Planet Formation

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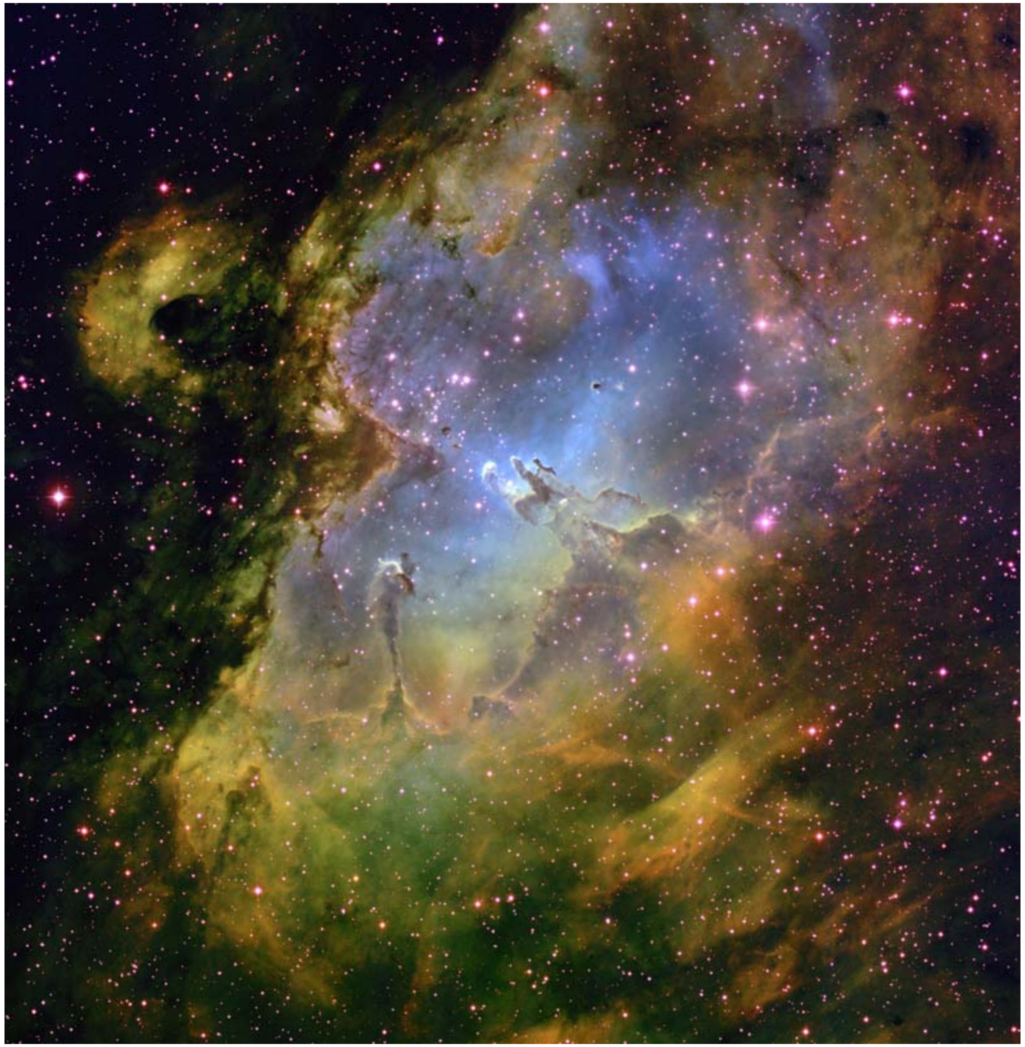
Overview

