Astr 2310 Thurs. May 1, 2014
Today's Topics

- Chapter 8: The Solar System in Perspective
  - Planets within the Solar System
    - Equilibrium Temperatures
    - Retention of Atmosphere
    - Physical and Orbital Properties
    - Trends in Composition
  - Origin of the Solar System
    - Nebular Hypothesis
    - Open Questions
    - How Unique is the Solar System
  - Detecting Exoplanets
    - Detection Techniques
    - Initial Discoveries
    - Selection Effects
    - Future Trends

Chapter 8: Homework

Chapter 8: #1, 2, 3, 4, 7

- Due Thursday May 1

Chapter 8: The Solar System in Perspective

- **Planets within the Solar System**
  - Planetary Orbits in Nearly the Same Plane
  - Sun’s Equator Close to the Plane
  - Planetary Orbits Nearly Circular
  - Orbital Angular Momentum Vectors Aligned
  - Rotational Angular Momentum Vectors Mostly Aligned
  - Orbital Debris Also Nearly Planar Orbits
  - Decreasing Mean Density with Radius
  - Chemical Composition with Radius
  - Differentiation Implies Melting of Terrestrial Planets
  - Evidence for Intense Early Bombardment

Equilibrium Temperature for Planets

A Planet Must Be in Thermal Equilibrium or its Temperature will Rise or Fall.

It Must Radiate as Much Energy as it Receives from the Sun:

Energy Received is the Flux from the Sun Times the Planet's Cross Section Times (1-A):

$W(r) = \frac{L_\circ}{4\pi r^2}\left(\pi R_p^2\right)\left(1 - A\right)$ where r is the planet's distance from the Sun and R_p is its radius

The Energy Radiated by the Planet is the Radiant Power per Meter^2 Times its Surface Area:

$L_p = 4\pi R_p^2 \sigma T_p^4$ and so if we set these equal:

$\frac{L_\circ}{4\pi r^2}\left(\pi R_p^2\right)\left(1 - A\right) = 4\pi R_p^2 \sigma T_p^4$ and so if we solve for T:

$T_p = \left[\frac{L_\circ}{16\sigma\pi r^2}\left(1 - A\right)\right]^{1/4}$ but we can simplify this further by substituting for $L_\circ$:

$L_\circ = 4\pi R_\circ^2 \sigma T_\circ^4$ and so we then have:

$T_p = \left(\frac{R_\circ}{r}\right)^{1/2}\left(\frac{1 - A}{4}\right)^{1/4} T_\circ$ and then when we insert numbers for the Sun:

$T_p \approx 279^o K(1 - A)^{1/4}\left(\frac{r}{1AU}\right)^{-1/2}$ and a couple of special cases are:

1) If the planet is fully absorbing (A = 0) the equilibrium blackbody temperature is:

$T_{bb} \approx 279^o K\left(\frac{r}{1AU}\right)^{-1/2}$

2) If the planet is slowly rotating the 1 m^2 with the Sun directly overhead:

$\frac{L_\circ}{4\pi r^2}\left(1 - A\right) = \sigma T_p^4$ and so we can define the sub-solar temperature as:

$T_{ss} = \left(\frac{R_\circ}{r}\right)^{1/2}\left(1 - A\right)^{1/4} T_\circ$ and putting in tthe Sun's numbers gives:

$T_{ss} \approx 395^o K(1 - A)^{1/4}\left(\frac{r}{1AU}\right)^{-1/2}$

Atmospheric Retention for Planets

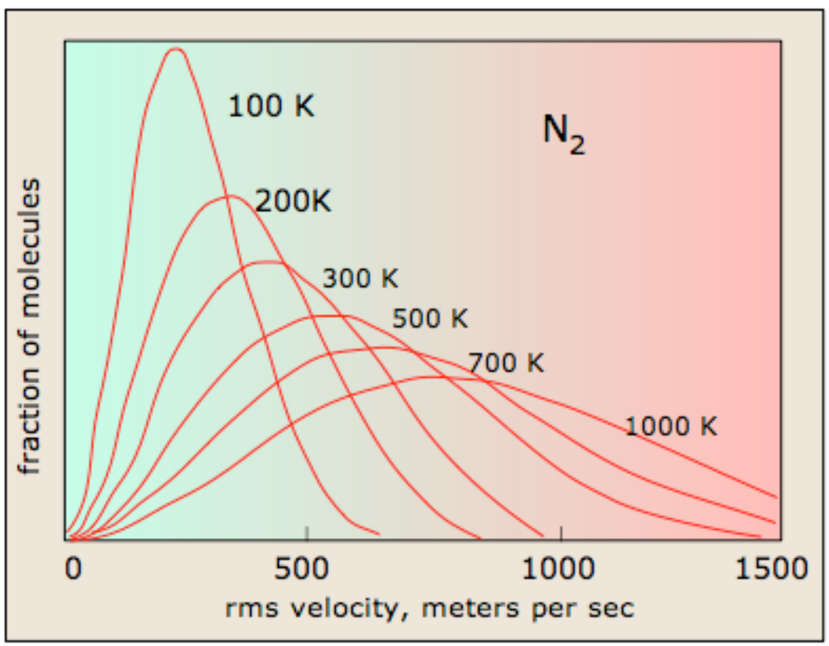
Statistical Mechanics Used to Compute the Velocity Distribution Function for Molecules

