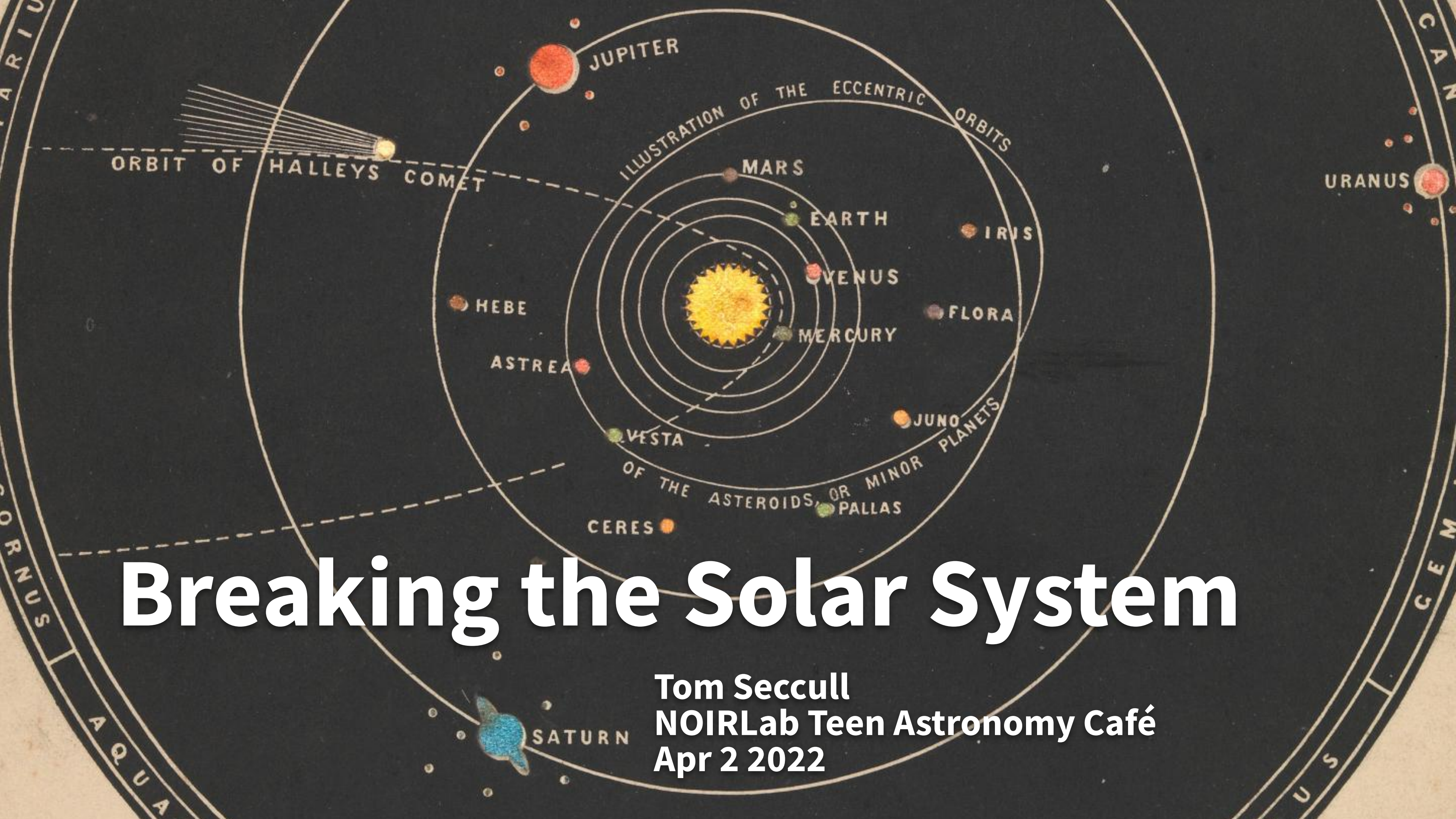
TEEN ASTRONOMY Café – To Go!

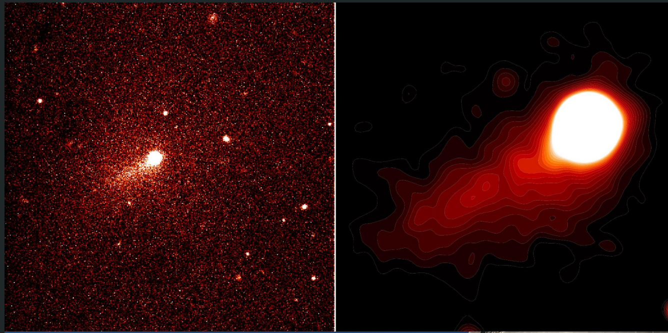


Breaking the Solar System

Tom Seccull
NOIRLab Teen Astronomy Café
Apr 2 2022

Tom Seccull

- Grew up in England
- 2011-2015: Undergrad at Queen's University Belfast in Northern Ireland
  - MSci Physics with Astrophysics
- 2015-2019: PhD in Planetary Science at QUB
  - Composition of Trans-Neptunian Objects (TNOs)
  - Effects of cometary activity on the surfaces of TNOs and Centaurs
- 2019-Today: Science Fellow at Gemini Observatory/NOIRLab
  - Supporting operations at the Gemini North telescope
  - Solar System research



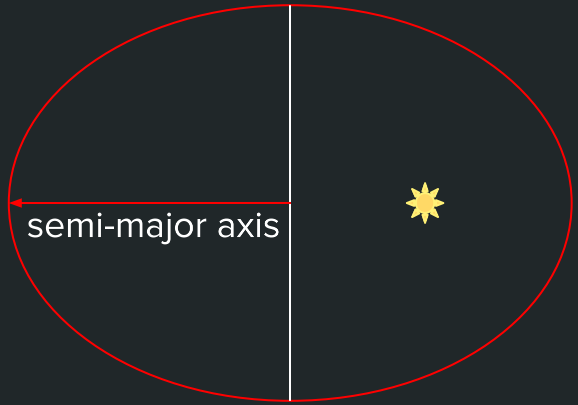
What do we mean by “Breaking” the Solar System?

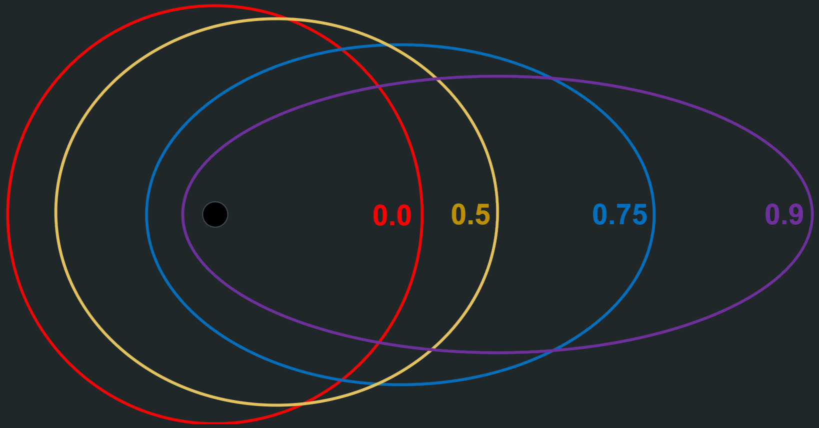
- Has the Solar System always looked like it does today?
- How stable are the orbits of the planets?
- What does it take to move a planet?
- Does changing a planet’s orbit cause anything unexpected to happen?
- Has the Solar System broken in the past?
    - How do we know it was broken?
    - How did break?
    - It doesn’t look broken anymore, why is that?