- History
- Planet formation
- After formation
- Extrasolar planet detection

History

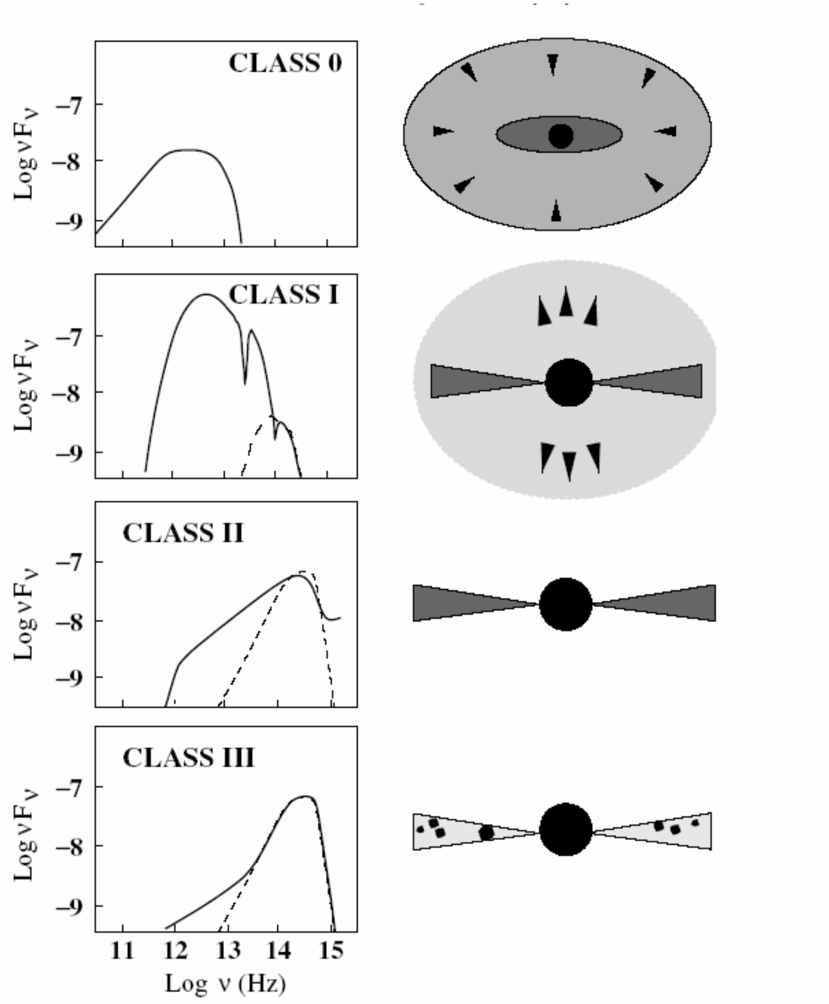
- 18th century, Swedenborg, Kant & Laplace
  Nebular hypothesis
- 20th century, Chamberlin, Jeans & Schmidt
  Planetesimal theory
  Tidal model
  Accretion model
  Protoplanet theory
- Now, Safronov
  Solar nebular disk model

Stellar system formation



Stellar system formation

- Cloud collapse
- Disk formation
- Envelope dissipation
- Planet formation



Stellar system formation

Disk mass loss

$$M_p \approx 0.01\, M_\odot$$

$$M_d \approx 0.3\, M_*$$

- Photo-evaporation
- Accretion
- Stellar winds
- Jets

Core growth

Planetesimal formation

- Sticking due to van der Waals interactions
- Growth to 1-100 kilometer sized objects
- Little gravitational influence

Oligarchic growth

- Planetesimals combine to protoplanets
- Gravitational force dominant

Core growth

$$\frac{\mathrm{d}M_{\mathrm{solid}}}{\mathrm{d}t} = F\rho_m v_{\mathrm{m}} \pi R_{\mathrm{M}}^2 \left(1 + \frac{v_{\mathrm{esc}}^2}{v_{\mathrm{m}}^2}\right)$$

Derive scaling law

$$v_{\mathrm{m}} \approx e_{\mathrm{m}} r \Omega \qquad i_{\mathrm{m}} \approx e_{\mathrm{m}} / 2 \qquad H \approx e_{\mathrm{m}} r / 2$$

$$v_{\mathrm{esc}}^2 = \frac{2GM}{R_{\mathrm{M}}} \qquad R_{\mathrm{M}} \propto M^{1/3} \qquad F = \begin{cases} 1, & r < r_{\mathrm{SL}} \\ 4.2, & r > r_{\mathrm{SL}} \end{cases}$$

$$\frac{\mathrm{d}M_{\mathrm{solid}}}{\mathrm{d}t} \propto \frac{\sigma_{\mathrm{m}} M^{4/3}}{e_{\mathrm{m}}^2 r^{1/2}}$$