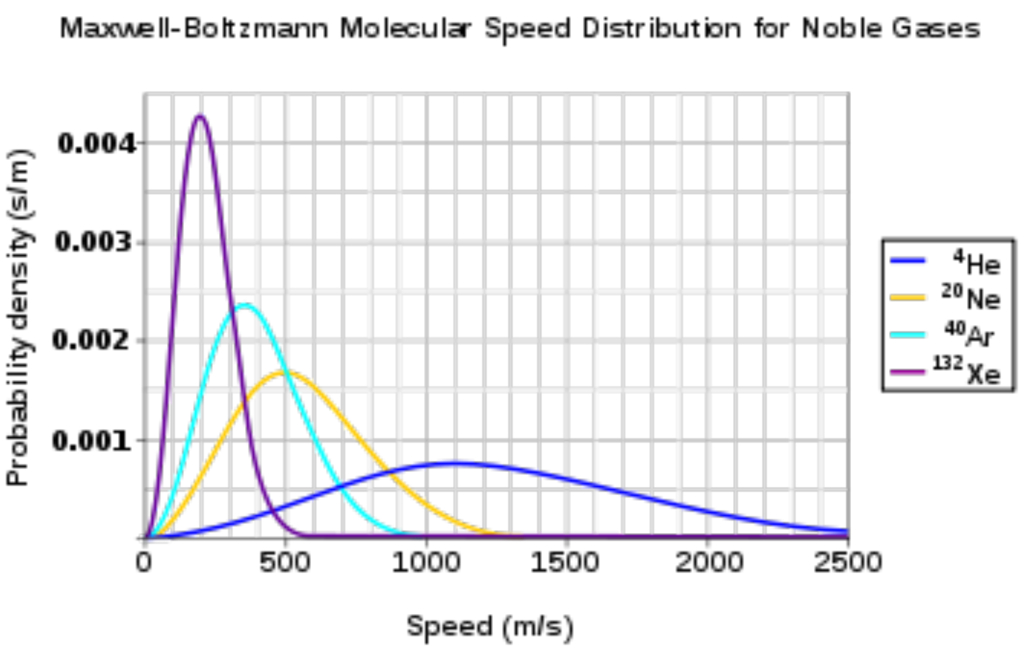
Derivation is Complicated so We Give Only Results, the Boltzmann Distribution:

$f(v) = 4\pi\left[\frac{m}{2\pi kT}\right]^{3/2} v^2 e^{-mv^2/kT}$ The distribution can be integrated and differentiated:

$v_p = \sqrt{\frac{2kT}{m}}$ (most probable speed) with $\langle v \rangle = \frac{2}{\sqrt{\pi}} v_p$ and $\sqrt{\langle v^2 \rangle} = \sqrt{\frac{3}{2}} v_p$

If the escape velocity of a planet is less than about 10x $\langle v \rangle$ the planet will evaporate atm. in 10^9 years.





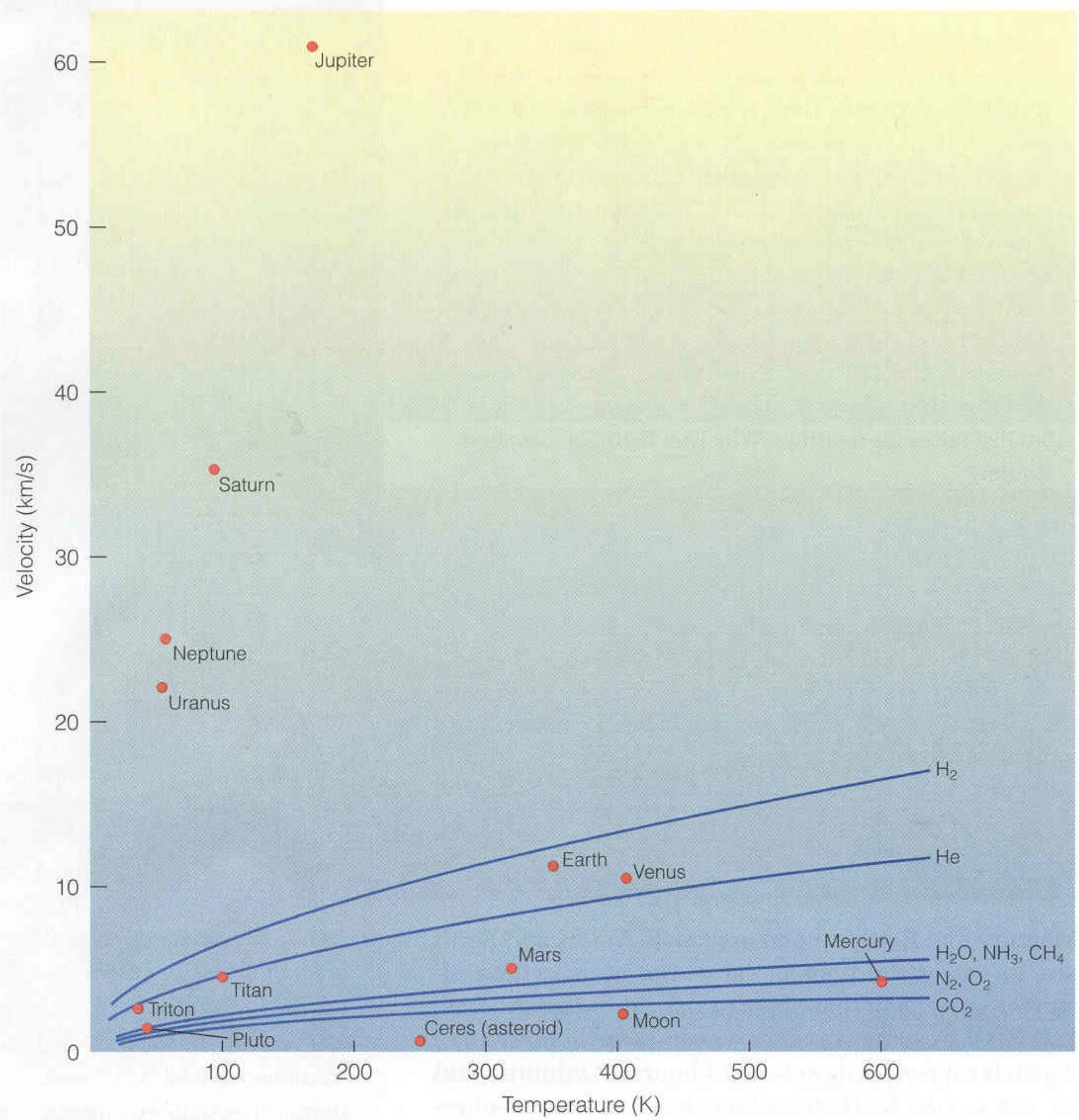
Why Some Atmospheres are Lost

- Compare velocity of gas atoms (V_{gas}) to planet's escape velocity V_{esc}
  - If any significant # of atoms have escape speed atmosphere will eventually be lost
  - In a gas the atoms have a range of velocities, with a few atoms having up to about 10 × the average velocity, so we need $10 \times V_{avg\ gas} < V_{esc}$ to keep atmosphere for 4.5 billion years.

