**

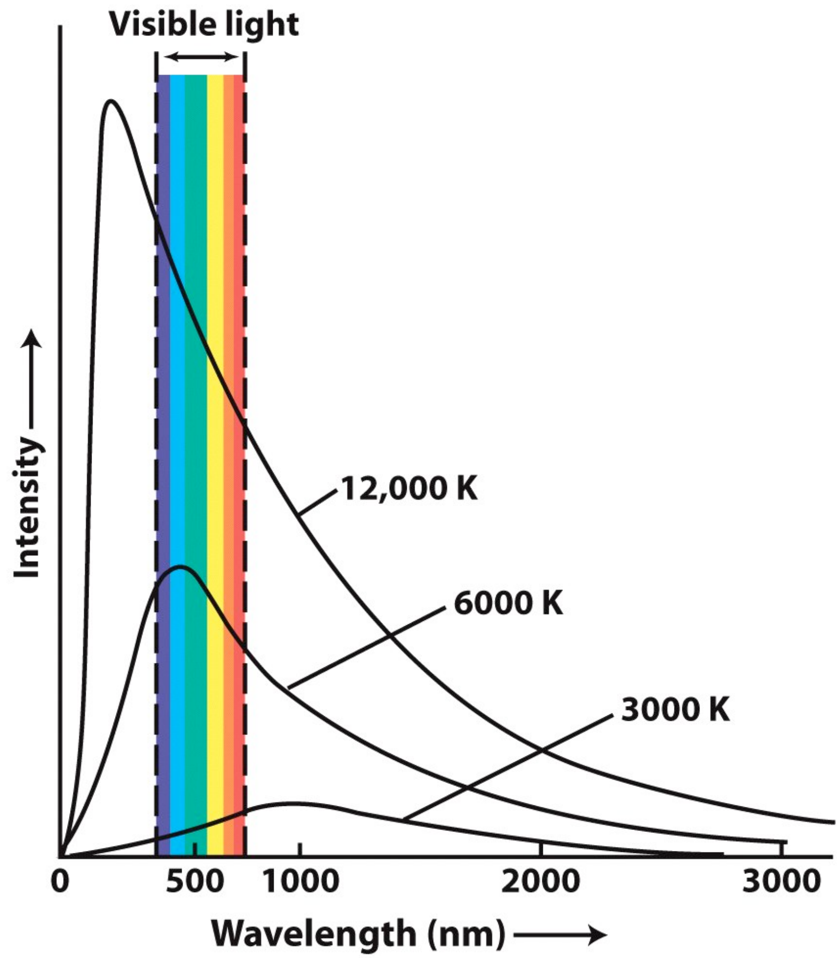
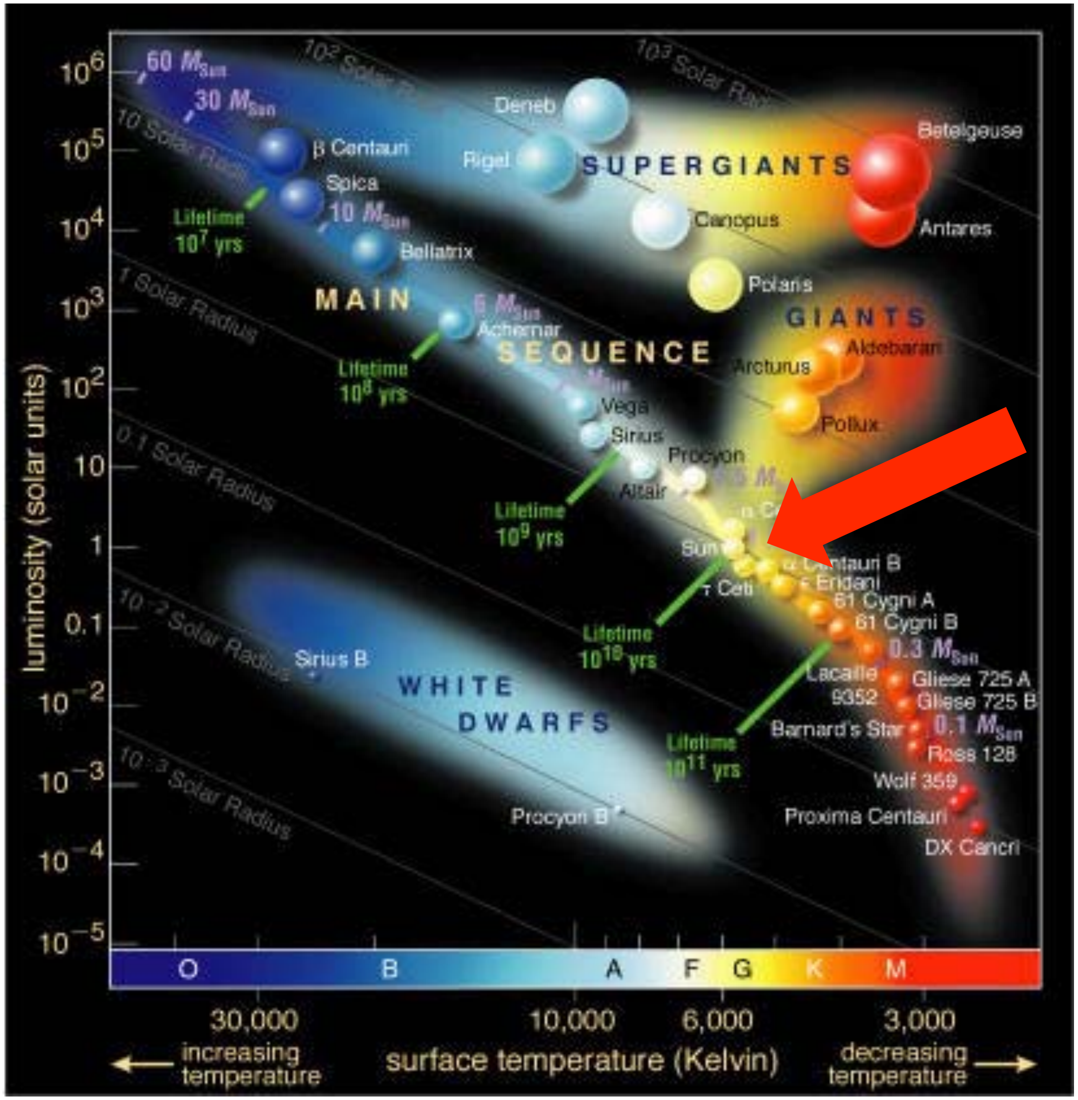
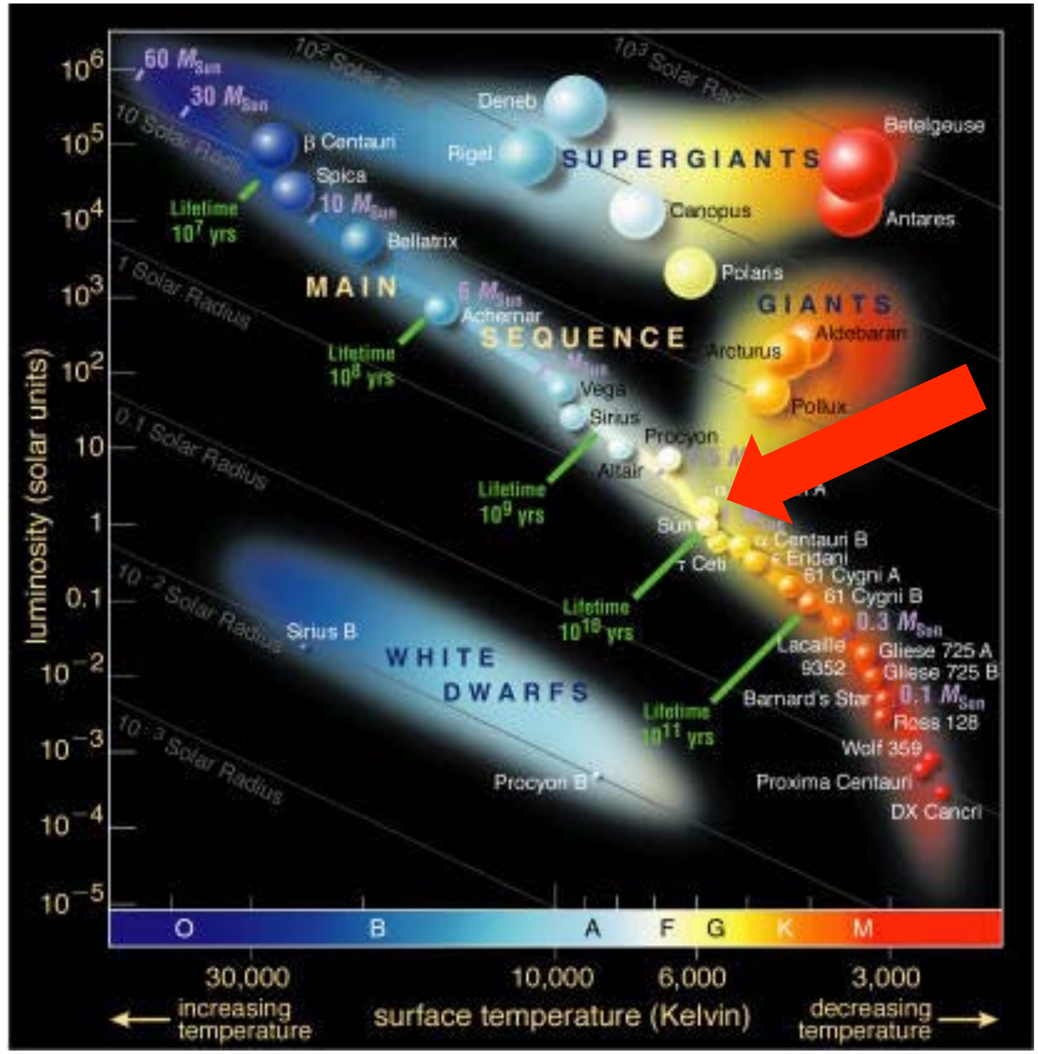


Figure 5-11
Universe, Eighth Edition



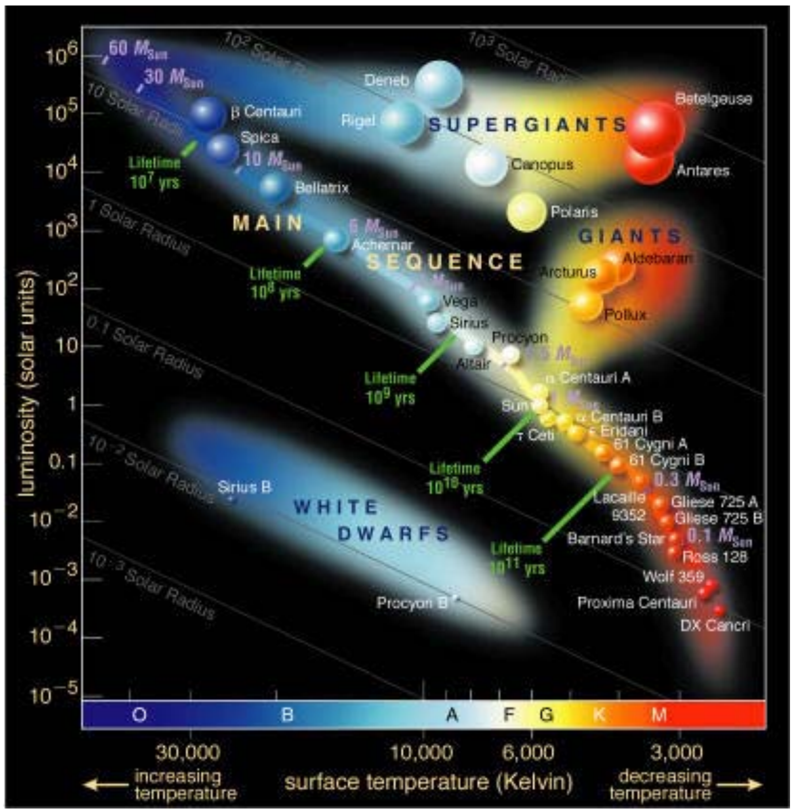
- When stars burn hydrogen
  - Bigger stars -> higher core pressures -> more energy produced
  - Bigger stars are hotter (and bluer)
    - This is the “main sequence”