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Two regimes

- Planetesimal growth $e_{\mathrm{m}} = \mathrm{cst}$ $\dot{M} \propto M^{4/3}$
- Core growth $e_{\mathrm{m}}^{\mathrm{eq}} \propto M^{1/3}$ $\dot{M} \propto M^{2/3}$

$$M_1 > M_2$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{M_1}{M_2} = \begin{cases} (M_1/M_2)(M_1^{1/3} - M_2^{1/3}) > 1 \\ (M_1/M_2)(M_1^{-1/3} - M_2^{-1/3}) < 1 \end{cases}$$

Runaway growth

Oligarchic growth

$$\sigma_{\mathrm{m}}(M) = \sigma_{\mathrm{m}}(0) - \frac{M^{1/3}}{2\pi r \Delta r} = \sigma_{\mathrm{m}}(0) - BM^{2/3}$$

$$\dot{M} = AM^{2/3}(\sigma_{\mathrm{m}}(0) - BM^{2/3})$$

$$M = \left(\frac{\sigma_{\mathrm{m}}}{B}\right)^{3/2} \tanh^{3}\left[\frac{AB^{1/2}\sigma_{\mathrm{m}}^{1/2}}{3}t + \tanh^{-1}\left(\frac{B^{1/2}M_0^{1/3}}{\sigma_{\mathrm{m}}^{1/2}}\right)\right]$$

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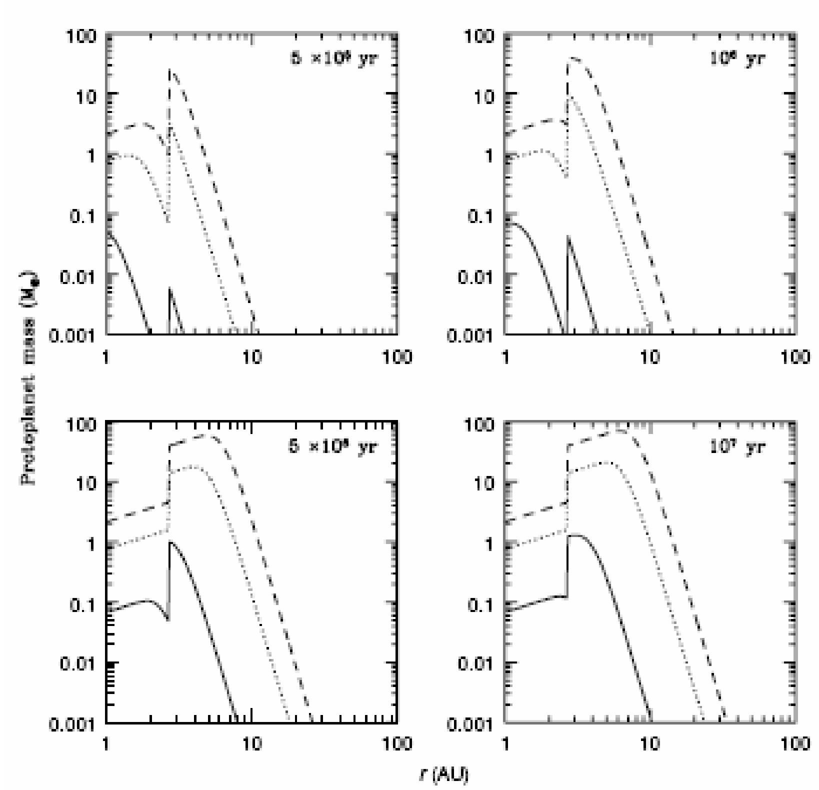
$$A = 3.9\left(\frac{bC_D\rho_{gas}}{\rho_m^{2/3}m^{1/3}}\right)^{2/5}\frac{G^{1/2}M_*^{1/6}}{\rho_M^{1/3}r^{1/10}} \qquad B = \frac{3^{1/3}M_*^{1/3}}{2\pi b r^2}$$

$$M_{iso} = \left(\frac{B}{\sigma_m}\right)^{3/2} \qquad t_{iso} = \frac{3}{AB^{1/2}\sigma_m^{1/2}}$$