Concepts: Orbits and Orbital Elements

All planetary orbits are elliptical, and have a shape, size, and orientation defined by six parameters.

1. Semi-major axis - furthest distance a planet gets from the center of its orbit
    a. Note: The Sun is only at the center of a perfectly circular orbit
2. Eccentricity - how elliptical a planet's orbit is





Concepts: Orbits and Orbital Elements

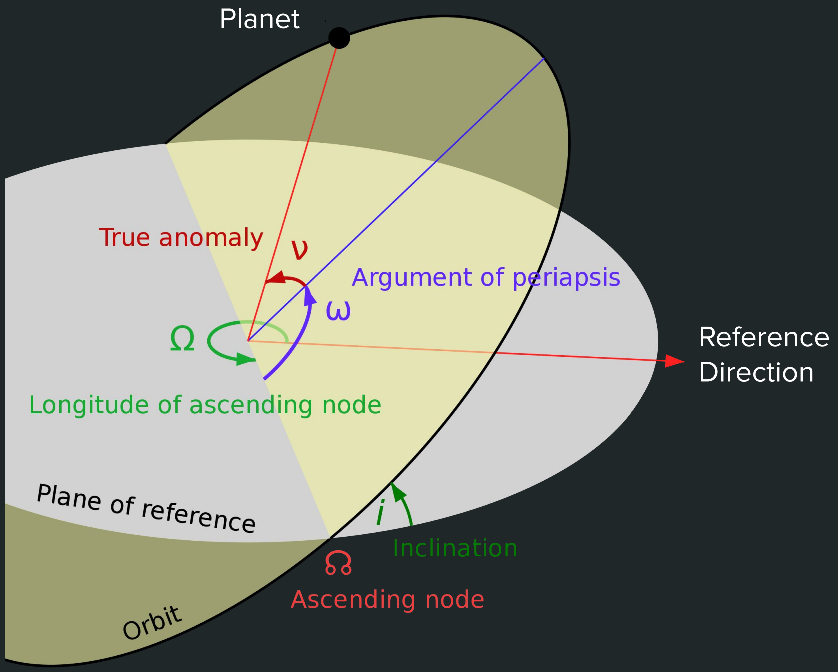
All planetary orbits are elliptical, and have a shape, size, and orientation defined by six parameters.

3. Inclination - tilt of the orbit relative to the ecliptic

4. Longitude of ascending node - where the planet crosses from below to above the ecliptic

5. Argument of periapsis - what direction the ellipse is pointing

6. True anomaly - where the planet is in its orbit at a certain time



Concepts: Gravity

Gravity is the main force that defines the motion of the planets.

Gravitational Constant

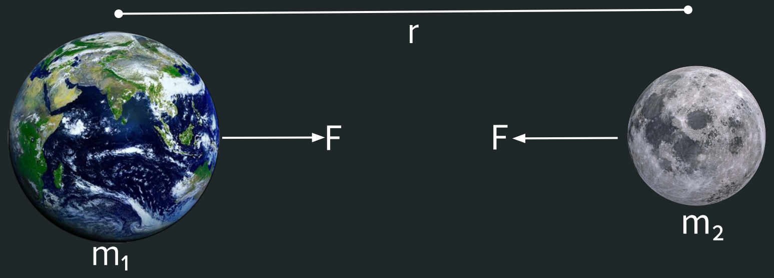
Masses of objects 1 and 2

$$F = \frac{Gm_1 m_2}{r^2}$$

Force of gravity felt by each object

Distance between objects 1 and 2

- Gravity is stronger between more massive objects
- Gravity is stronger between objects that are closer together
- Strength of gravity drops as $1/r^2$
    - E.g. increasing distance x2 decreases strength of gravity x4



Concepts: Angular Momentum

Any mass that rotates around a central point has angular momentum.

Orbital velocity of the planet

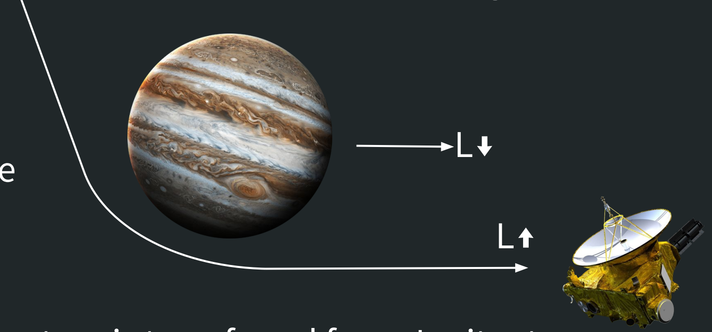
Mass of the planet

$$L = mvr$$

Distance between the planet and the the object it orbits

An orbiting planet’s angular momentum

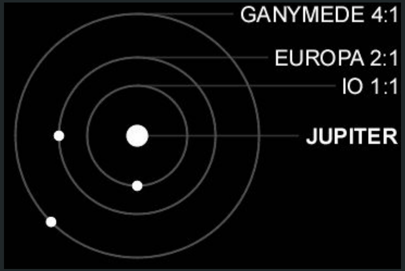
- Faster, more massive objects on orbits further from the Sun have more angular momentum.
- Objects can exchange angular momentum through gravitational interactions, which changes their orbital velocity.
    - We exploit this fact when we use planets to speed up spacecraft with gravity assists.



Angular momentum is transferred from Jupiter to a space probe.