$$V_{\text{Avg Gas}} = \sqrt{\frac{3kT}{m}} \qquad V_{\text{Escape}} = \sqrt{\frac{2GM}{R}}$$

  - In above equations R = planet radius, M = planet mass, T = planet temperature, m = mass of atom or molecule, *k* and *G* are physical constants
- Big planets have larger V_{esc} (i.e. larger $M/R \propto R^3/R$) so hold atmospheres better
  - Earth would retain an atmosphere better than Mercury or the Moon
- Cold planets have lower V_{gas} so hold atmospheres better
  - Saturn's moon Titan will hold an atmosphere better than our moon
- Heavier gasses have lower V_{gas} so are retained better than light ones
  - CO_2 or O_2 retained better than He, H_2, or H
  - Even with "heavy" gasses like we H_2O we need to worry about loss of H if solar UV breaks H_2O apart. That is what happens on Venus.

Which Planets can Retain which Gasses?



From our text Horizons, by Seeds

- **Jovian Planets**
  - **can retain all gasses**
- **Earth and Venus**
  - **can retain all except H_2**
  - **Cold trap on Earth preserves our H**
- **Mars**
  - **can retain CO_2**
  - **barely retains H_2O**
- **Titan and Triton**
  - **only moons which can retain atmospheres**

Age Dating Planetary Surfaces

The Most Reliable Method for Age-Dating Uses Radioactive Decay (see Ch. 9)

A Radioactive Isotope has an Unstable Nucleus Which Ejects a Particle or Photon

${}^{235}_{92}\mathrm{U} \rightarrow {}^{231}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$ but eventually resulting in ${}^{206}_{82}\mathrm{Pb}$ but Pb is found in nature so we have to account for the natural amount in a particular mineral that also has U (hard).

But if we can measure the decay (daughter) product and we know the decay rate we can compute the elapsed time:

$dN = -\lambda N dt$ [number of decays depends on number of nuclei (N) and the decay rate (λ)]

$\frac{dN}{N} - \lambda dt$ and so integrating we have:

$\ln[N(t)] - \ln[N(0)] = -\lambda t$ and so:

$\frac{N(t)}{N_0} = e^{-\lambda t}$ or $N(t) = N_0 e^{-\lambda t}$ [number decreases (decays) exponentially]

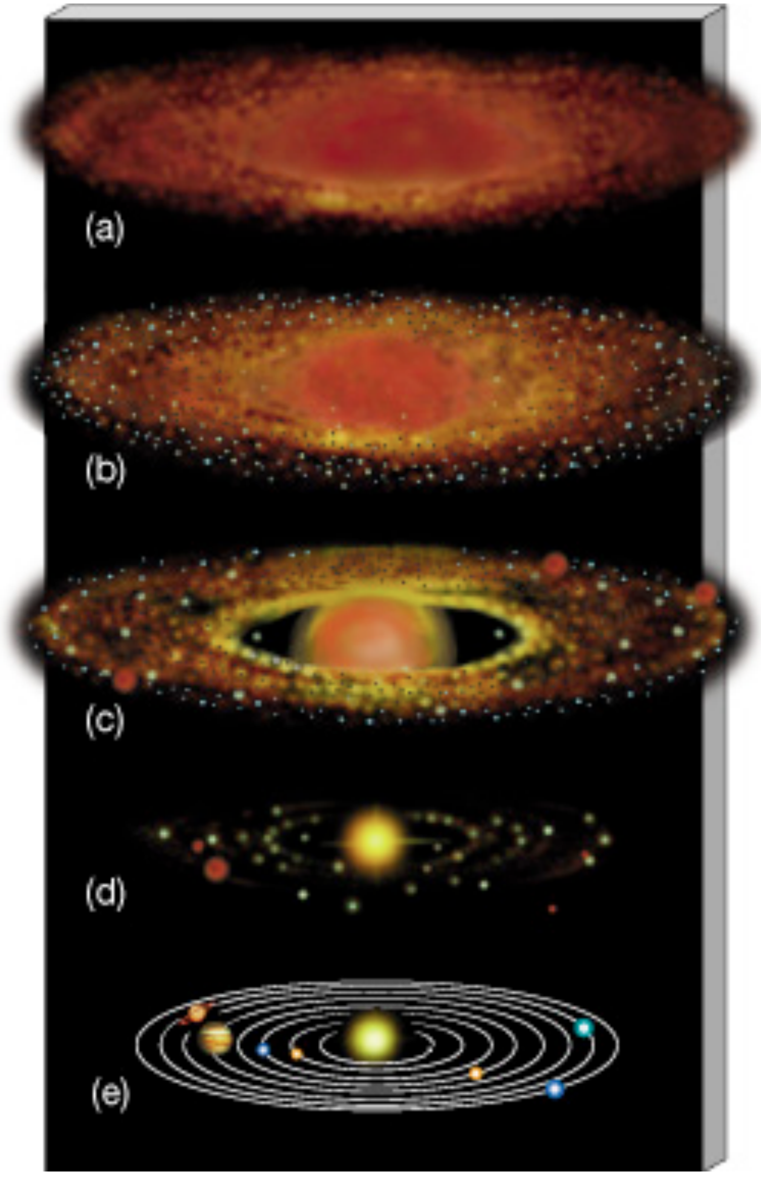
The half-life (τ) is the time for half of the radioactive isotope to decay:

$N(t) = N_0 e^{-\left(\ln 2 \frac{t}{\tau}\right)}$ for ${}^{235}_{92}U$ the half-life is 700 x 10^6 years.

