Lecture_12

February 28, 2023

1 Solar System Formation

The general picture of formation of the solar system suggests that it was formed from the collapse of a giant dust cloud (called a protosolar nebula, more on this in 3rd year) which was mostly composed of hydrogen. A key feature of this model is that the total angular momentum of the system must be conserved.

There is some direct observational evidence for this feature:

- The direction of the Sun's rotation, and of the rotation and orbital motion of (nearly) all the planets coincide ("prograde" direction).
- The rotation axes of nearly all planets are within 25-30^o of being perpendicular to their orbital planes
- The planets orbital planes all coincide to within 7^o (most are even within 1-3^o)

So, since the angular momentum for the Sun's rotation, the planet's rotation, and the planet's orbital motion all have the same direction, then is was likely the angular momentum for the protosolar nebula.

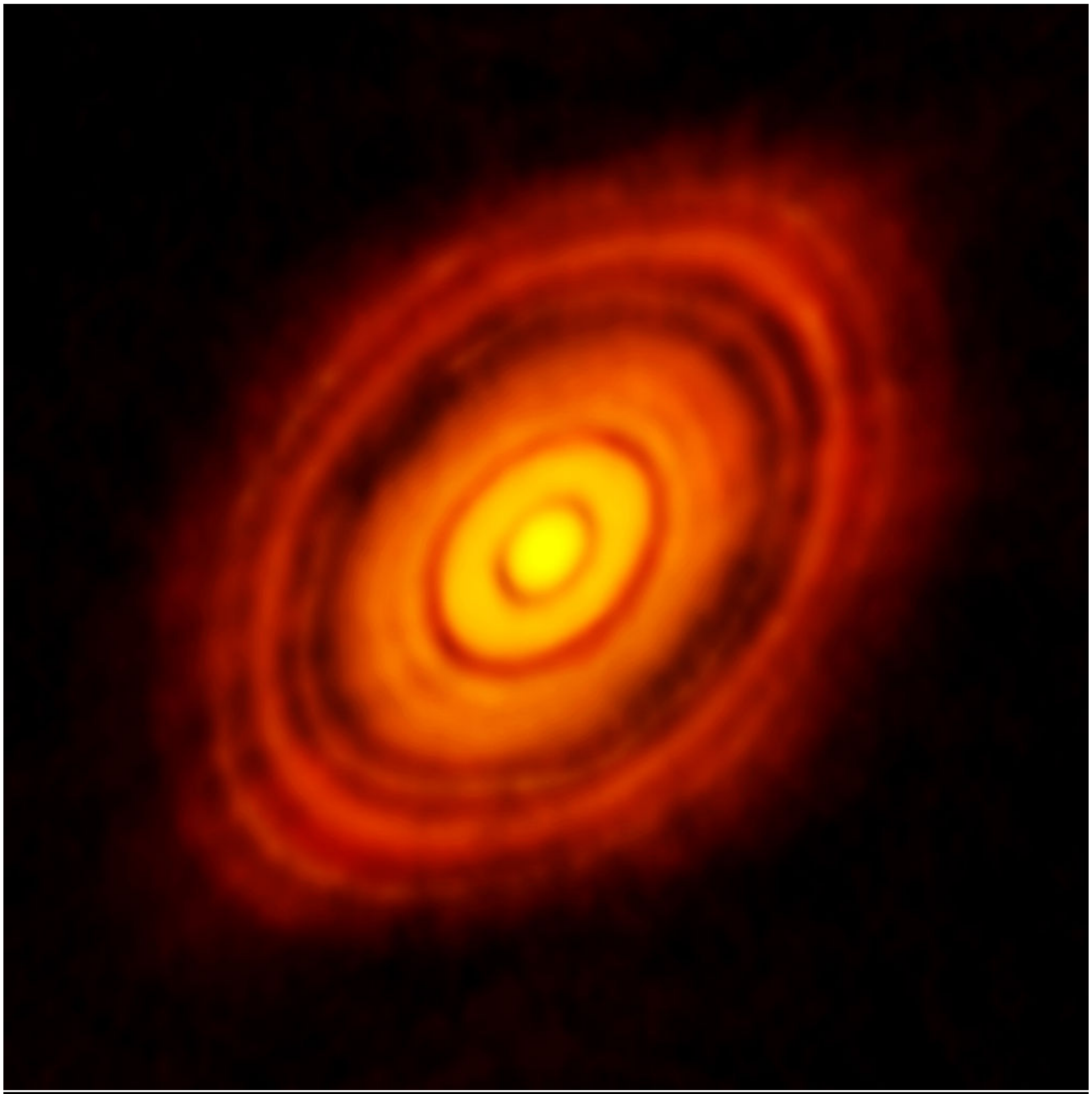
Now, not all observational evidence does support this model:

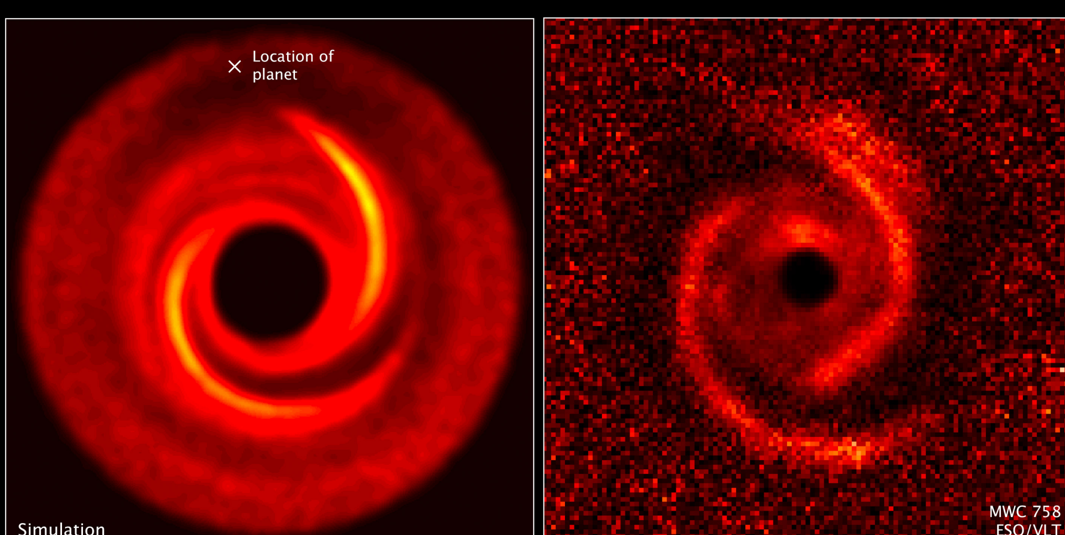
- Venus and Uranus' rotations are "retrograde" (that is, they rotate opposite to everything else)
- Uranus' rotational axis is inclined 98^o to it's orbital plane (that is, it's rotating on it's side)
- Earth, Mars, Saturn, and Neptune have angles between their orbital and rotational planes of 23-29^o

A proposed solution to all of these issues is that these planets collided with planetesimals during formation.

1.1 Protoplanetary discs

Below, I've included some real/simulated observations of protoplanetary discs.