Concepts: Orbital Resonance

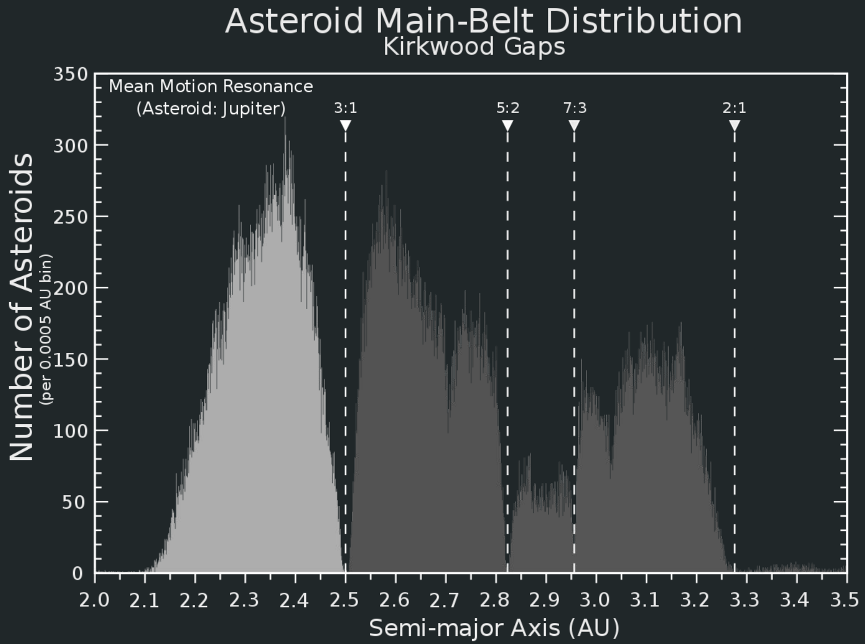
Sometimes the orbits of planets and moons fall into resonant patterns where objects gravitationally pull on each other at regular intervals.



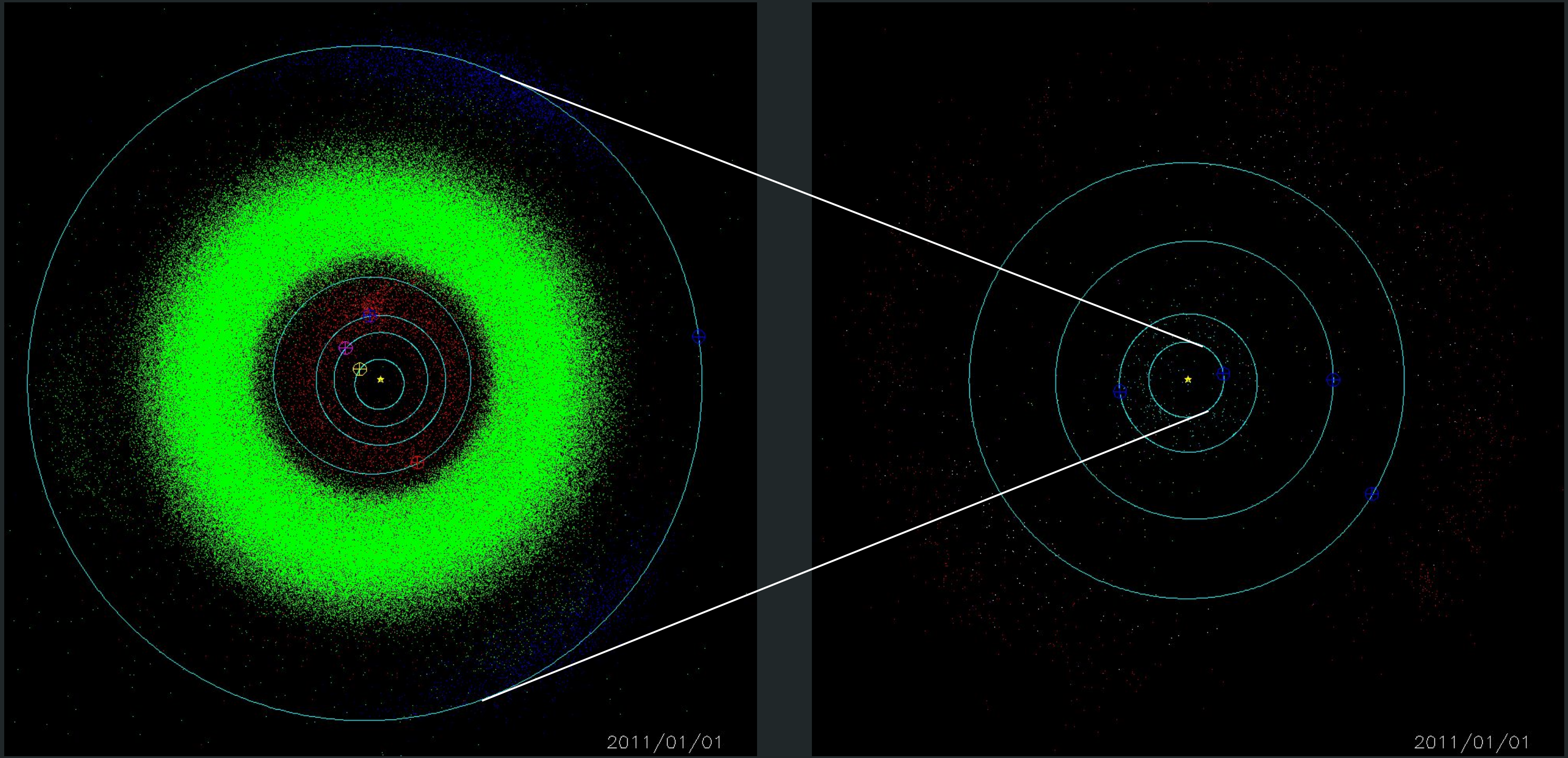
Three of Jupiter's largest moons are in resonance with each other.

Pluto is also in 3:2 resonance with Neptune.

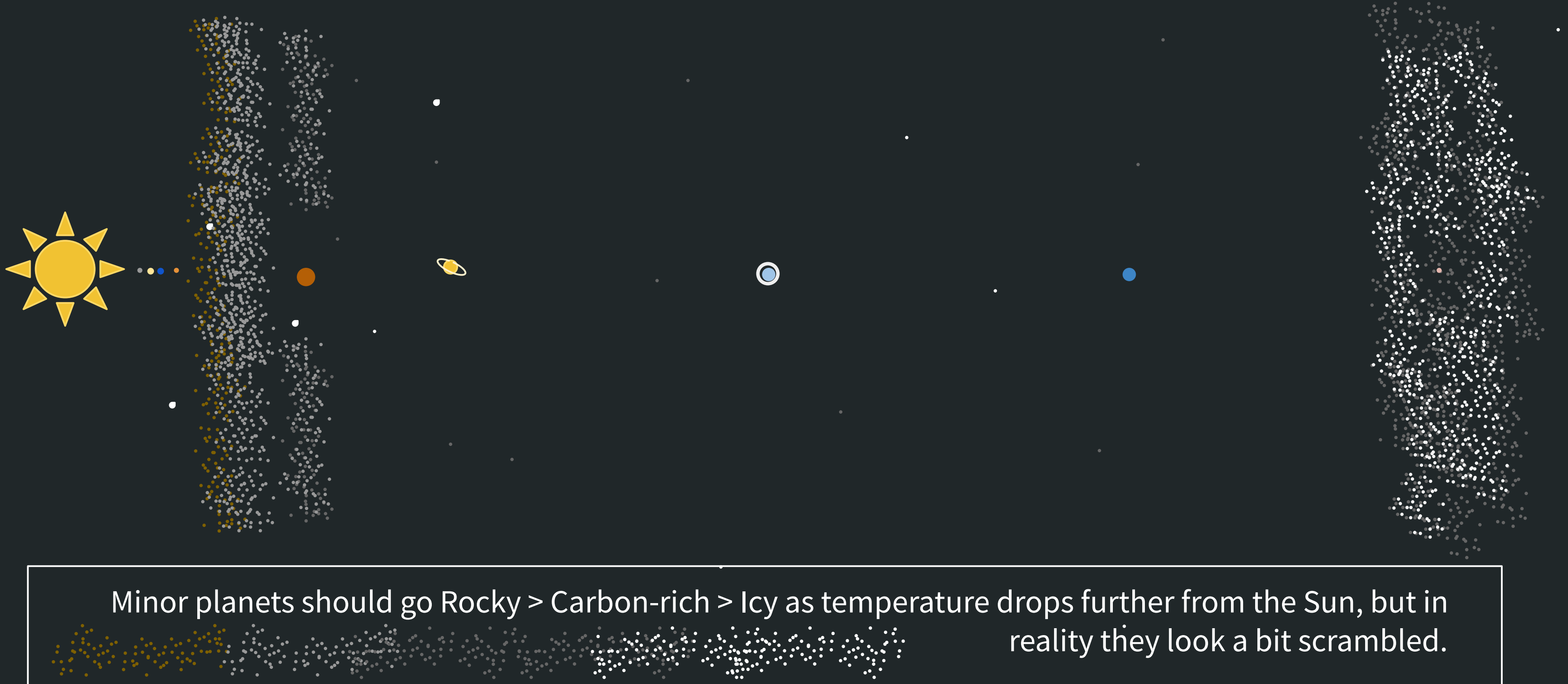
- Some resonant systems are stable and self-correcting.
- Others are unstable and cause the orbits of objects to change so they fall out of resonance.
- Planets may preserve the orbits of asteroids in their resonances, but can also clear asteroids out of certain regions of space.