Core growth

- Peak in mass at 5-10 AU
- Rapid decrease

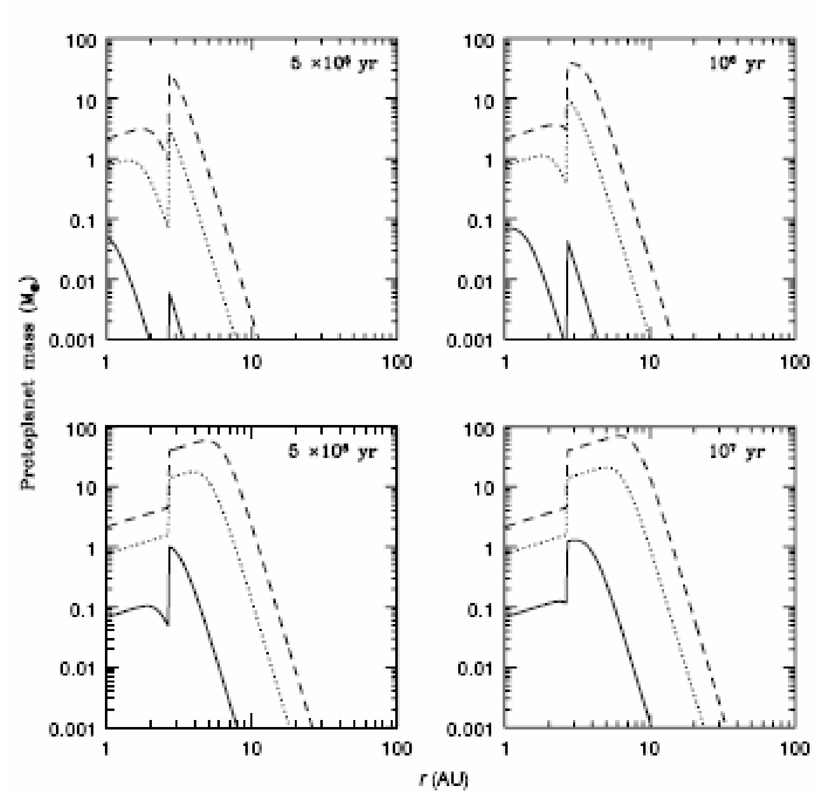
$$t_{\mathrm{earth}} \simeq 10^{8}\,\mathrm{y}$$



Core growth

Problems

- Incorrect for the outer planets
- No radial migration considered
- Effects of gas simplified
- Overestimation of mass
- Numerical calculations yield improved results



The final step

Terrestrial planets:

Mars sized protoplanets merge

Gas giants:

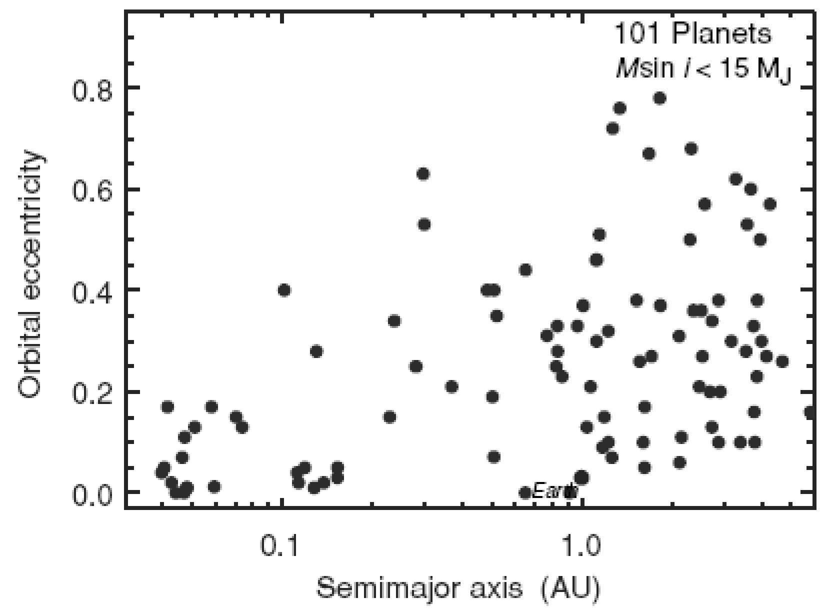
The already big protoplanets accrete gas