- **Requires a Sample from Planet or Meteorite**
  - **Known or Presumed History**

Solar Nebula Hypothesis

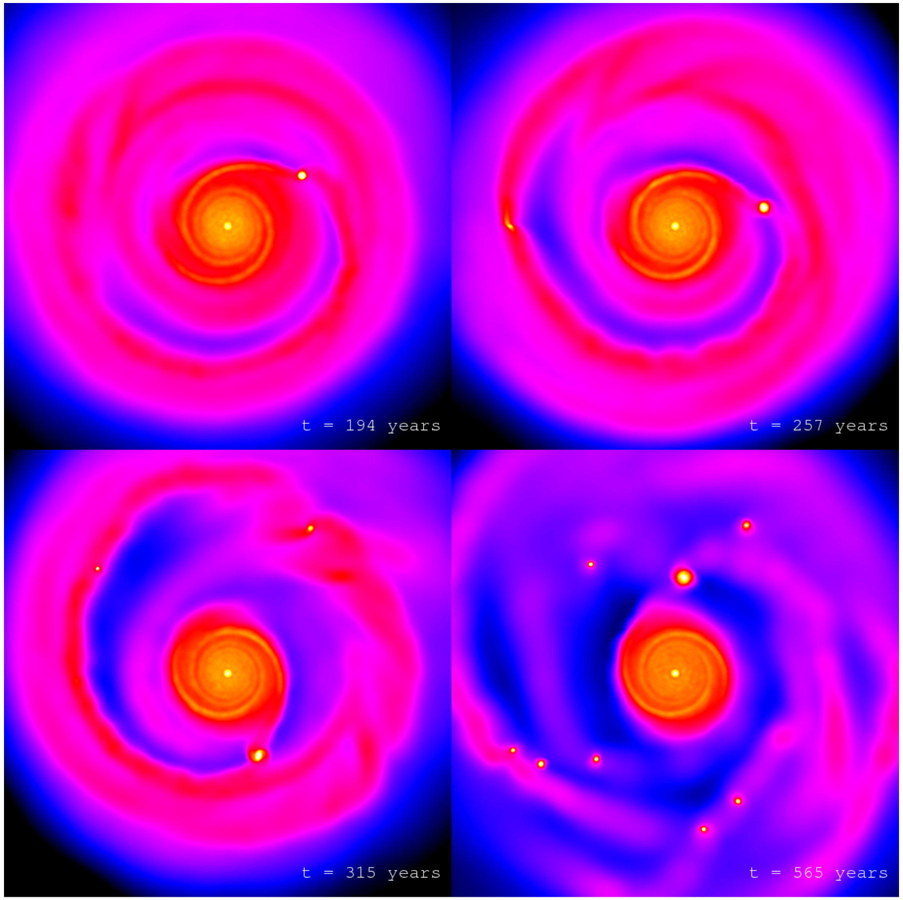
- **Flattened Solar Nebula**
  - **High Angular Momentum**
- **Temperature Gradient with Radius**
  - **Heating of Terrestrial Planet Material**
  - **"Snow Line" of Condensation**
- **Most Planets Formed Near Their Current Orbits (?)**
- **Intense Cratering Ended After ~ 1Byrs**
  - **Lunar Maria**
  - **Martian Volcanoes**
- **Unanswered Questions**
  - **Origin of the Kuiper Belt?**
  - **Origin of the Oort Cloud?**
  - **Origin of Earth's Water?**

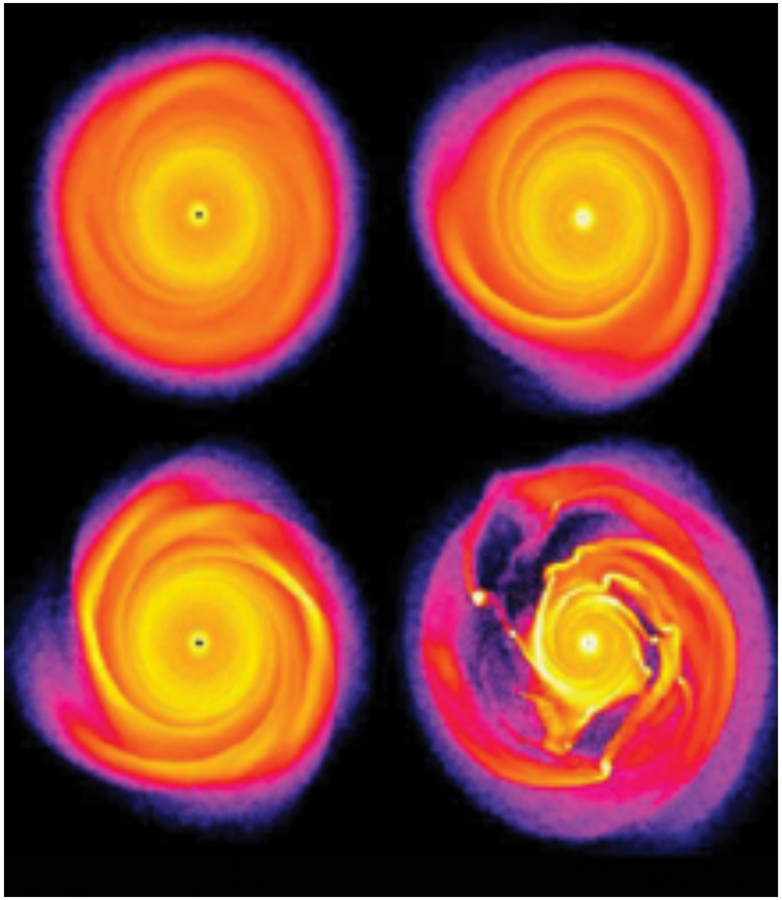


Standard Model for Formation of the Solar System

- Dusty Debris Disk Forms as Star Forms
  - Rotationally Flattened (Ang. Mom. Conserved)
  - Temperature and Density Gradient
  - Gas and Dust Condense
    - Ices Condense Further Out (cooler)
    - Silicates Condense in Interior
  - Dust Sticks Together (clumps)
    - Growth Continues Until Gravity is Significant
    - Planetesimals (~ 1km in diameter)
  - Star's Luminosity Increases
    - Inner Disk Swept of Gas
    - Inner Terrestrial Planets with Little Gas, Ice
    - Gas Planets Have Longer Time to Grow (?)