What does the Solar System look like?

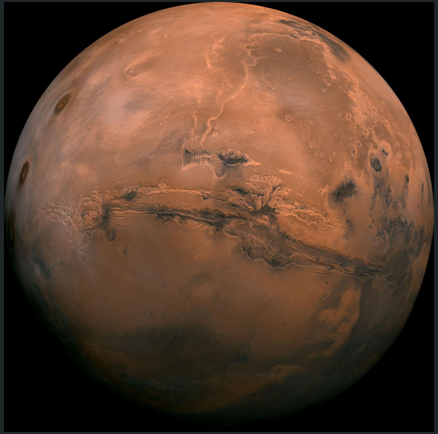


The Solar System looks stable, but was it always?



Minor planets should go Rocky > Carbon-rich > Icy as temperature drops further from the Sun, but in reality they look a bit scrambled.

Other Evidence of Disruption and Planet Migration

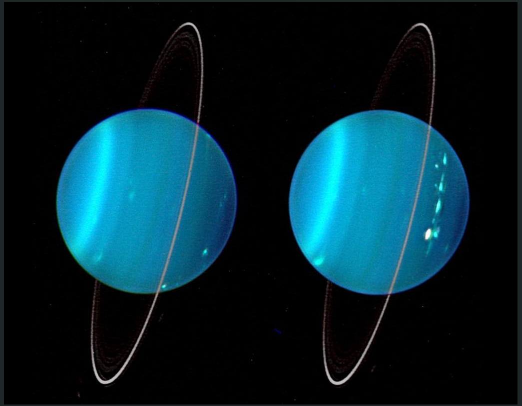


Mars is smaller than expected.
$r\square = 0.533r_e$
$m\square = 0.107r_e$

Was less material available when Mars formed?

We observe interstellar objects like 1I/’Oumuamua and 2I/Borisov.

These objects could have been kicked out of their planetary systems by migrating planets.

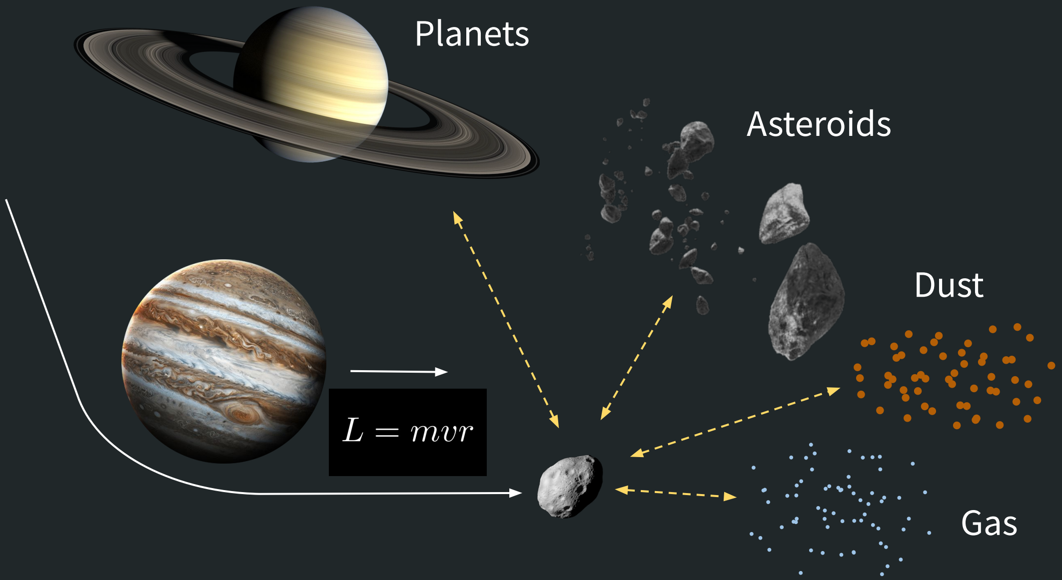


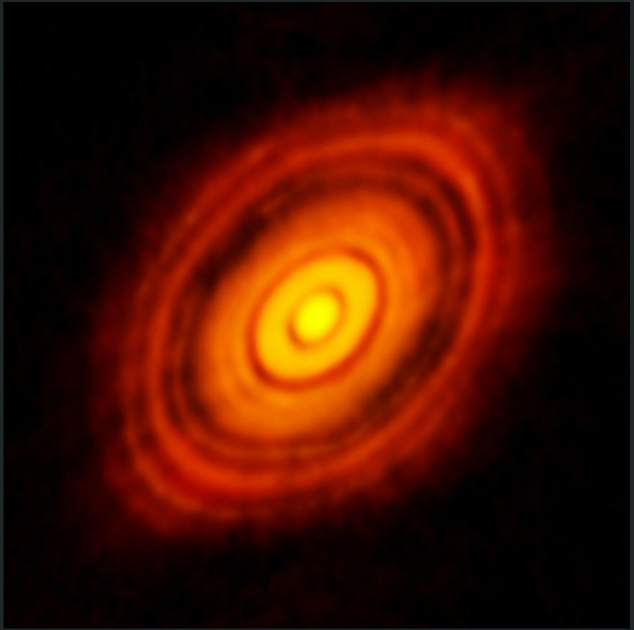
Uranus is tilted over by 97.7° relative to its orbit.