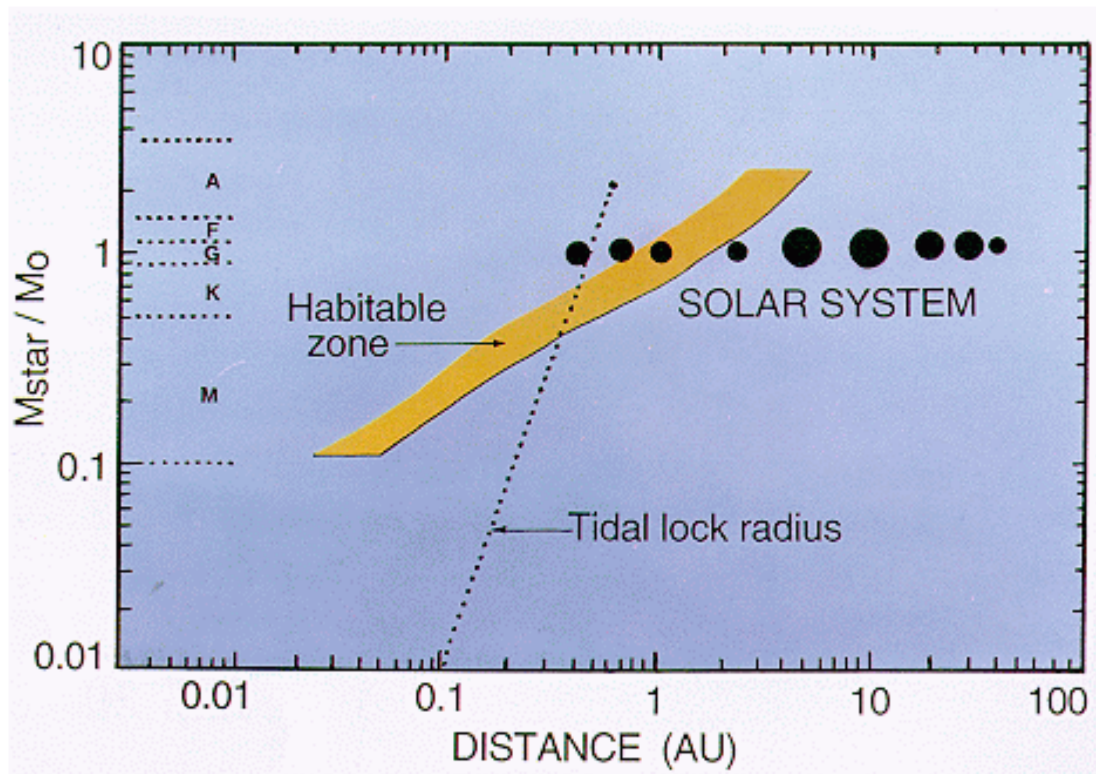


- The sun is a “main sequence” star

- Bigger stars burn hydrogen faster
  - Bigger = short-lived
  - Sun lasts ~10 billion years
  - We’re about half-way through

- Implications for extra-solar planets and life
  - Big stars – too short-lived and too hot!
  - Very Small stars – Don't produce enough energy
  - Solar type stars are the best





- **What stars have planets?**
  - **Not all stars have the same composition**
    - **All roughly ¾ hydrogen, ¼ helium**
    - **With a few percent other stuff**
    - **It's the 'other stuff' that builds planets!**
  - **Stars with more impurities are more likely to have planets**

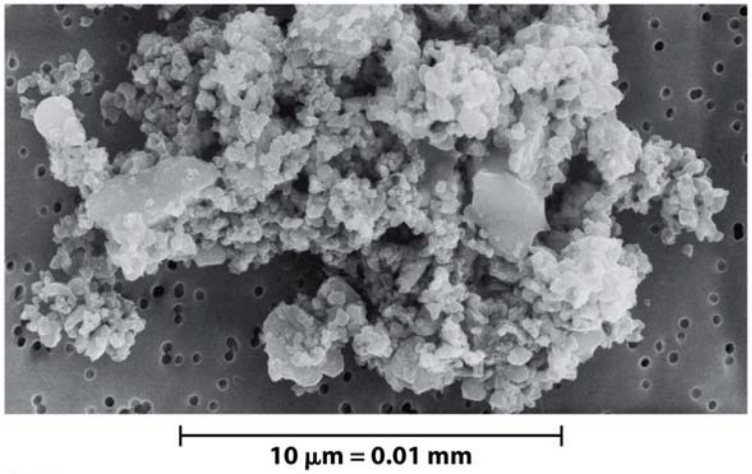


Figure 8-9
Universe, Eighth Edition

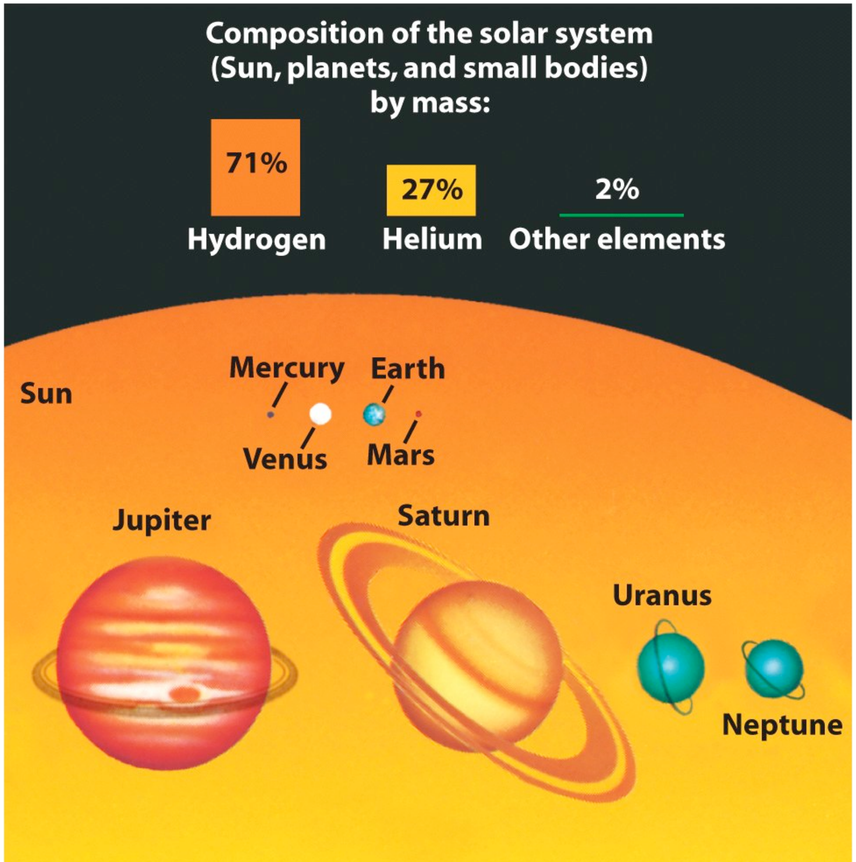
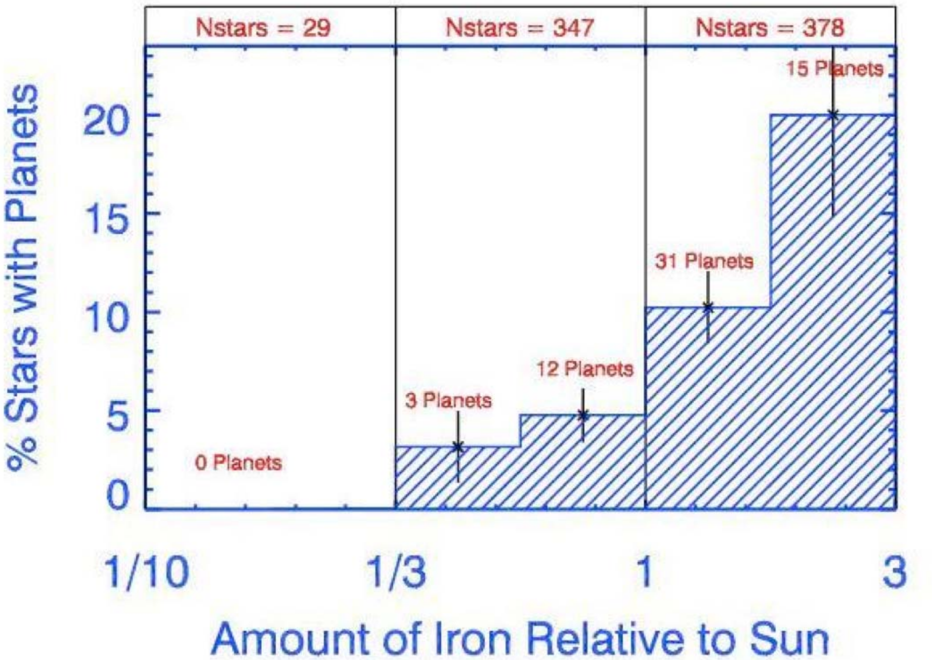