Numerical Models of Planetarium Formation

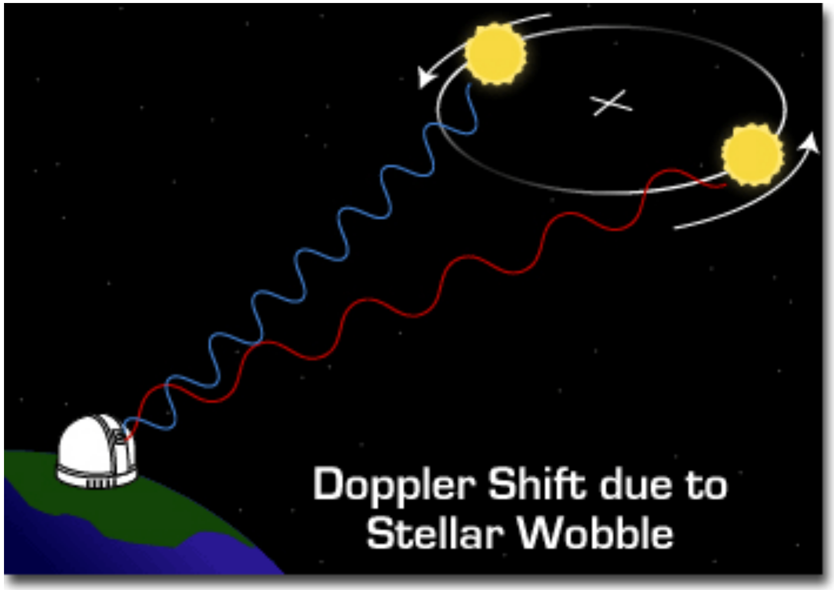


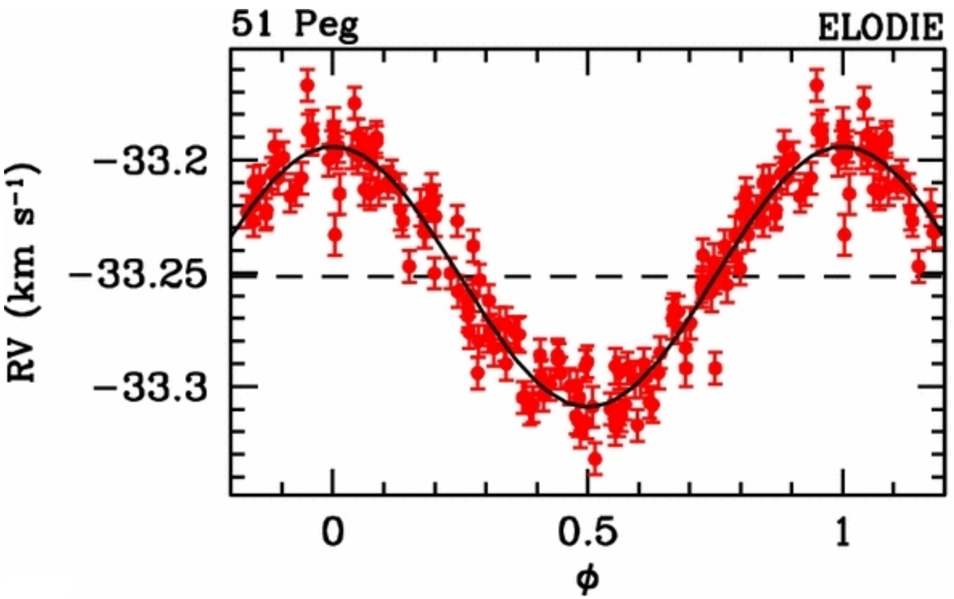


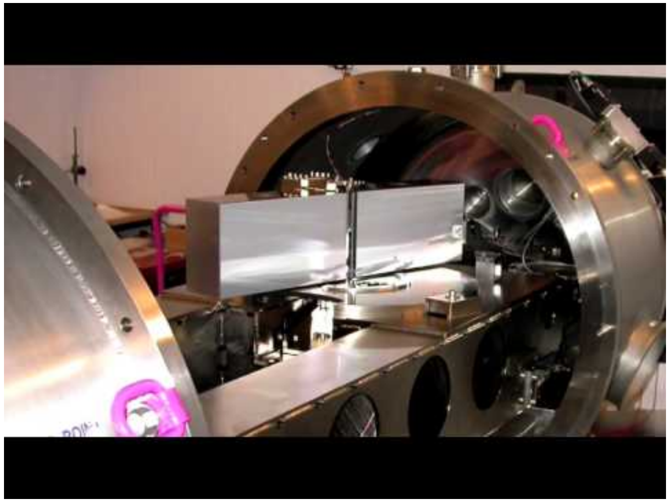
Numerical modeling of Sun and Planetary Disk Formation

Extrasolar Planet Detection

- Radial Velocities
  - Reflex Motion of the Star (2-body problem)
  - Systematic Errors Difficult to Control
  - Amplitudes about 50 m/s for Jupiter-class planets
  - Amplitude about 300x smaller for Earth!
  - Unknown Projection