It’s thought that a collision with an Earth-sized object could have caused this.

Planet migration in a nutshell

Moving a planet is all about exchange of angular momentum.

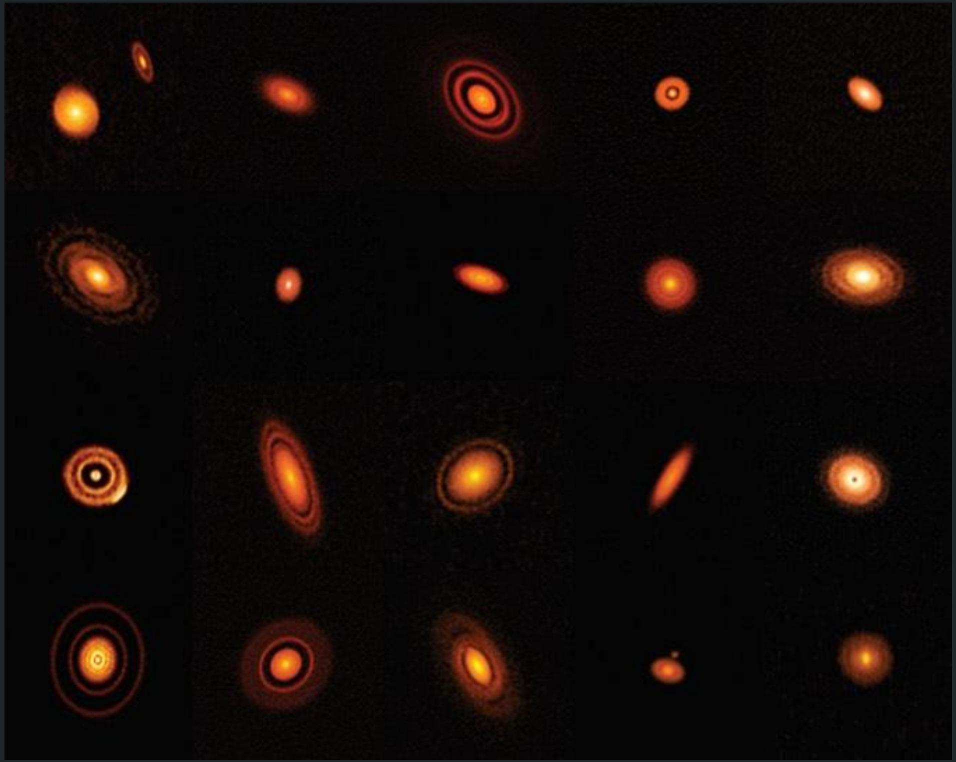




Angular momentum exchange between one small object and a planet has only a tiny effect on the planet’s orbit, but if the planet orbits within a dense disk of material those small exchanges add up fast.

How do we test our ideas?

- Observations?
  - We can only get snapshots of forming and evolving planetary systems.
  - Monitoring the whole process would take millions of years.
- n-body simulations?
  - Physical mechanisms can be accounted for separately.
  - One simulation can show us the entire evolution of a planetary system.



How do we test our ideas?

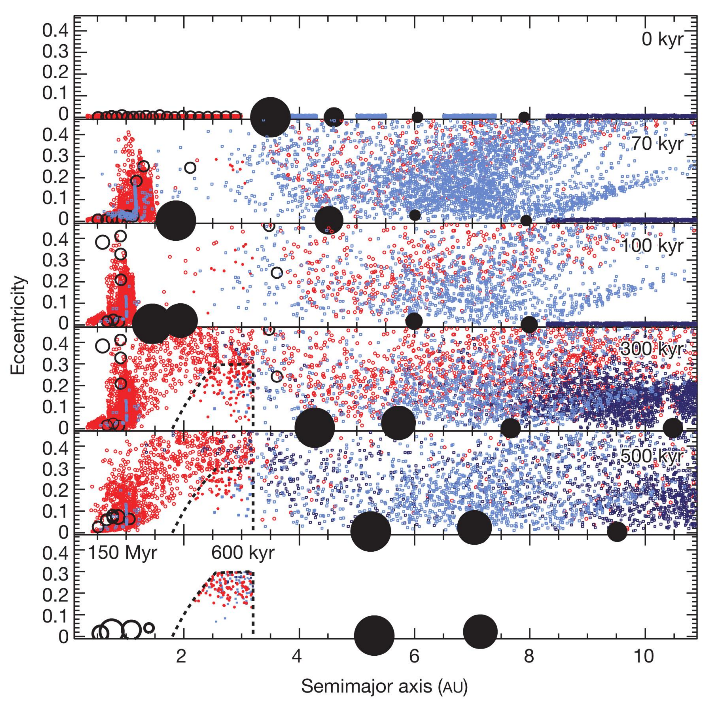
The process:

1. Use our hypothesis about how the Solar System started to set the initial conditions of the simulation.
2. Define the physics of the dynamical processes we are trying to test/observe in the simulation.
3. Run the simulation (you may need a supercomputer for this part).
4. When the simulation is finished, study what the final Solar System looks like and compare it to the real thing.
    a. Have the dynamical processes had the effect you thought they would?
    b. Have they reproduced the dynamical structure of the Solar System as we observe it now?

Our Best Theories: The Grand Tack

Setting the scene:

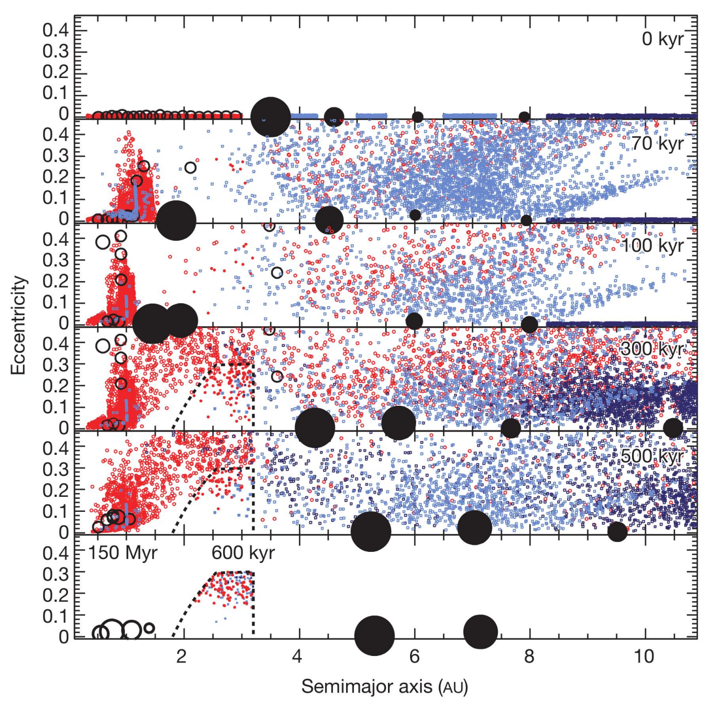
- We think the Solar System started off compact.
- Solar System is < 5 million years old
  - Lots of gas in the protoplanetary disk
- Jupiter has just finished forming
- Other planets haven't fully formed yet
- Lots of dust and planetesimals in the disk
  - Rocky, Carbon-Rich, Icy
- What happens when we include gas-driven migration to this scenario?