Figure 8-1
***Universe*, Eighth Edition**

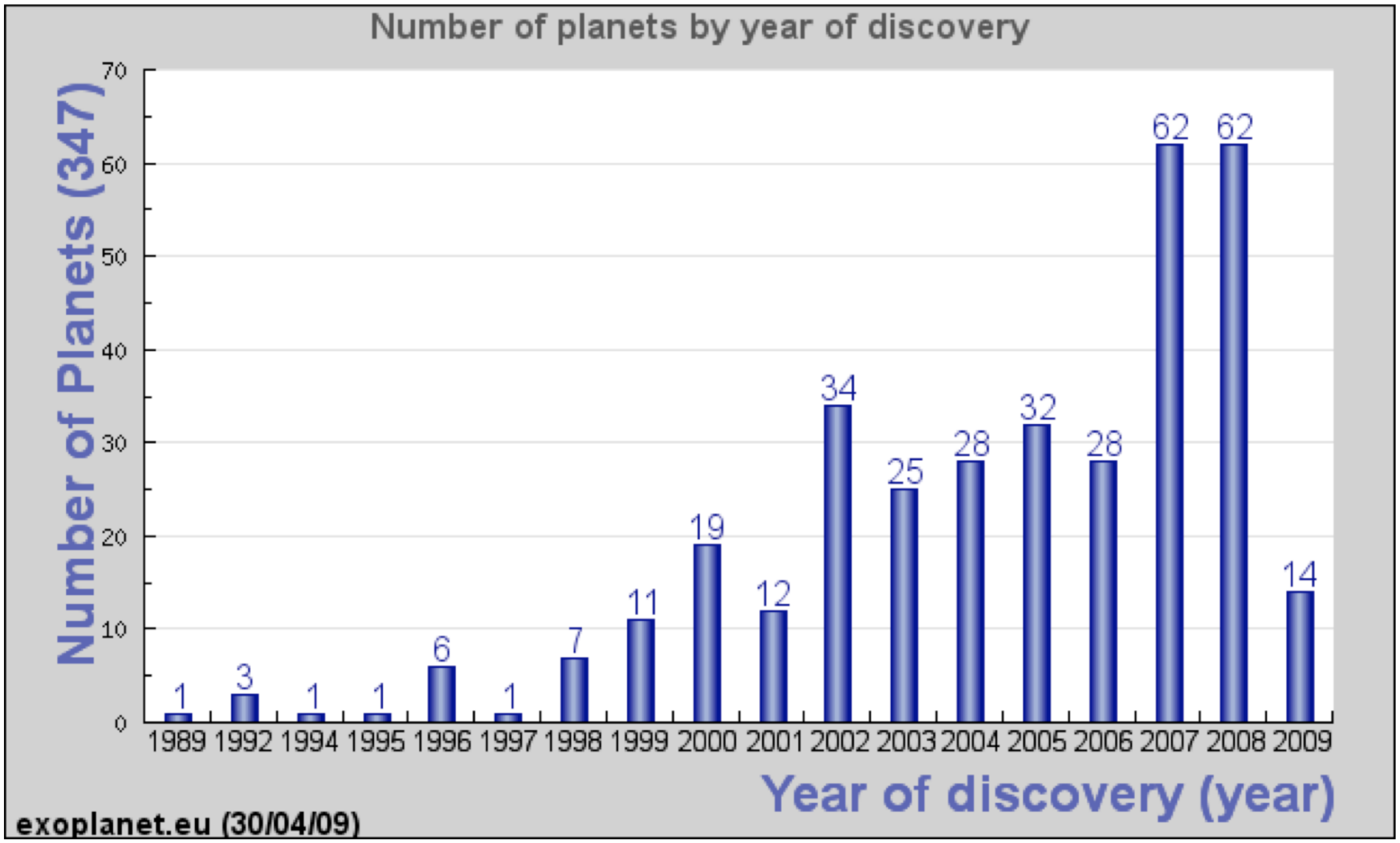
Planet Occurrence Depends on Iron in Stars



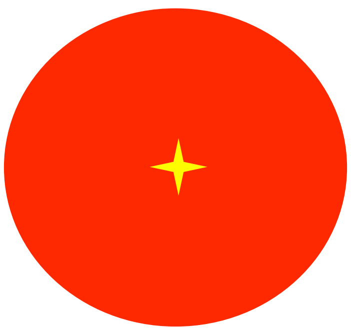
Fischer & Valenti

Detecting Extrasolar Planets

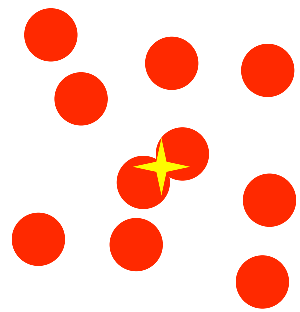
- **Despite the difficulties of seeing extrasolar planets we know of hundreds of them**
  - **347 discoveries so far**
  - **Almost all discovered in the last 10 years or so**
  - **Number known doubles every ~3 years**



- **What's the center of mass?**
  - **Objects orbit around the center of Mass**
    - **Planets don't strictly orbit the Sun**
    - **They orbit a point in space close to the center of the Sun**

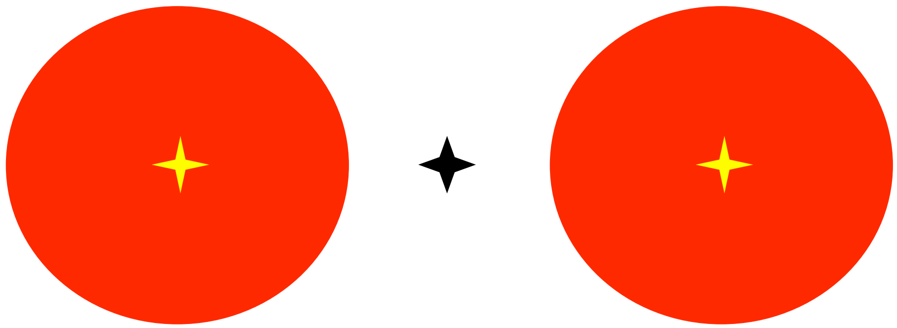
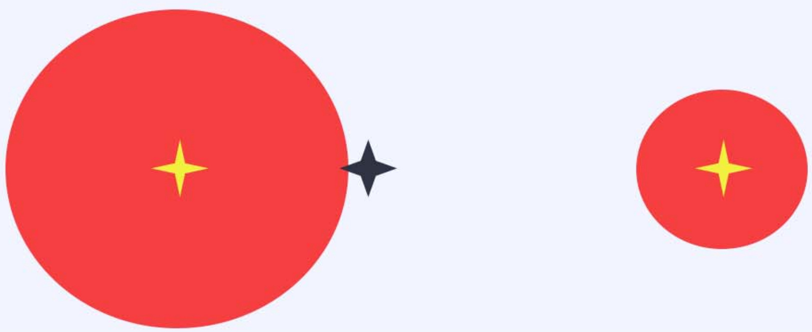
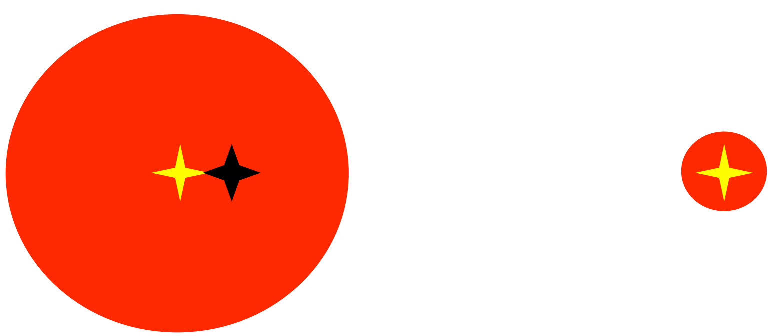


Center of mass of a spherical body is in the center

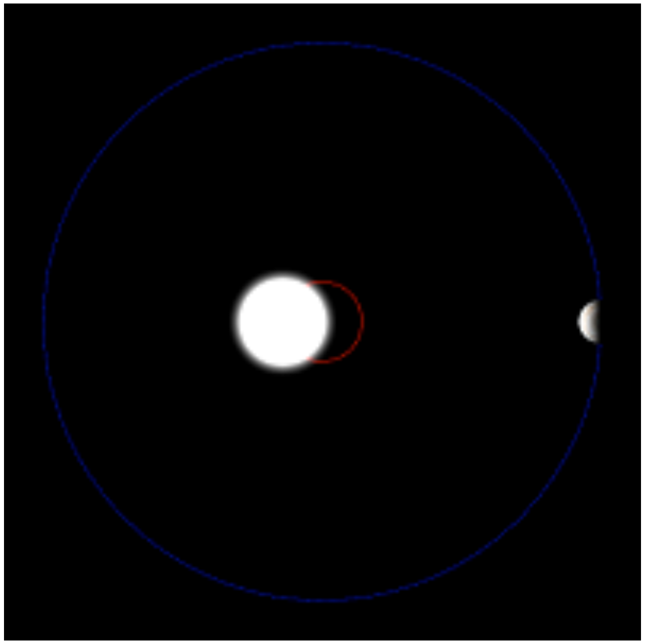


Center of mass of a group of particles is in the center

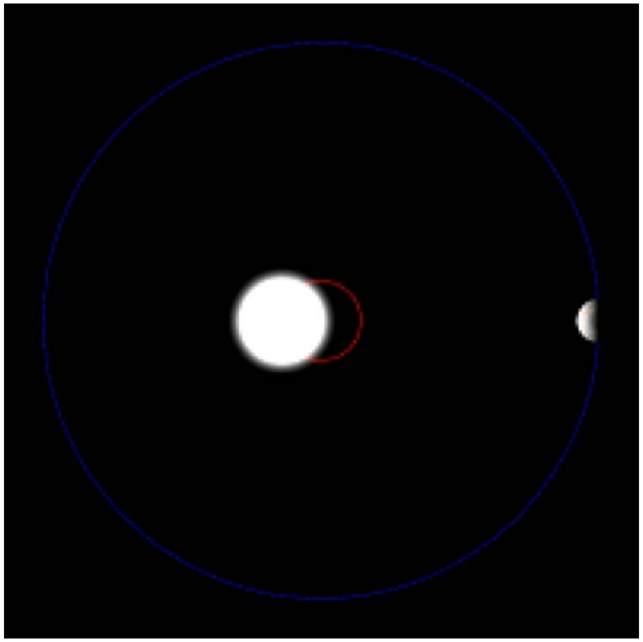
- **Center of mass for two bodies is closer to the bigger body**

	**Two bodies of equal mass**
	**Two bodies of unequal mass (like Pluto & Charon)**
	**Two bodies of very unequal mass (like Earth & the Moon)**

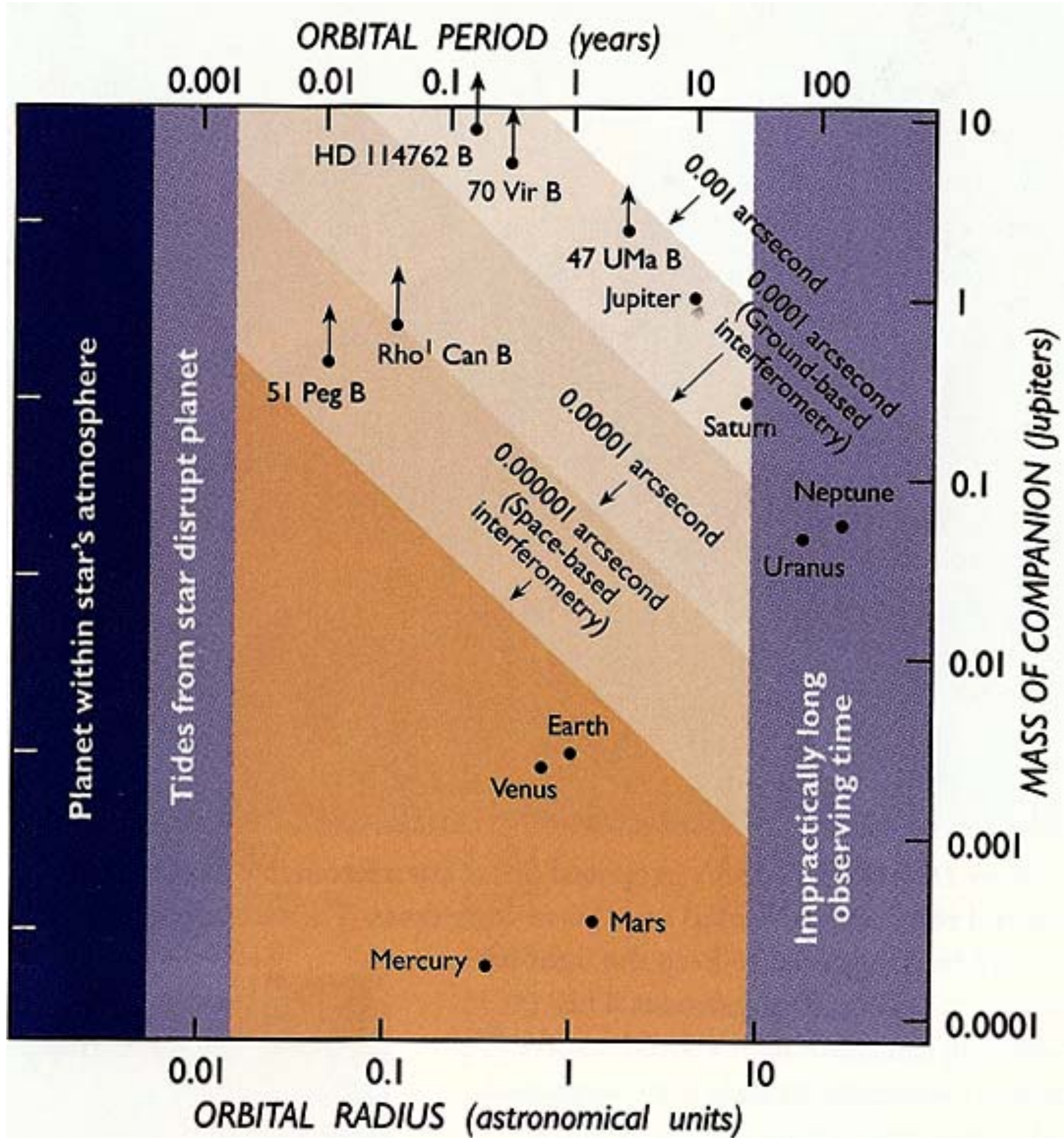
- The star and the planet move
  - Planet has a large orbit
  - Star has a small orbit
- We can look for the star wobbling like this