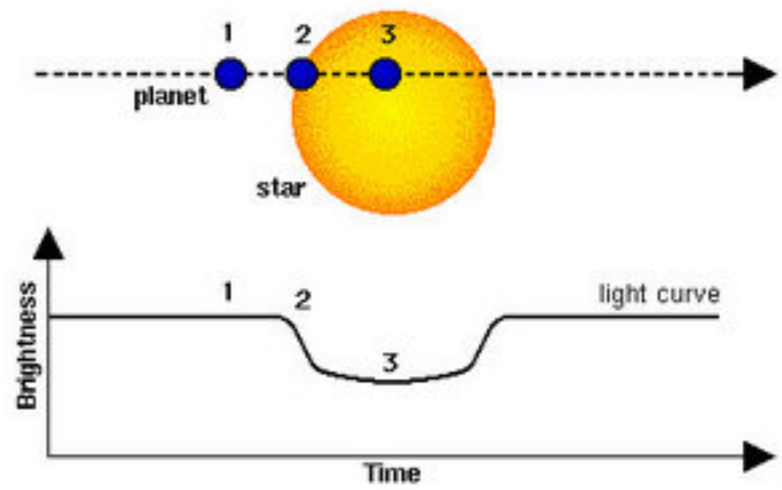


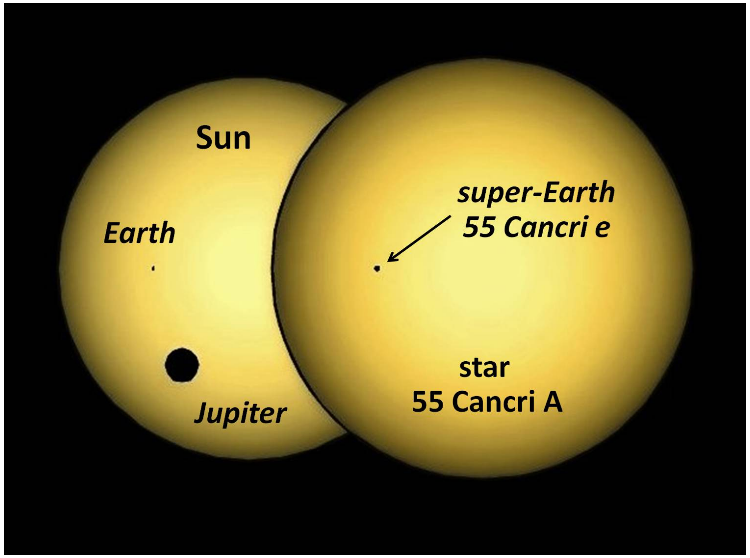


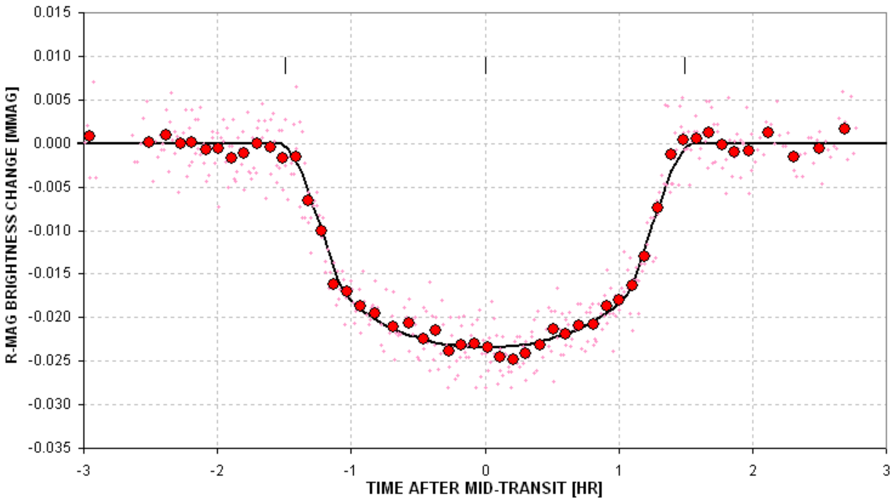


Extrasolar Planet Detection

- **Planetary Transits**
  - **Eclipse Means Drop in Star's Brightness**
  - **Jupiter-class Planets Produce Only 0.5% Drop**
  - **Multi-wavelength Data and Spectra Provide Atmospheric Data**
  - **Can Detect Only Narrow Range of Inclinations**