Our Best Theories: The Grand Tack

Simulation is run for 0.5 million years

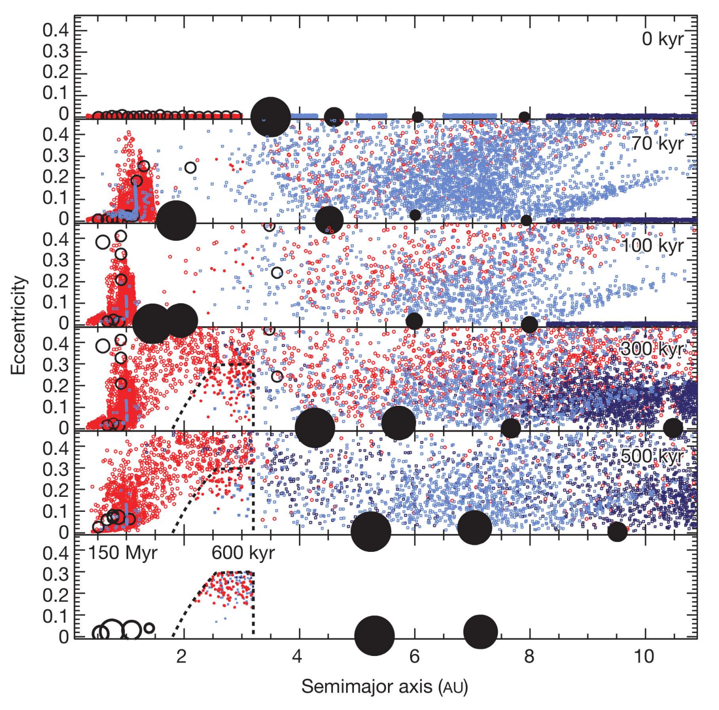
- Jupiter gravitationally interacts with gas in the disk, loses angular momentum, and starts migrating toward the Sun.
  - Rocky and carbon-rich asteroids get caught in resonances or are scattered outwards
- Jupiter reaches 1.5 AU. Saturn becomes massive enough to start migrating inward.
  - More rocky and carbon-rich asteroids are scattered outwards.
- Saturn catches up to Jupiter's 2:1 resonance and they become gravitationally coupled.
  - Combined their angular momentum exchange reverses and they migrate outward.
  - Rocky and carbon rich asteroids get scattered inward again.
- Uranus and Neptune interact with the disk and start migrating outward
  - Icy planetesimals get scattered inward.



Our Best Theories: The Grand Tack

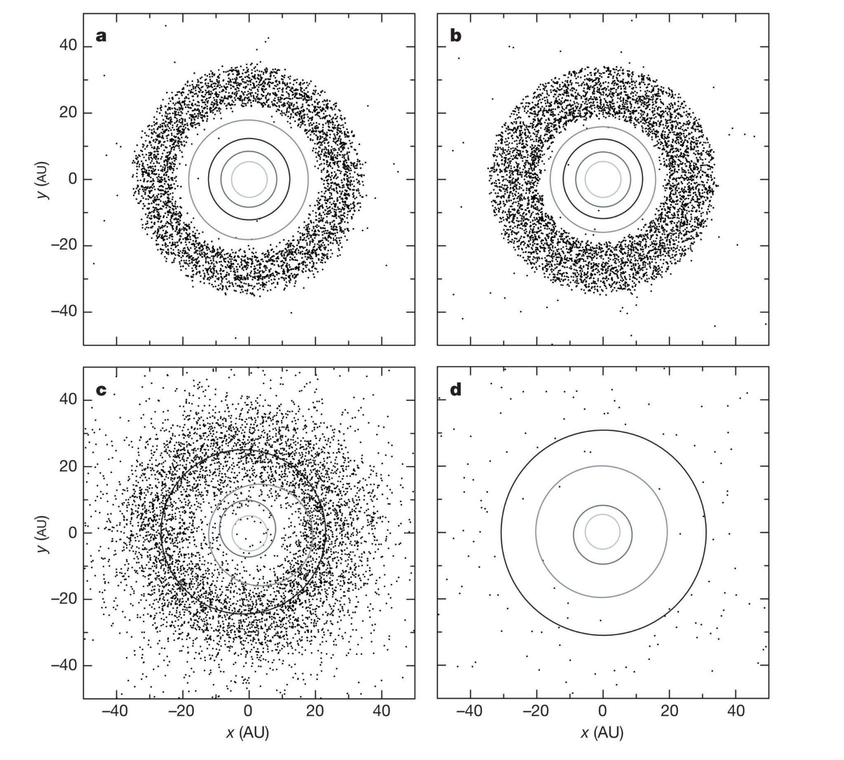
Results of the simulation

- Giant planets end up more spread out and resonant with each other
- Planetesimals end up scattered everywhere
  - Mixture of rocky and carbon-rich objects where the modern asteroid belt is.
  - Planetesimals are removed from the area around Mars, so Mars does not grow as large as the Earth or Venus.
  - Many planetesimals are thrown out of the Solar System completely -> Interstellar objects
- If Saturn hadn't migrated and stopped Jupiter, the Earth probably wouldn't exist.
- That's not the end of the story though…



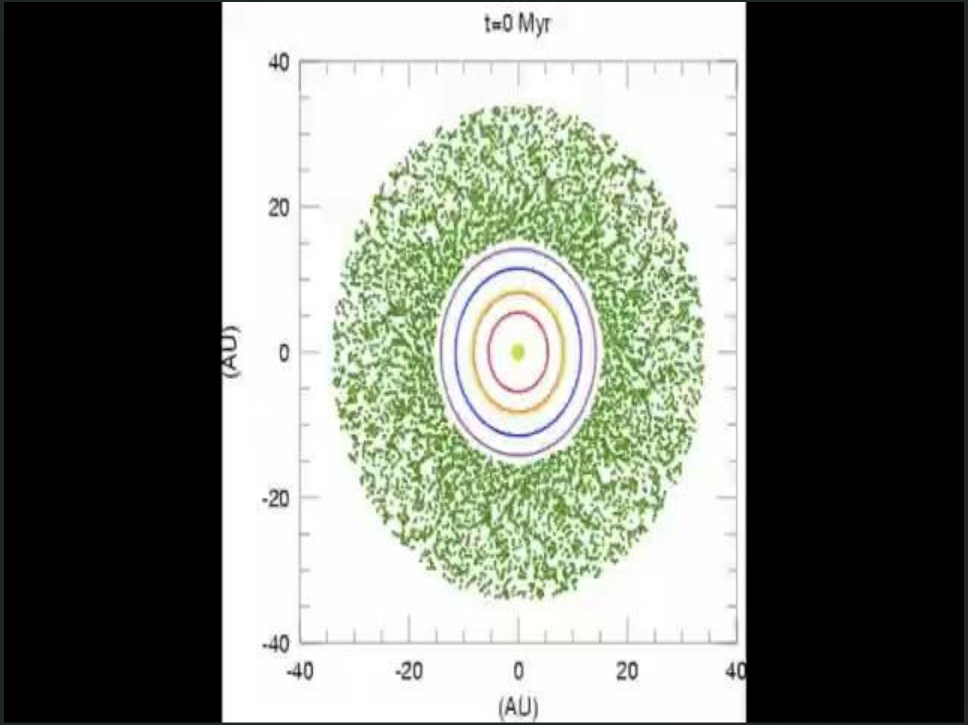
Our Best Theories: How the Nice Instability Broke the Solar System