- When we see the system face-on
  - The star moves in a small circle
  - We can look for this wobble directly
  - Size of the wobble is biggest when
    - The planet is big
    - The planet's orbit is big
  - Technique called ASTROMETRY



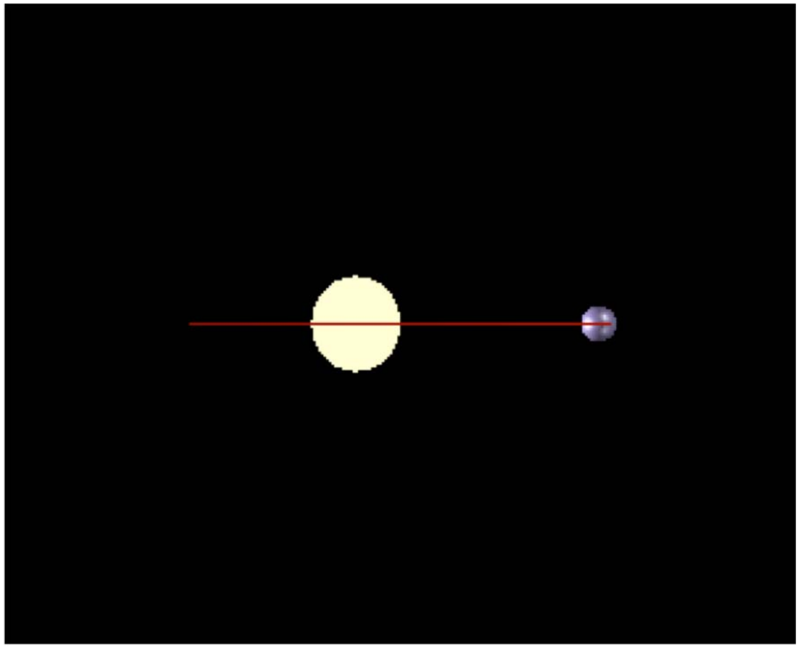
- Astrometry limits

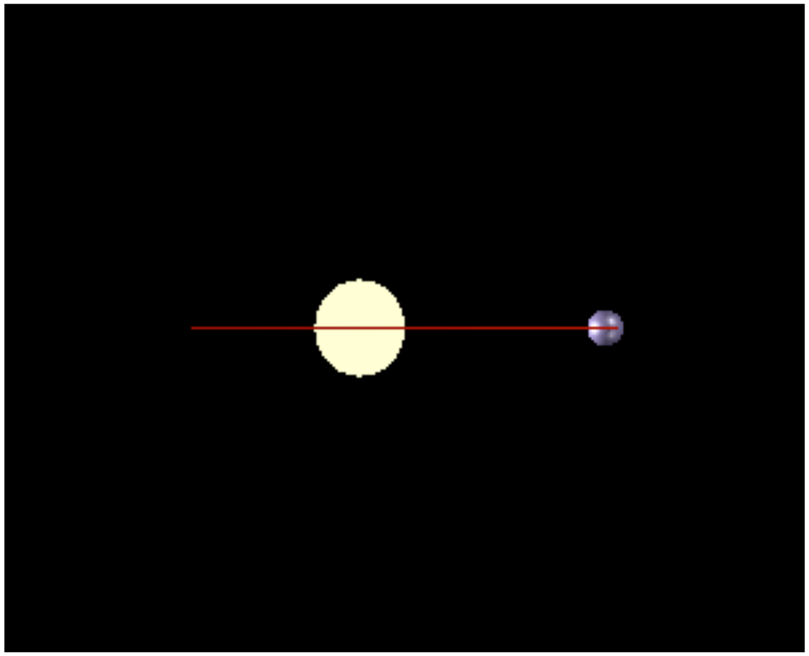


- **When we see the system edge on the motion isn't as obvious**

- **We can detect this motion in other ways**
  - **The star moves towards us and away from us**
  - **Causes light emitted to be blue-shifted or red-shifted**
  - **Doppler effect**

- **This is called the RADIAL VELOCITY technique**





- Doppler shift depends on relative motion of the sourced and the observer
  - Only motion from toward and away from the observer matters
  - Side to side motion doesn’t produce this effect

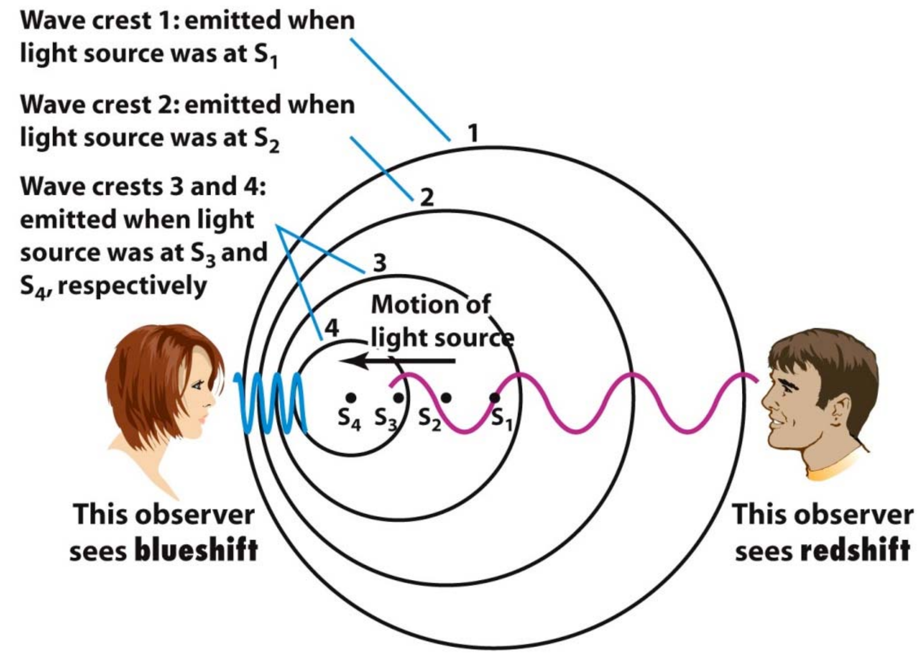
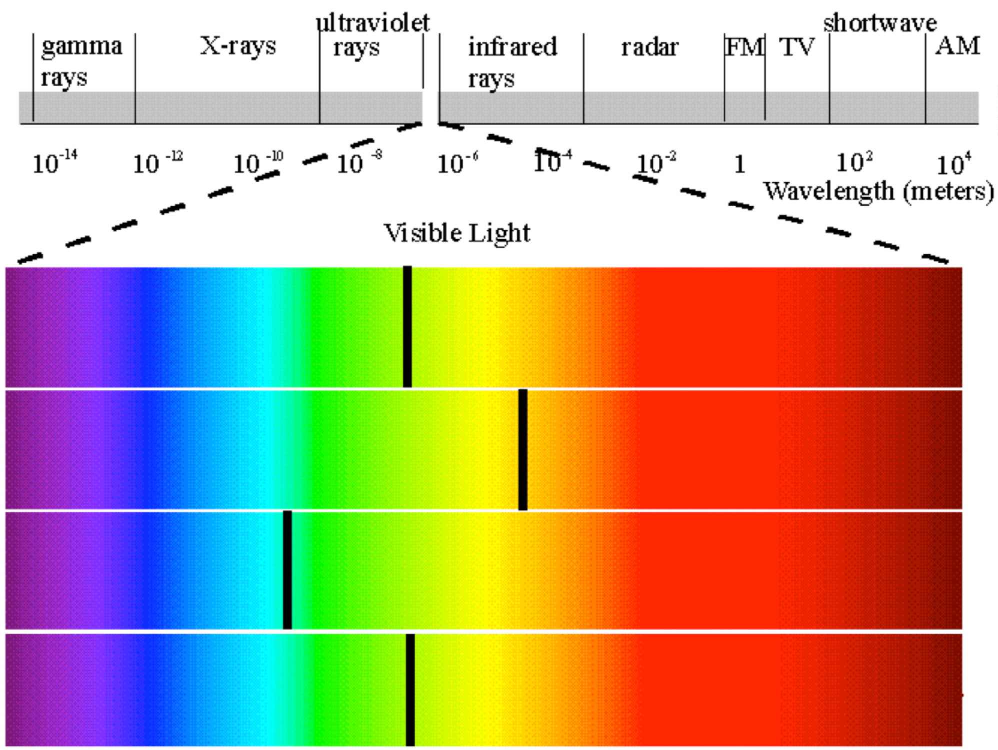