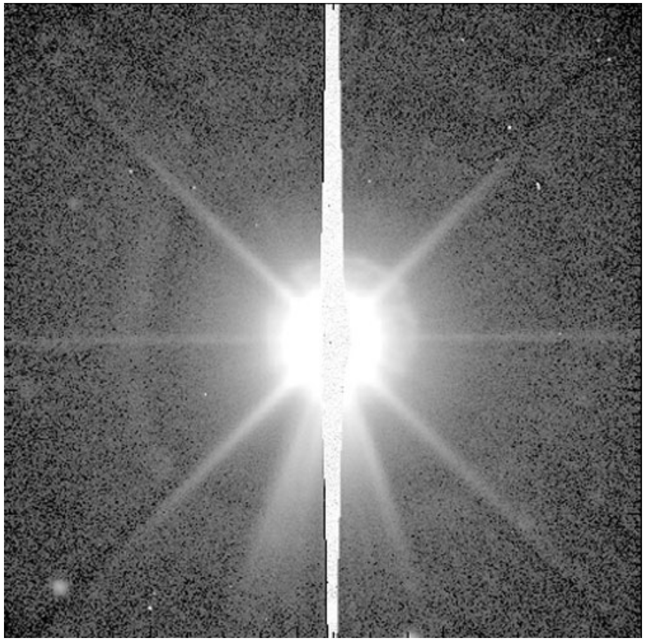


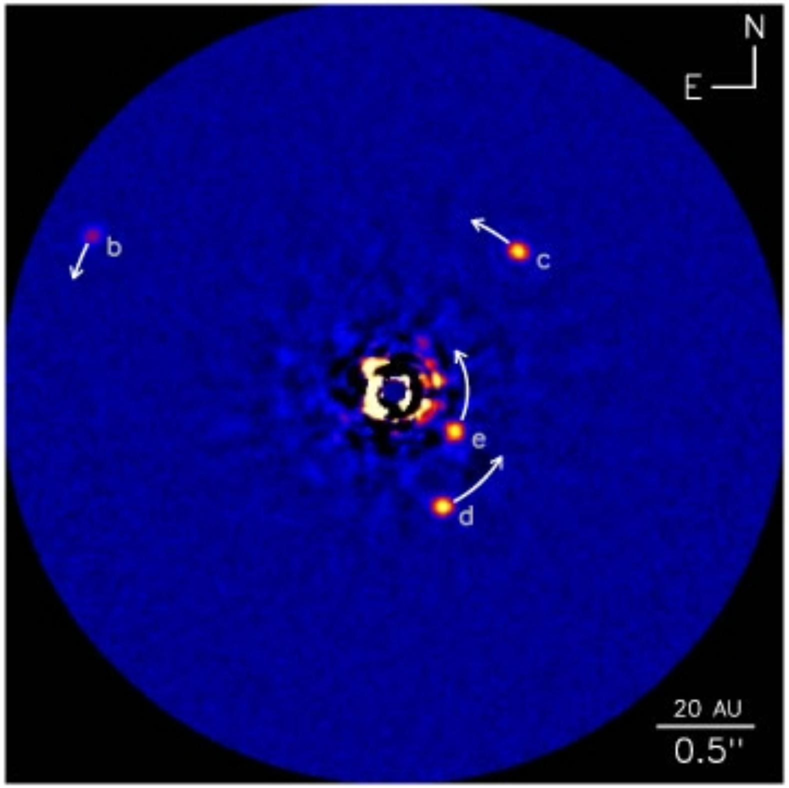


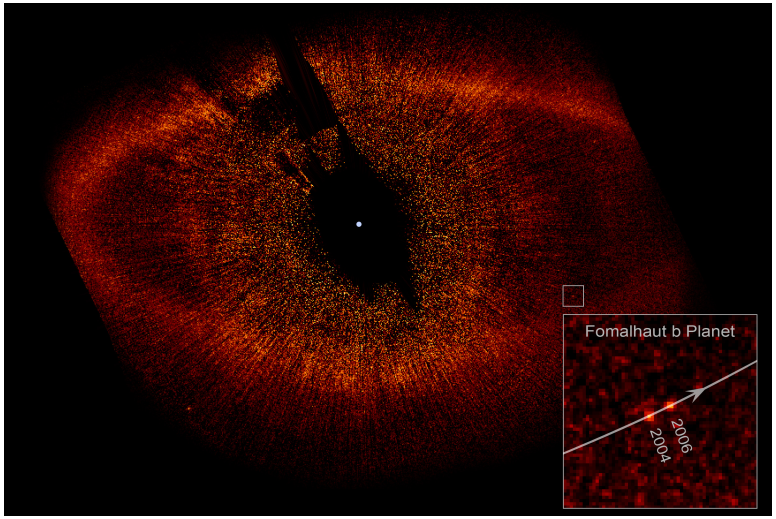


Extrasolar Planet Detection

- **Direct Detection**
  - **Supression of Star's Light**
  - **Star is ~ 10^6 times brighter!**
  - **Optical Defects Create "Dazzle" due to Diffraction**

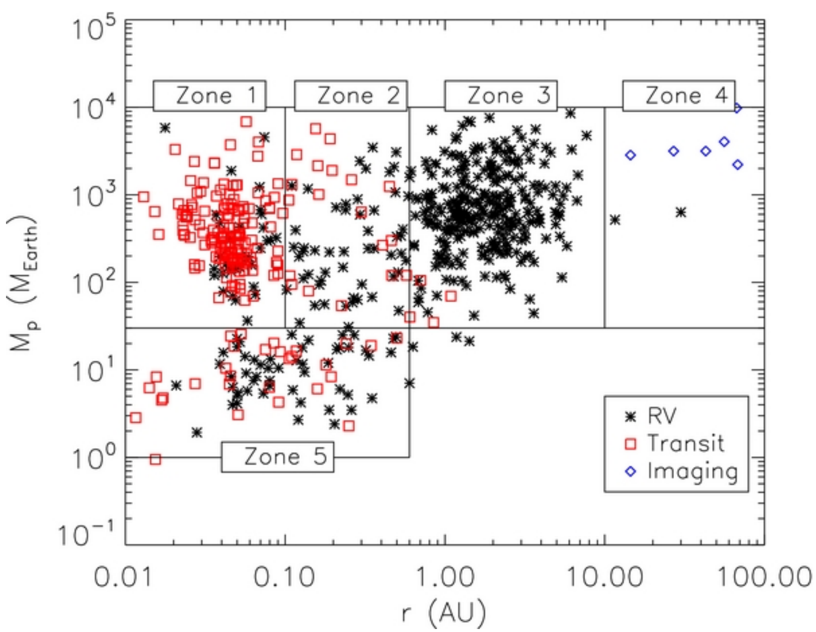


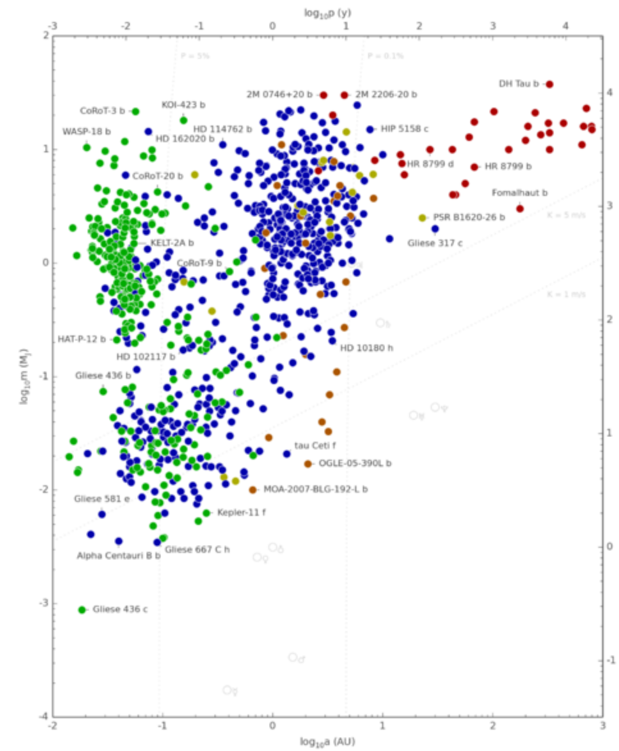


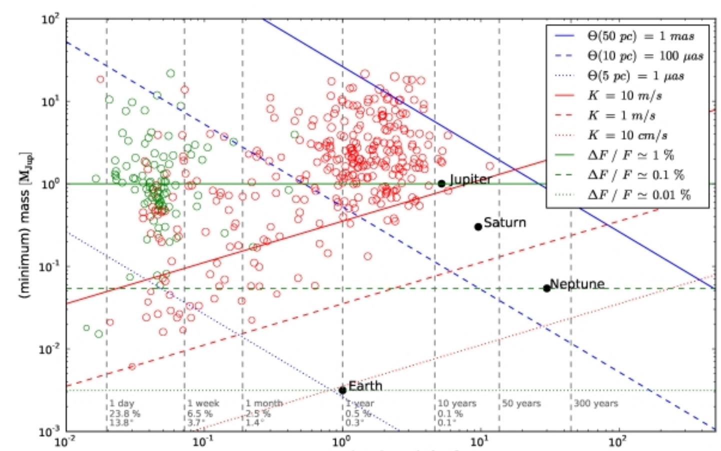


Extrasolar Planet Statistics

- **Current Techniques Limited to Massive Planets**
  - **Early Results Revealed Jupiter Mass Planets Very Close to Star**
    "Hot Jupiters"
  - **Moderate-sized Planets Common**
  - **Earth-mass Planets Just Being Detected**
  - **Stars Found with Several Planets**