- After 500 million years the Solar System had settled into a somewhat stable configuration with Saturn and Jupiter in 2:1 resonance with each other.
- Large outer disk of planetesimals still causes the planets to slowly migrate outward.
- Suddenly Jupiter and Saturn pop out of resonance and the planets start scattering off each other.
- Neptune and Uranus migrate out until the number of planetesimals is too low to move them anymore.
- Again planetesimals are thrown everywhere. Many are lost to interstellar space.



Our Best Theories: How the Nice Instability Broke the Solar System

This is the cool video part…

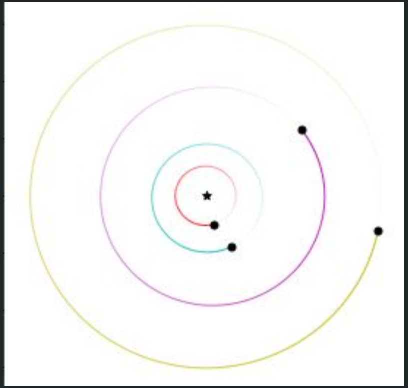


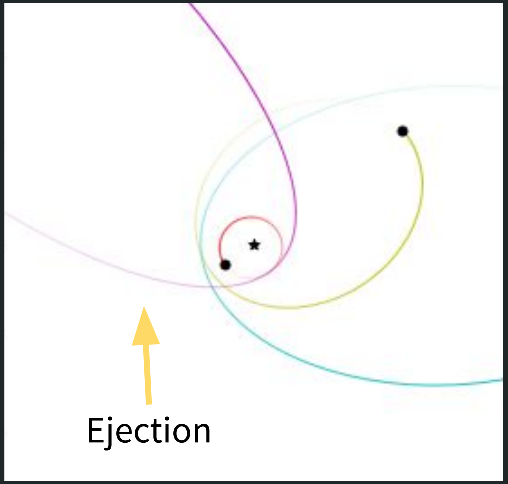
Now it’s your turn to break the Solar System

- How different can you make the Solar System look by changing the starting conditions?
- Which planet do you think has the biggest effect if you change its orbit?
- Is the Solar System as stable as you thought it was before?
- Would Earth be less hospitable to life if the other planets had different orbits?