Figure 5-26
Universe, Eighth Edition

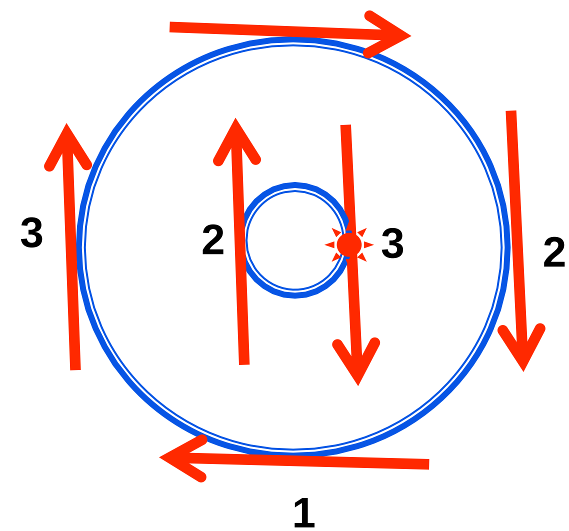


Time 1

Time 2

Time 3

Time 4



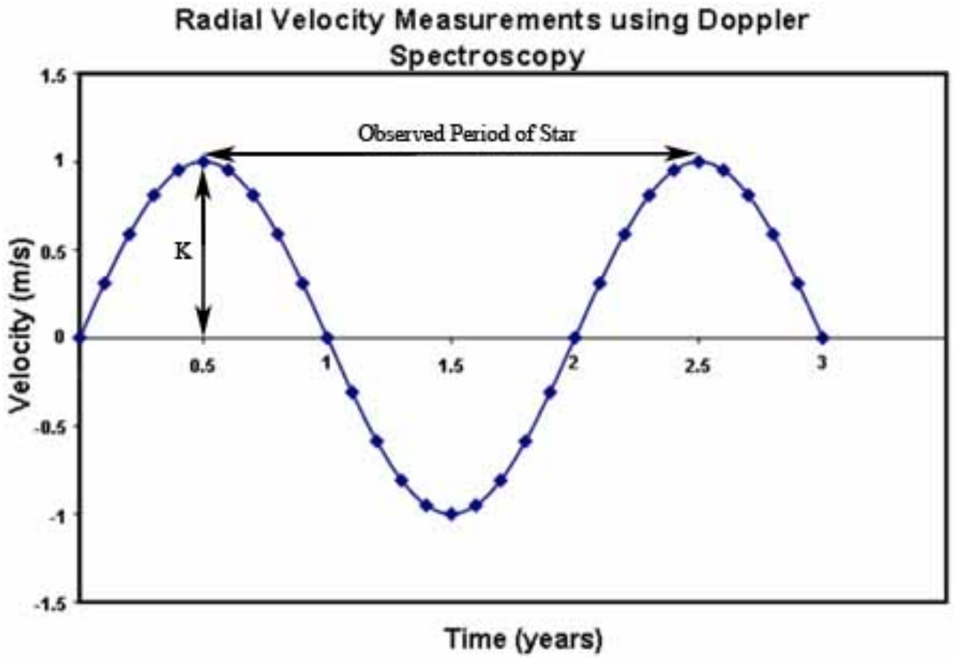
Observer down here

- **How fast do the stars move?**
  - **Much slower than the planet tugging them**
  - **Depends on how big the planet is…**
  - **Depends on the speed of the planet**
    - **How far from the star it is**
    - **Closer planets move faster and are easier to detect**

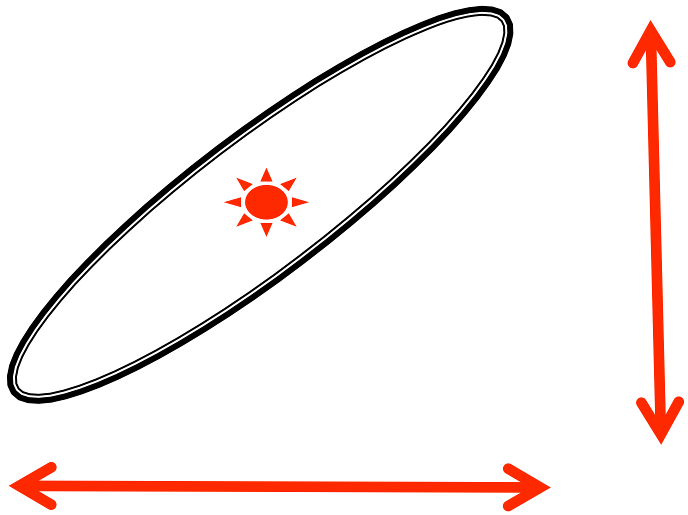
$$V_* = \frac{M_{pl}}{M_*} V_{pl}$$

  - **For Jupiter around the sun**
    - **M_J / M_* = 0.001**
    - **Velocity of Jupiter is ~13 km s^{-1}**
    - **So the sun moves 0.013 km s^{-1} or 13 m s^{-1}**
  - **For Earth around the sun**
    - **M_E / M_* = 0.000001**
    - **Velocity of Earth is ~27km s^{-1}**
    - **So the sun moves 0.000027 km s^{-1} or 0.027 m s^{-1}**
    - **Just 2.7 centimeters per second!!**
  - **It's <u>much</u> easier to detect big planets that move fast (close to their star)**

- What's the best we can do today?
- We can detect radial velocities of ~3 ms^{-1}
  - Jupiter moves the Sun at 13 m s^{-1}
  - Earth movers the Sun at 0.027 m s^{-1}
  - We can detect Jupiter-like planet but not Earth-like planets
- We've been watching stars like this since the early 1990s
  - Jupiter takes ~10 years to orbit the Sun
  - ..but Uranus takes 84 years!!
  - We need patience to detect these distant objects



- **Another complication…**
  - **We rarely see other solar systems exactly edge on**
  - **What we estimate is really M*sin(i)**
  - **So we get a minimum mass for the planet**



- The same system can have both
  - Astrometric wobble
  - Doppler shifts from radial velocity

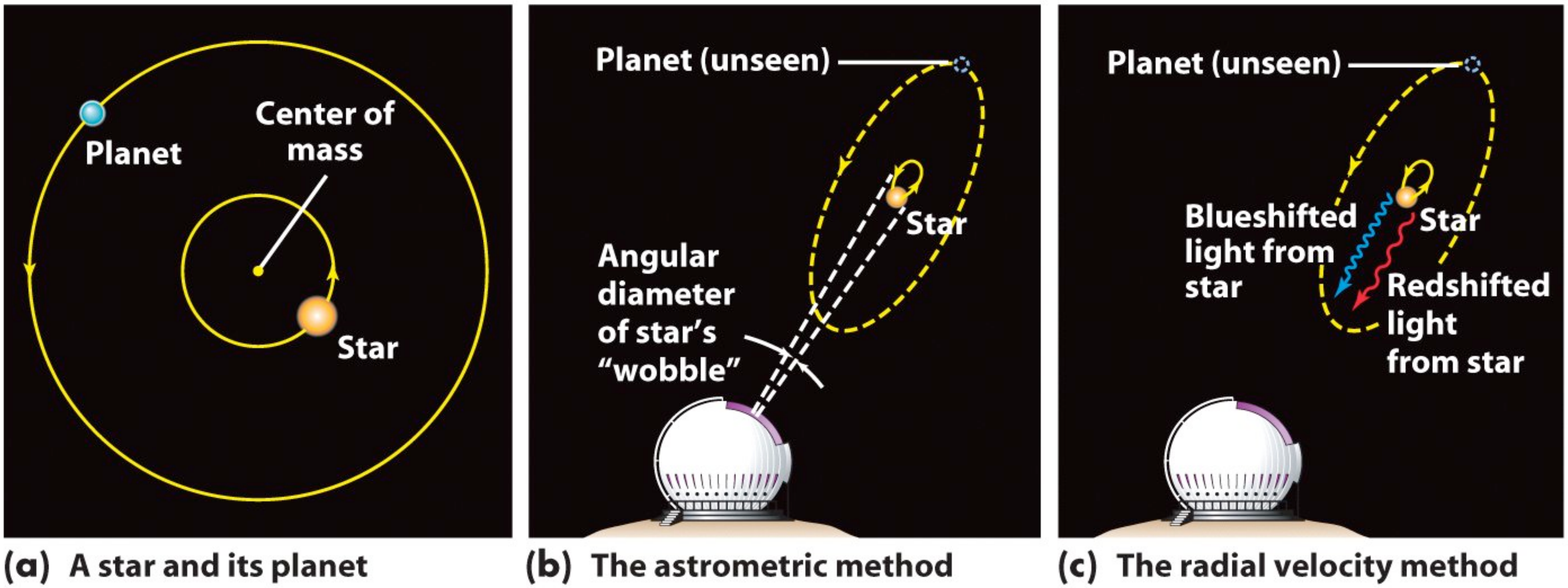
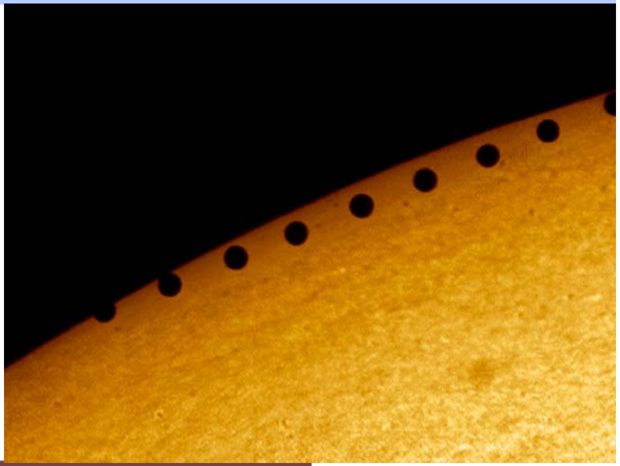


Figure 8-16
Universe, Eighth Edition

- **The transit technique is new and promising**
  - **Gives information we never had before – the planet's size**
  - **…but not it's mass, we still use radial velocities for that**
  - **Can also give us compositional info as starlight passes though the planets atmosphere**



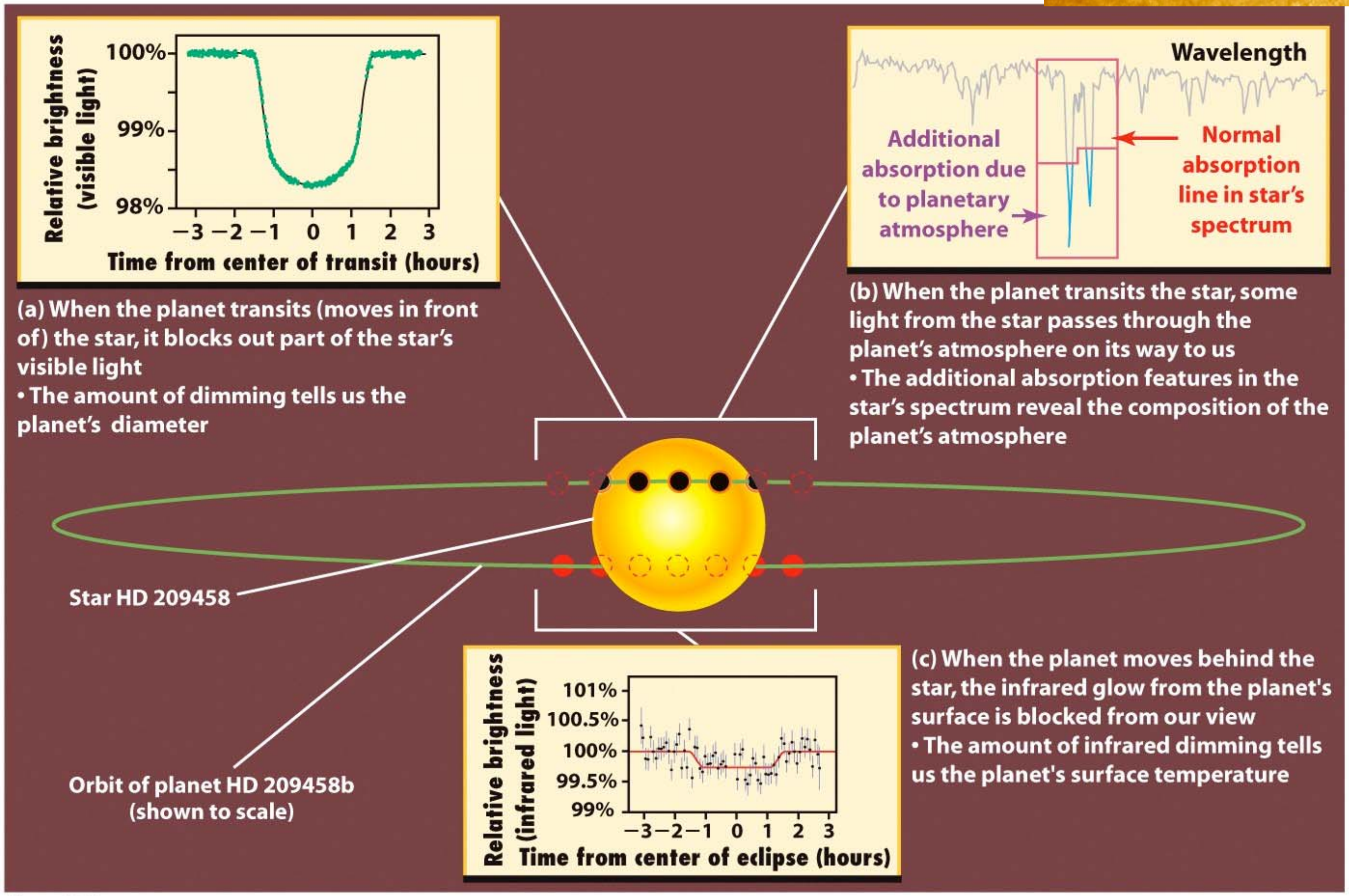


Figure 8-18
Universe, Eighth Edition

- **Planets can now also be directly imaged**
  - **We get an idea of the planet's size and composition**