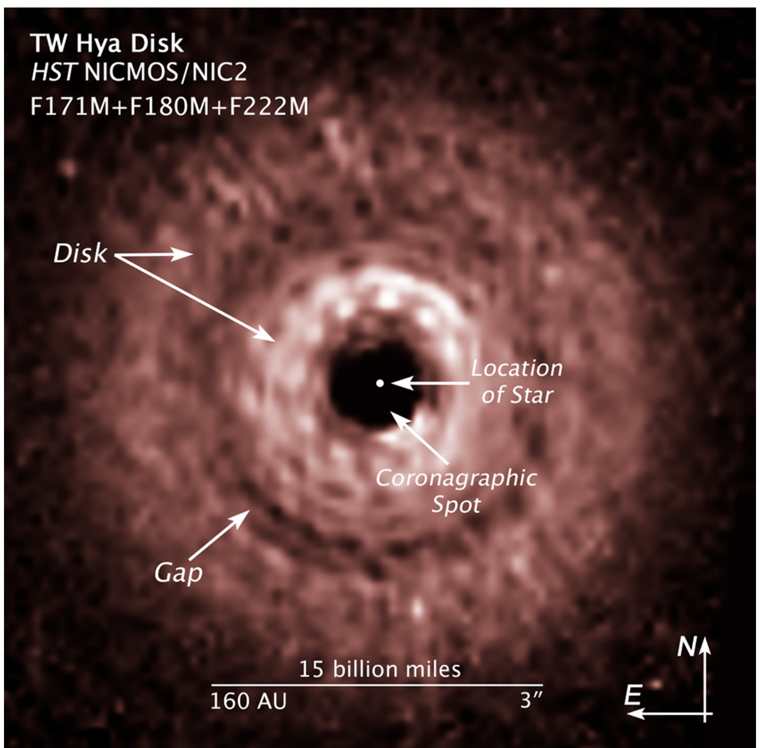


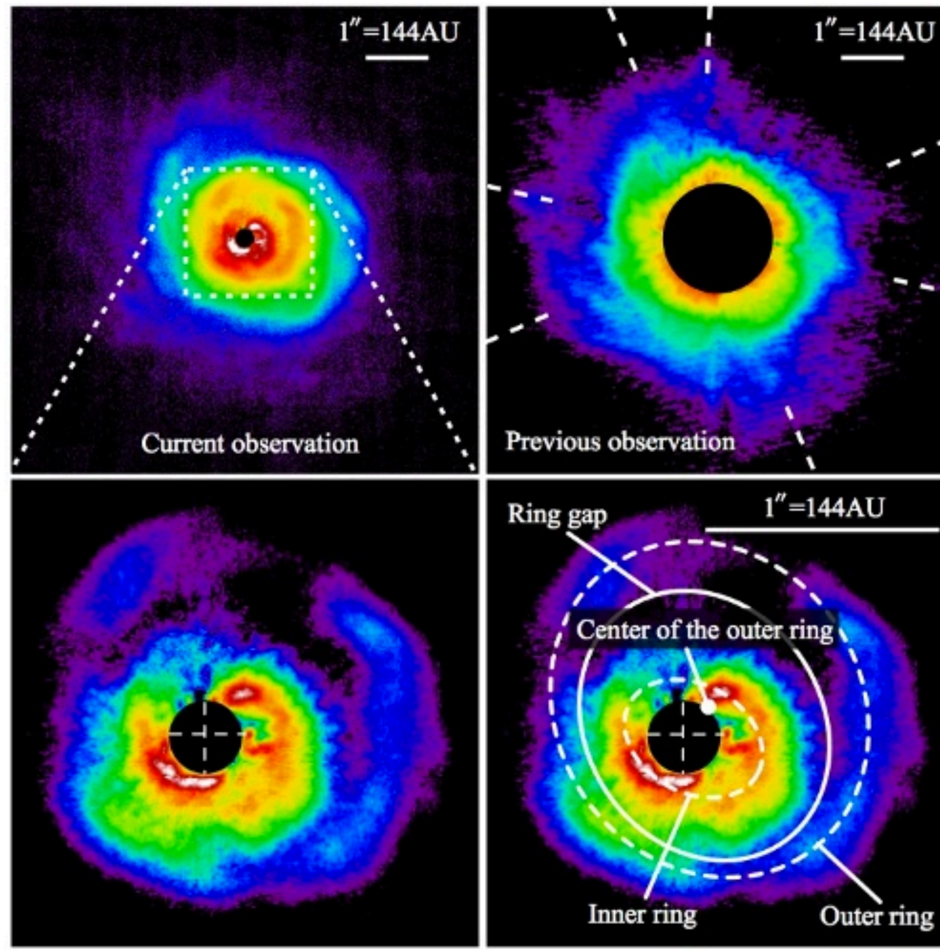




Extrasolar Planetary Systems

- Some Stars Have Debris Disks
  - Infrared Excess
  - Disks are Common Around Young Stars
  - Gaps Suggestive of Planets





Future of Extrasolar Planet Detection

- Future Detection Techniques
  - Space-based Interferometry
  - Specialized Supression Techniques
  - Terrestrial Planet Finder Designed to Detect Earth-like Planets
  - Next Generation Large Telescopes will Enable Atmospheric Spectroscopy