Ice giants:

“Failed” gas giant cores

After formation

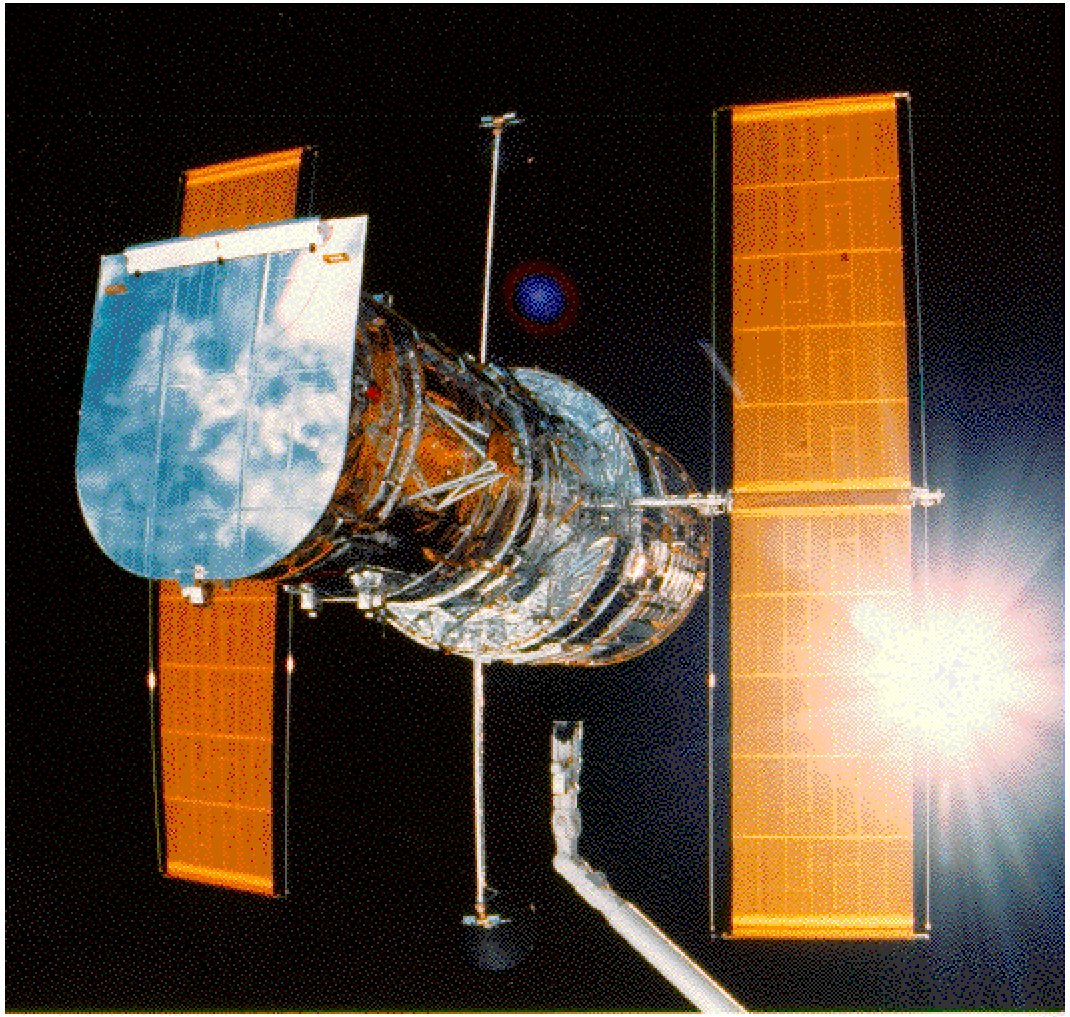
- High eccentricities for larger orbits
- Due to planet planet interactions
- Planet migration