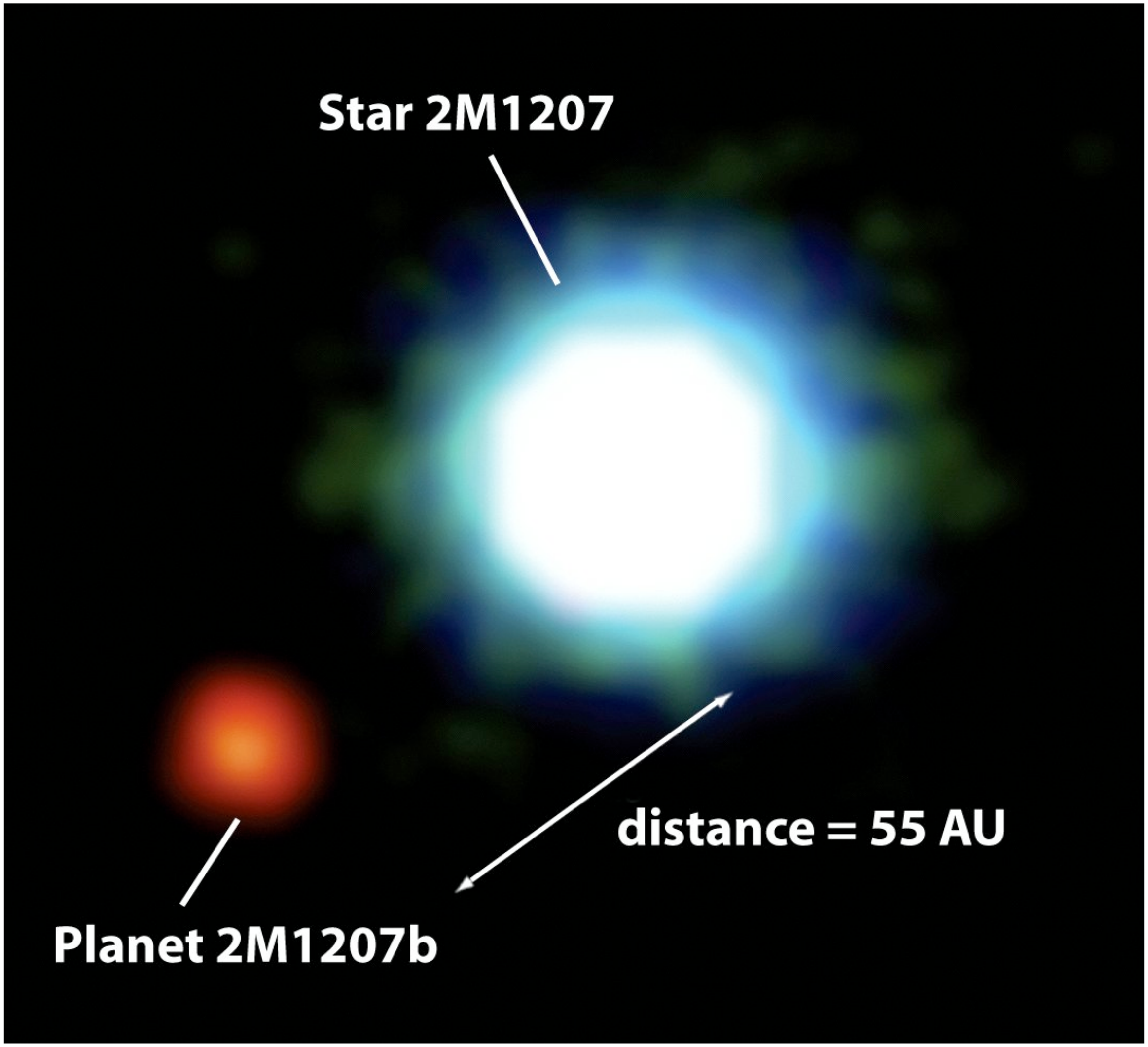


Figure 8-20
Universe, Eighth Edition

Properties of these planets

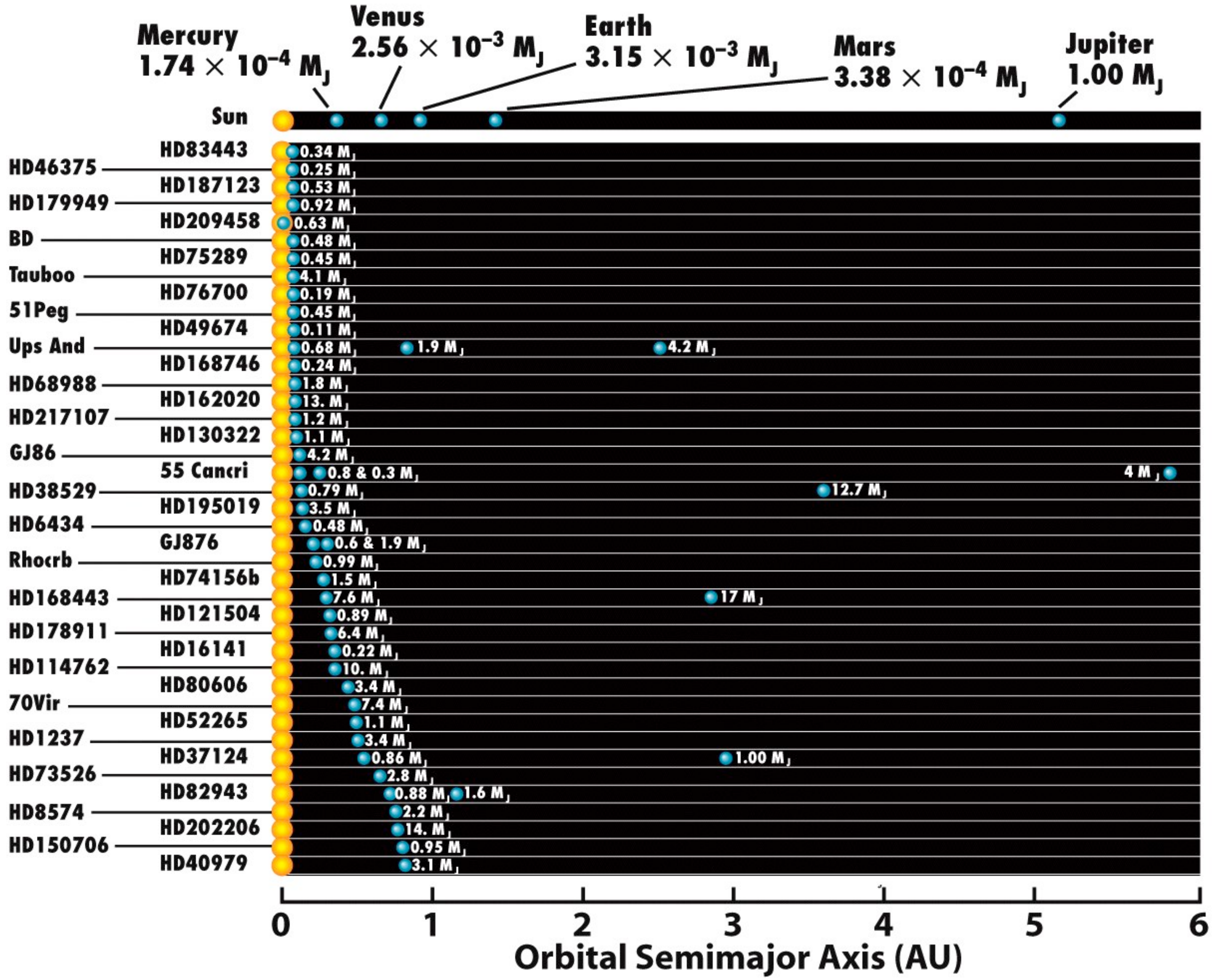


Figure 8-17 part 1
Universe, Eighth Edition

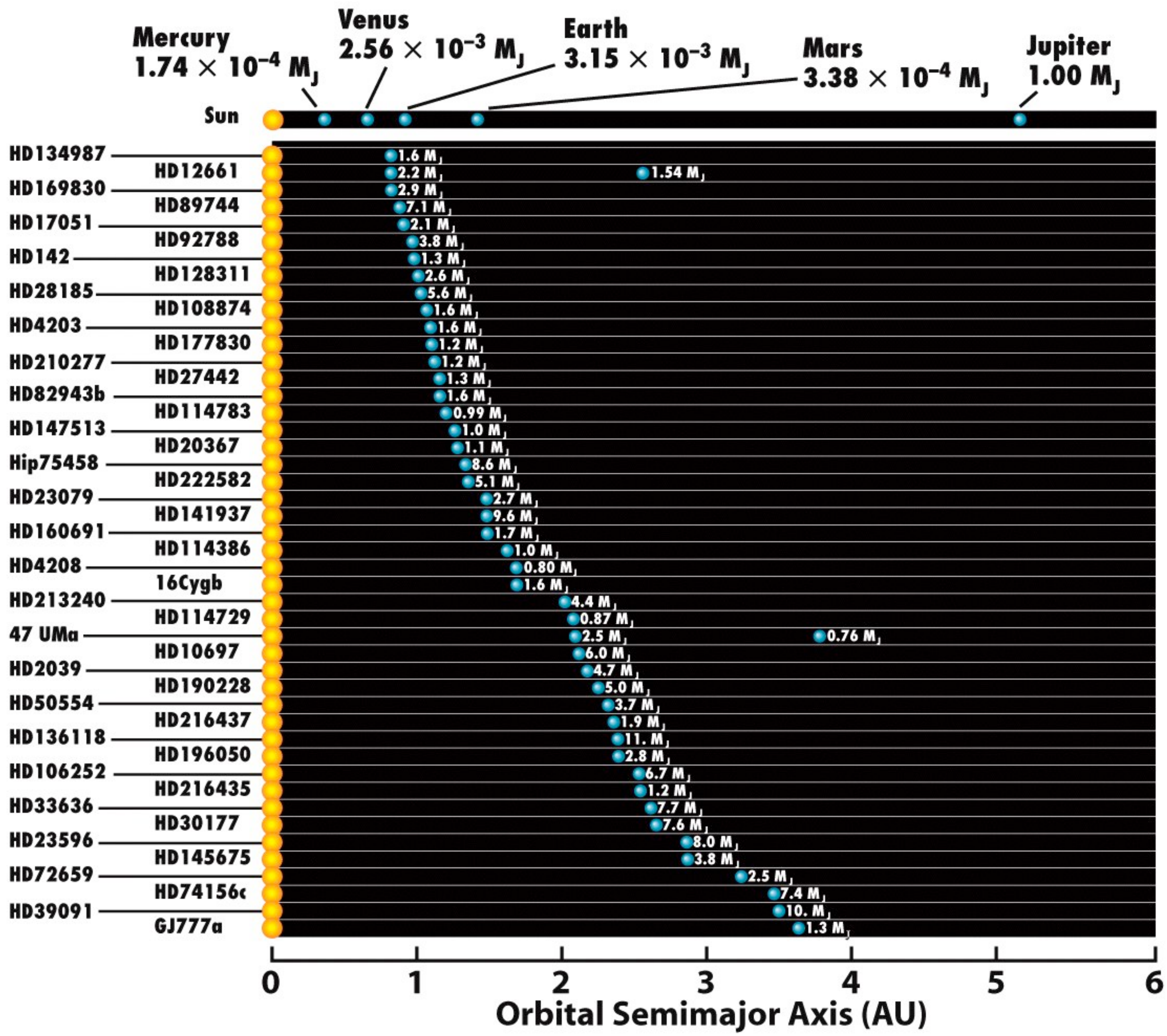
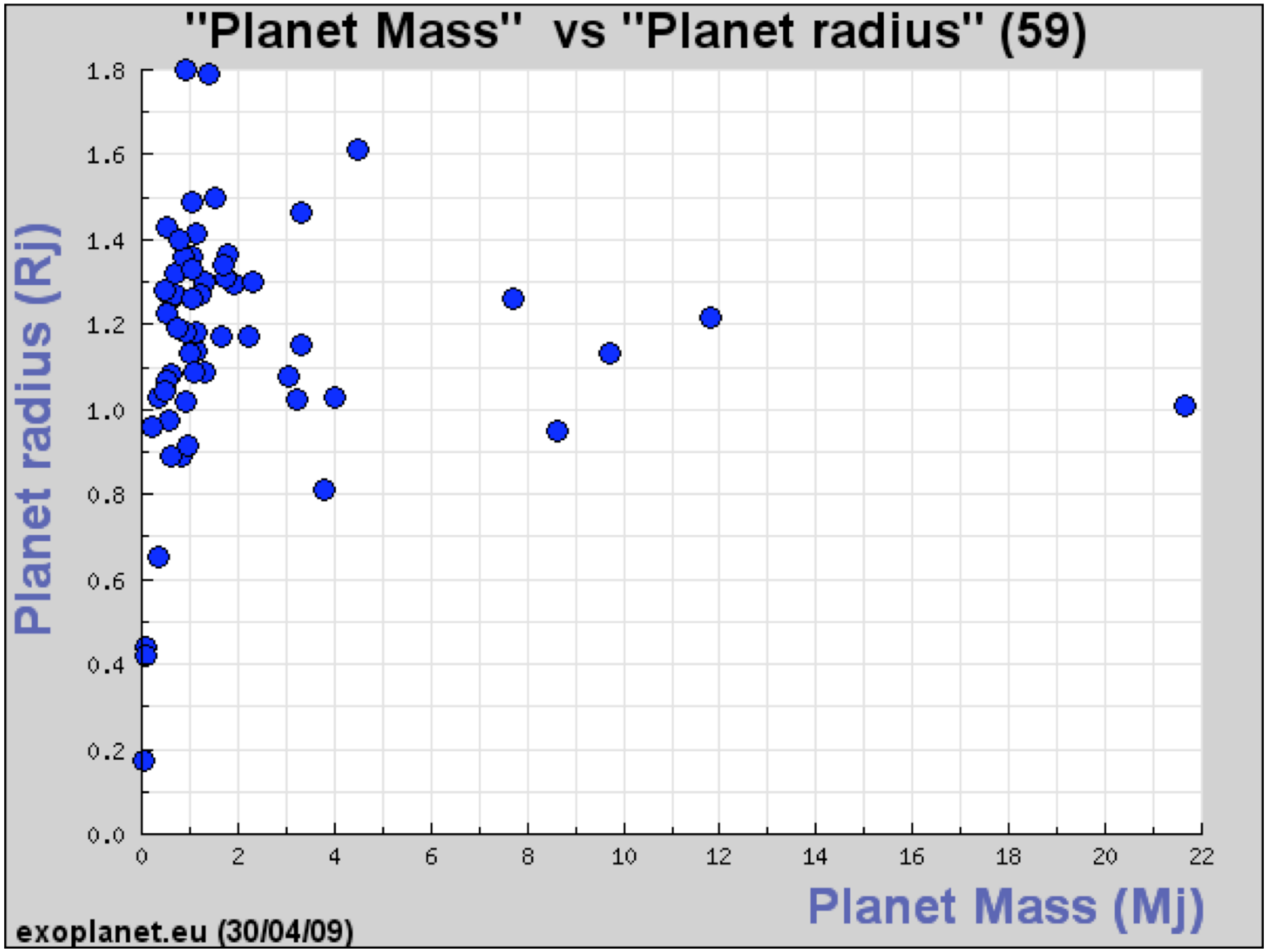
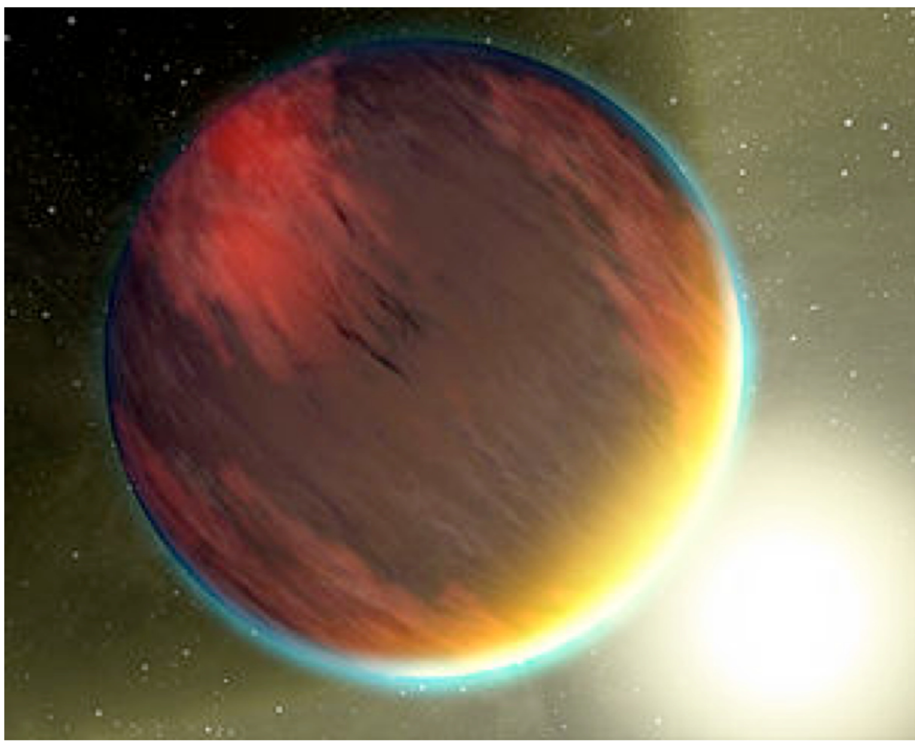