Protoplanetary Disk ▪ Simulated Spiral Arm vs. Observational Data
ESO/VLT

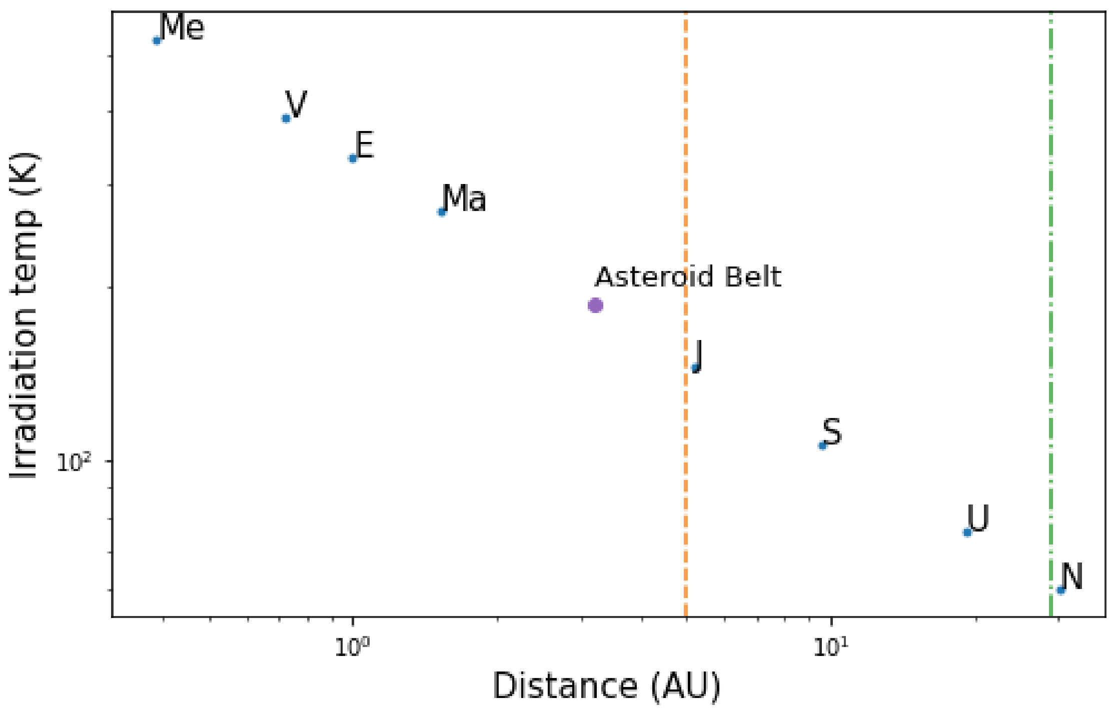
NASA, ESA, and ESO

STScI-PRC15-40a

1.2 Terrestrial versus Gas Giant Planets

So why do we have these two types of planets? And how does this feed into a model of forming the solar system? First, let's propose a model.

- As the protosolar nebula contracted and formed a disc, heavier elements condensed out first.
- Water had not yet condensed when terrestrial planest formed. It's suspected most water on Earth comes from collisions with cometary nuclei.
- Water could condense beyond some distance from Sun, near orbit of Jupiter (as shown below, where we've calculated the irradiation temperature for different distances from the Sun, and found where the snow line (condensation temperature for water = 150 k) lies.



2 Quirks of planets

2.1 Mercury

- Its rotation is studied using rader signals transmiteed by the Arecibo radio telescope (which has since collapsed) in 1965, using the Doppler effect. The rotational period is $P_{\text{rot}} = 58.65$ d.
- This is exactly 2/3 of the orbital period of the planet ($P_{\text{orb}} = 87.97$ d). Since Mercury feels the strongest tidal force at perihelion (point of closest approach to the Sun), this means that the tidal bulges always line up with the Sun at this time (as there is 1.5 rotations per orbit, see figure).
- Gravitational influence of other planets causes the perihelion to shift in a counter clockwise rotation by 574"/century. Newtonian gravity can only explain 531"/century - the remainig

43”/century explained using Eintein’s theory of general relativity.

2.2 Mars and the asteroid belt (between Mars and Jupiter)

- Mars has a low mass of 0.107 $M_\oplus$.
- To explain this, it may be that Jupiter became very massive before Mars finished forming, which perturbed orbits of planetesimals near Mars.
- This would meant the “missing mass” of Mars has endde up in the asteroid belt.
- Numerical simulations suggest mars rotational axis may vary chaotically with tilts between 11-49^o on timescales as short as a few million years (due to its low mass and gravitational influence of other planets).

2.3 Venus

- Also studied using radar signals sent from Earth, but also using Doppler shifts of reflected sunlight.
- Venus rotates in a retrograde direction, with $P_{\rm rot} = 243$ d and $P_{\rm orb} = 224.7$d.
- Main gas in atmosphere is C02 (96.4%). At the base of its atmosphere, it has $T = 740$ K and a pressure of 90 atm.
- This temperature is 2-3 times higher than the irradiation temperature we get when we use the formula from last weeek - due to the greenhouse effect.
- Surface accurately mapped by the Magellan spacecraft. The frequency of the radio signals sent to Earth were Doppler shifted depending on the speed of the spacecraft as it passed over regions of higher/lower mean density.
- It also potentially has traces of phosphine in its upper atmosphere (which **may** be due to life).

2.4 Gas Giants

All planets produce heat due to the decay of radioactive nuclei, including the terrestrial planets, but the Gas Giants show excess heat on top of this. Ti figure out why Gas Giants show this, and terrestrial planets do not, let’s think about the energy that was released by the gravitational collapse of the disc in to the planets, and how long it should take for bodies to dissipate this heat:

$$\tau_{\rm cool} = \frac{\text{total energy}}{\text{energy loss rate}} \sim \frac{V}{A} \sim \frac{r^3}{r^2} \sim r$$

So, the bigger the planets radius, the longer it takes for it dissipate all of the heat due to contraction. This is the Kelvin-Helmoholtz mechanism. Given this, we would expect Jupiter to still be contracting due to the it’s formation.