Exoplanet detection

Star displacement

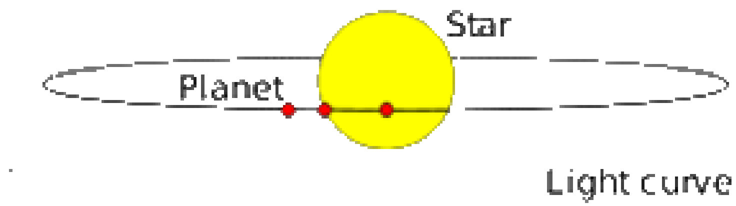
- Astrometry (Hubble space telescope)
- Radial velocity (HARPS)



Exoplanet detection

Transits

- Spitzer telescope
- COROT



Advantages

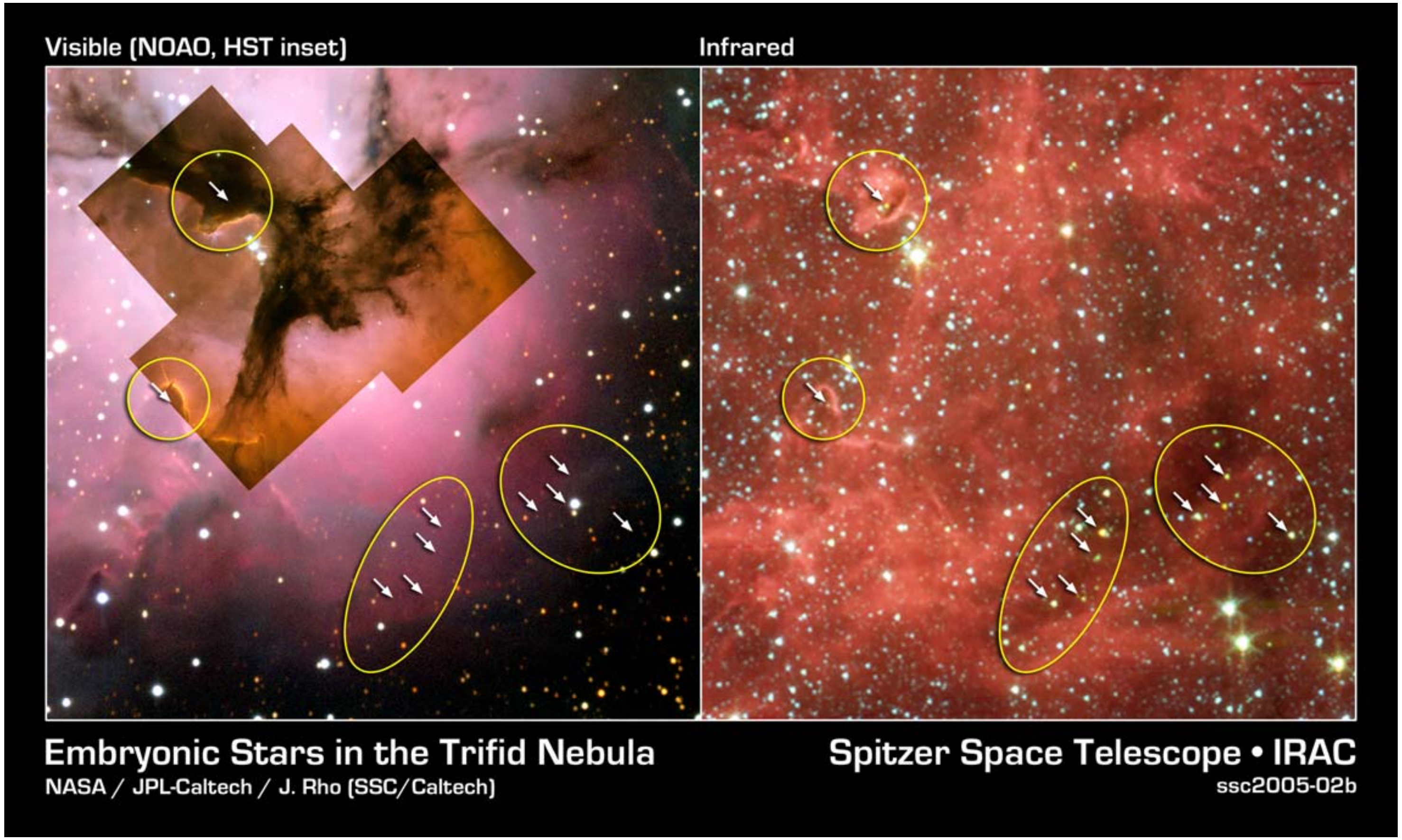
- Measures size
- Atmospheric composition