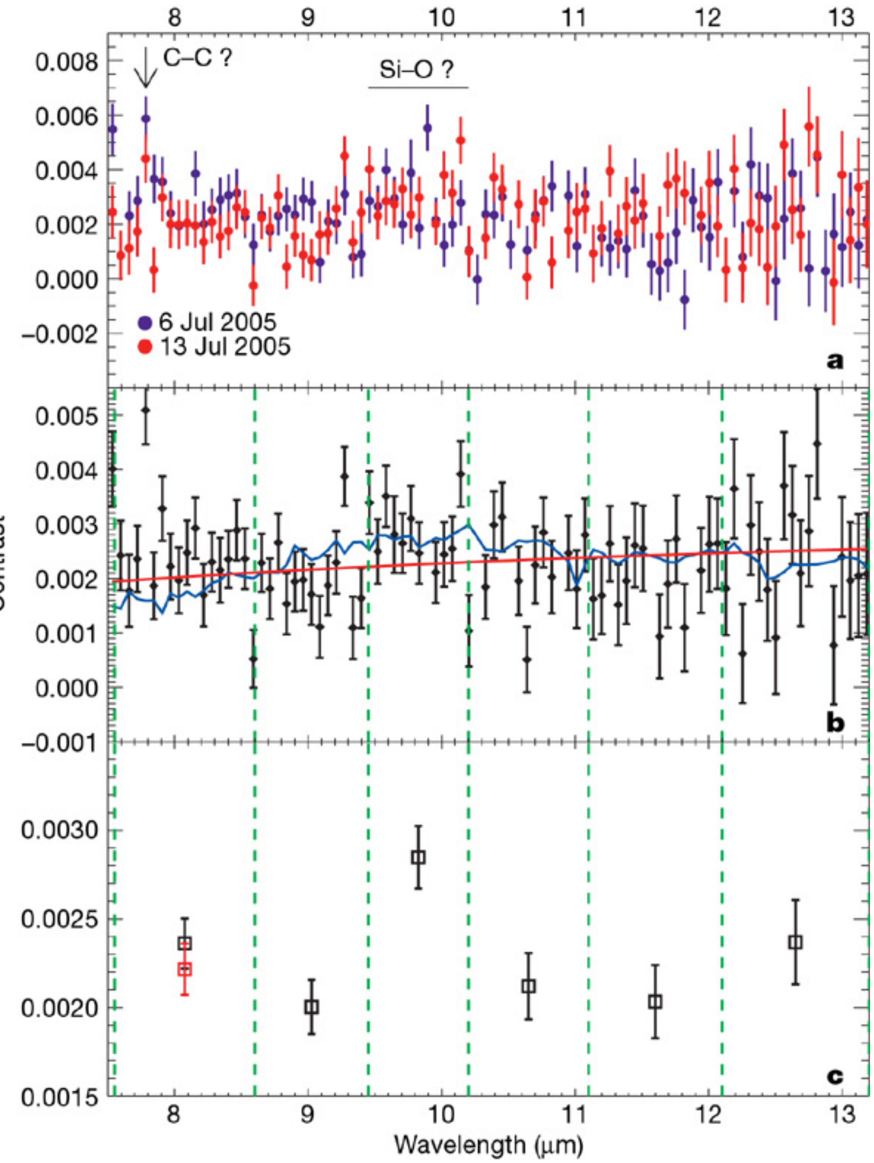
Figure 8-17 part 2
Universe, Eighth Edition

- The transits give us planetary size so we can calculate their densities
  - Most of these planets are Jupiter sized
  - Most have 0.5-2 Jupiter masses
  - Densities from ~600 to ~2500 kg m^{-3}