Disadvantages

- P_{detect}=0.47% at 1AU
- Large chance of false detections

Exoplanet detection

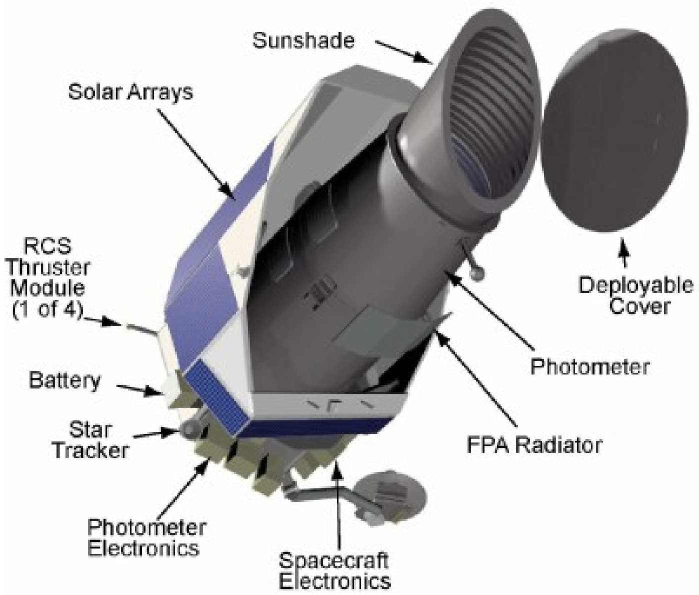
Spectrum analysis

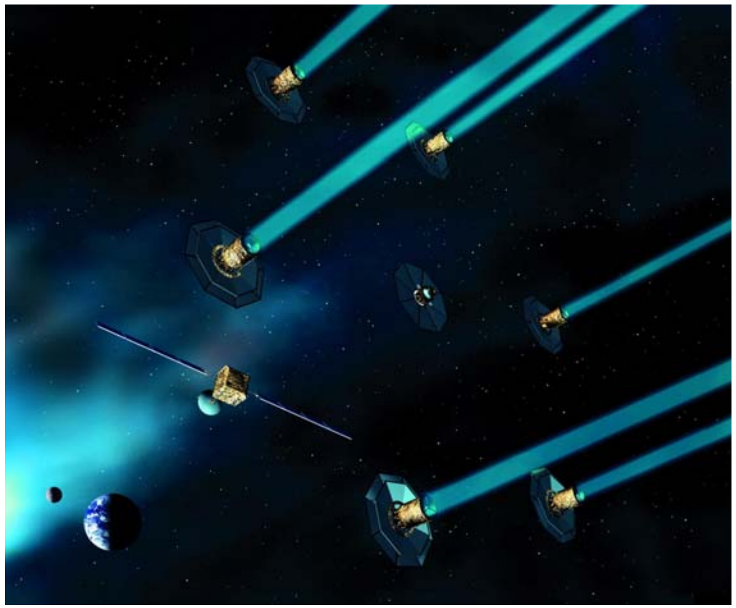


Exoplanet detection

Future programs

- Kepler mission, transit method, early 2009
- ESA's Darwin, direct imaging, 2015
- Terrestrial planet finder, direct imaging, --





Discussion

How typical is the solar system?

Features of the solar system

- 8 planets
- Circular orbits in plane

From observations

- Many single planet systems (bias)
- High eccentricities
- Many “hot jupiters”