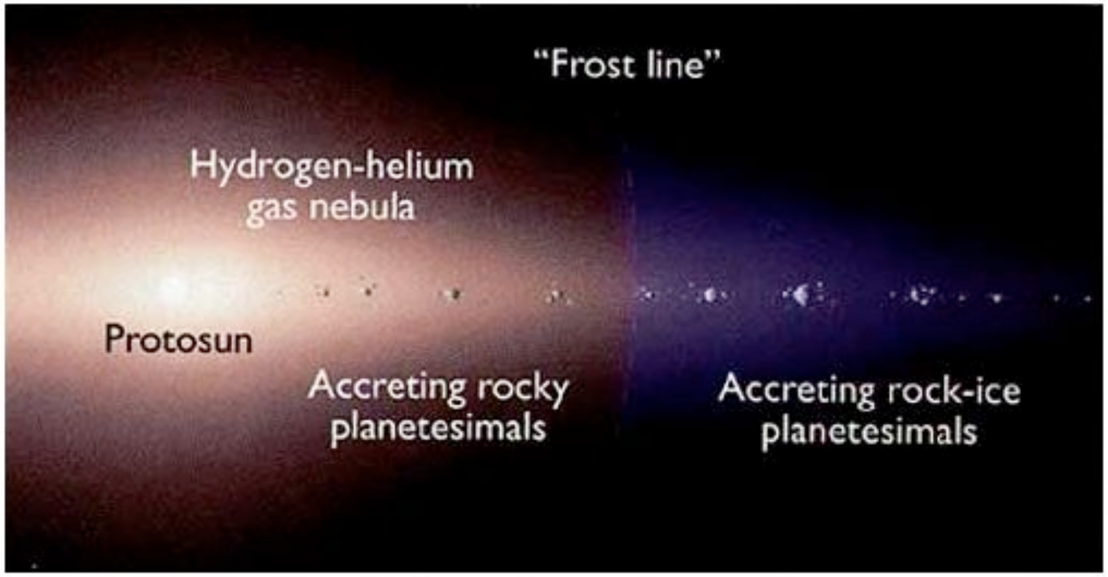


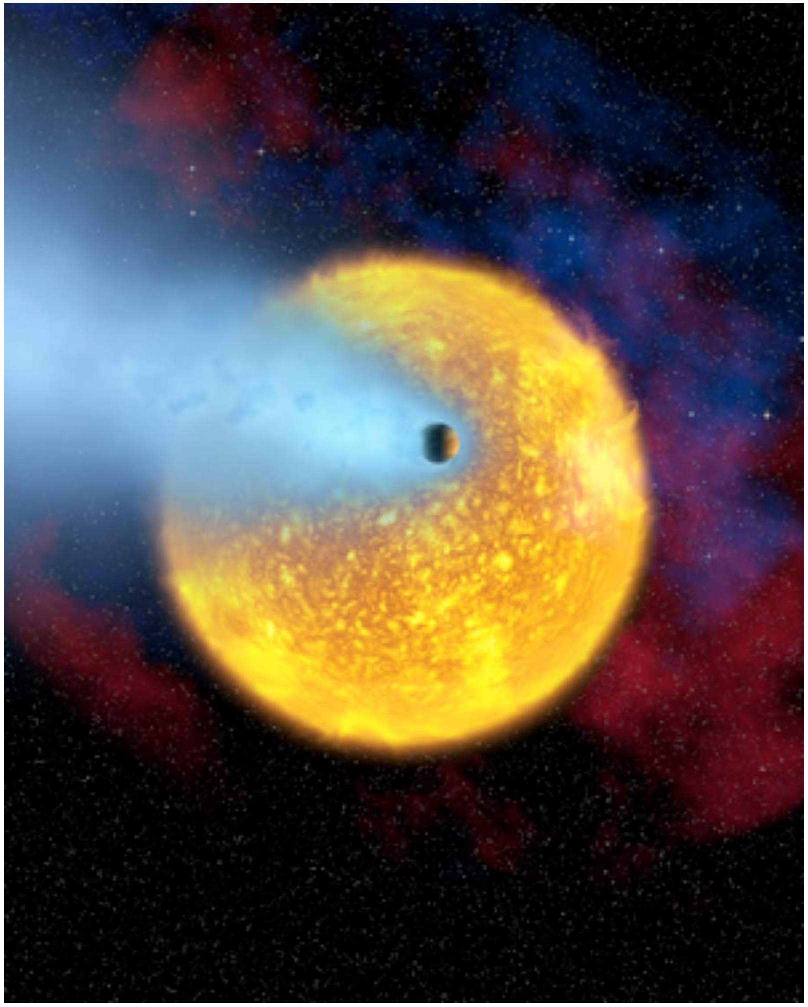
- **Some atmospheric spectra available**
  - **E.g. HD209458b**
  - **Noisy and low-resolution so far**
  - **Silicates in the atmosphere**
  - **Little water**



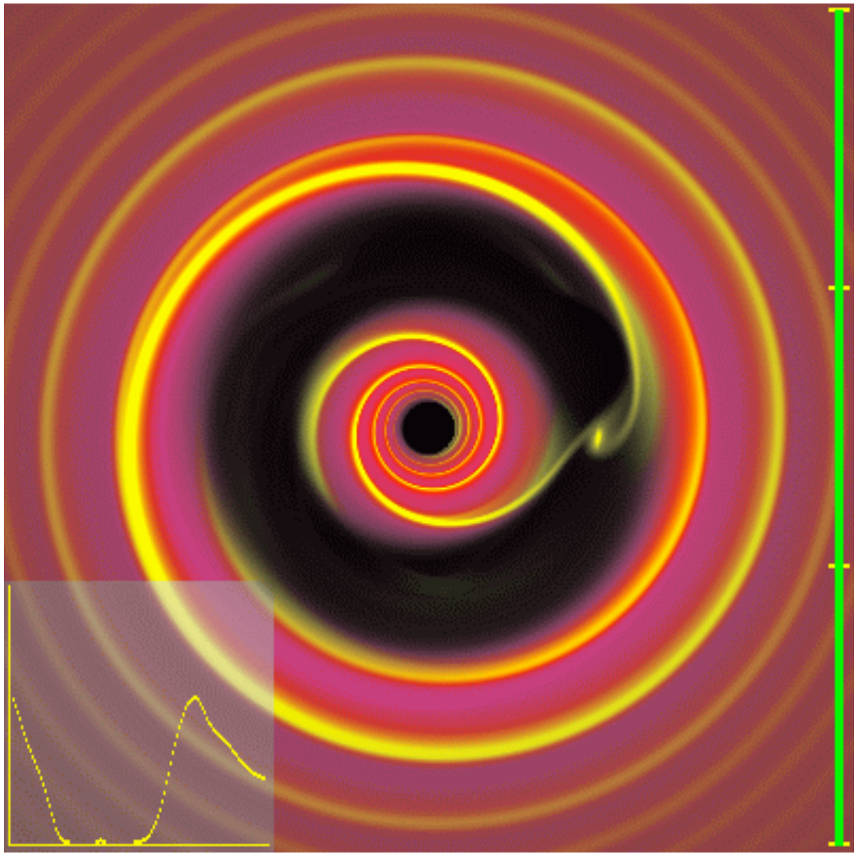


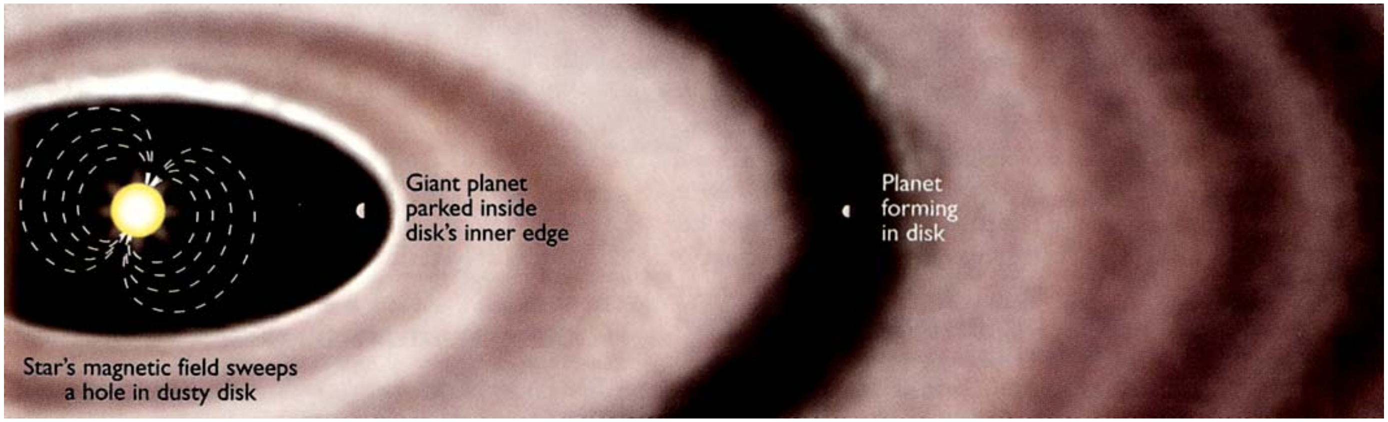
- How did things get this way?
  - Gas giant planets need to start from big cores
  - Big cores need to from far from the star where water ice is abundant
  - Yet these planets are right up next to their stars





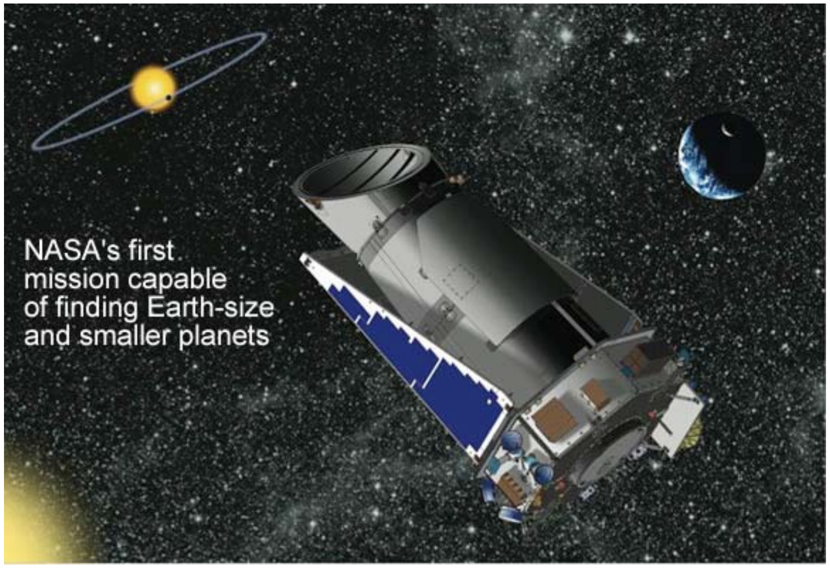
- Gas giant planets likely migrated due to interactions with the disk
  - Planet causes density waves to appear in the disk which dissipate energy
  - As the planet looses energy it spirals inward
  - Disks have inner holes – so planets tend to get parked near this inner edge





Future missions

- **Kepler will look for transits at 100,000 nearby stars**



- **Gaia will use astrometry and look at a billion stars**
  - **Launched in 12/2011**

In this lecture…

- How we detect extrasolar planets
  - Radial velocity
    - Good for planets close to their stars
  - Astrometry
    - Good for planets far from their stars
  - Transits
    - Gives size and some composition
  - Direct imaging!
- Characteristics of extrasolar planets
  - Orbits
  - Atmospheres
  - Densities

Next: Origin of life here and elsewhere

- Reading
  - Chapter 8-7 to revise this lecture
  - Chapter 28 for next (and final) lecture