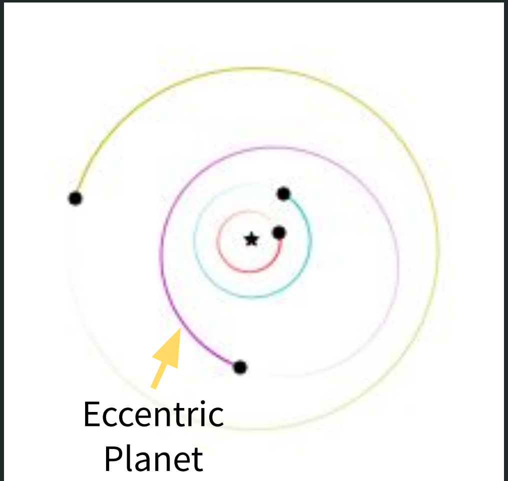
Bonus Slides for Colab Activity

Original Solar System

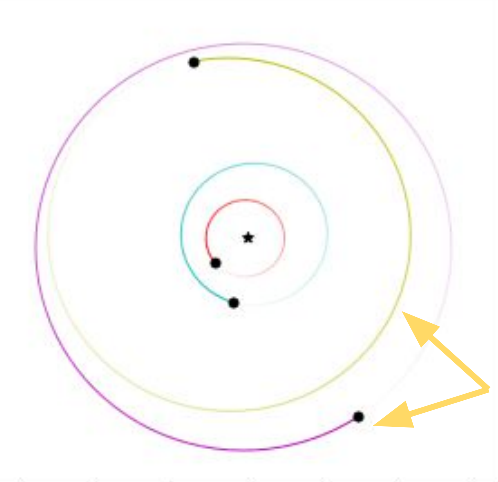




Ejection

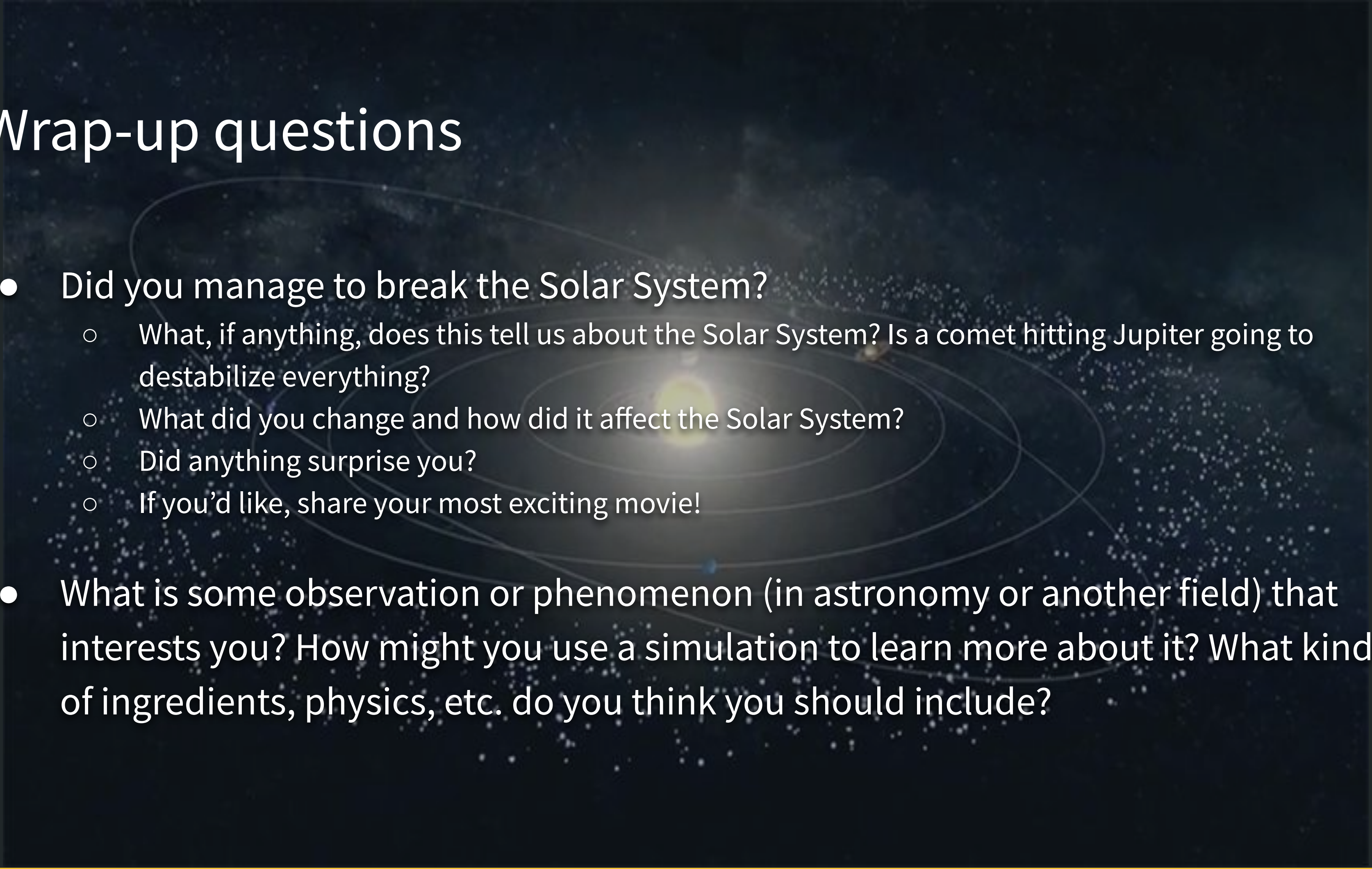


Eccentric Planet



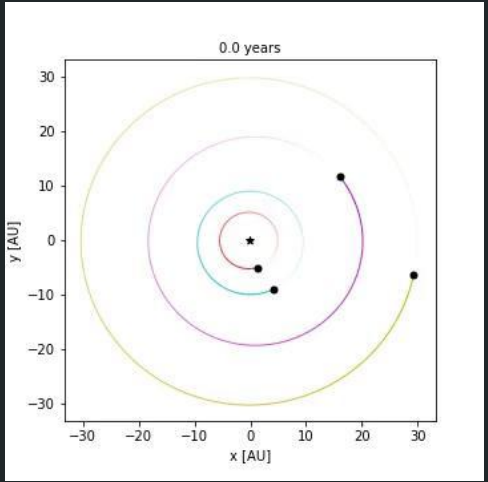
Planets Swap Orbits

Wrap-up questions

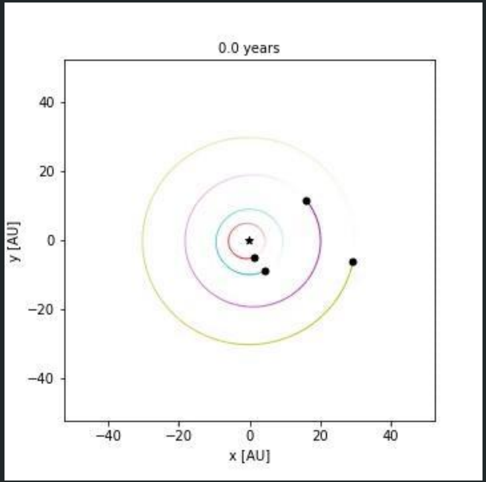


- Did you manage to break the Solar System?
  - What, if anything, does this tell us about the Solar System? Is a comet hitting Jupiter going to destabilize everything?
  - What did you change and how did it affect the Solar System?
  - Did anything surprise you?
  - If you'd like, share your most exciting movie!
- What is some observation or phenomenon (in astronomy or another field) that interests you? How might you use a simulation to learn more about it? What kinds of ingredients, physics, etc. do you think you should include?

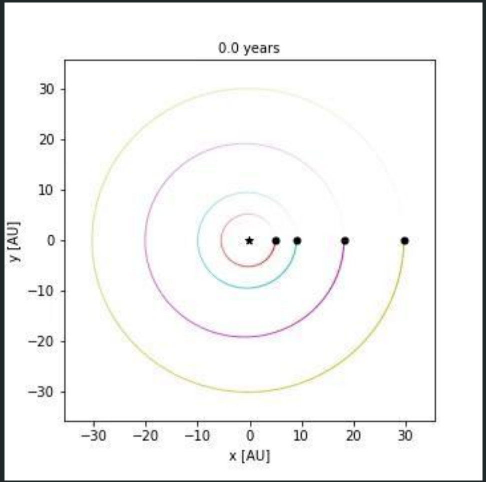
Sun’s mass=0.2



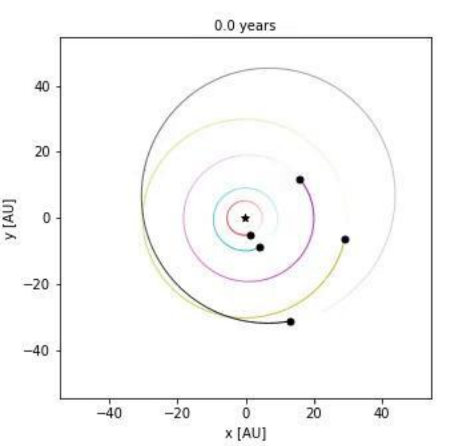
Jupiter ecc=0.15



Planets start aligned



Pluto=Neptune’s mass



Jupiter i=50°

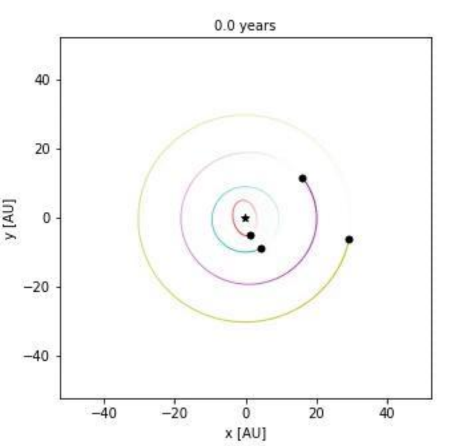


Image Credits & Links

- NASA Minor Planet Orbit Viewer: https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=pluto&view=VOP
- Title image: Engraving showing the Solar System, originally published by James Reynolds of the Strand, London, in 1846. Today it's in the Royal Greenwich Observatory Collection.
- Slide 2: Comet Images - Seccull et al. 2019, AJ, 157, 88
- Slide 5: https://en.wikipedia.org/wiki/Orbital_inclination#/media/File:Orbit1.svg
- Slide 9: Animations from the IAU Minor Planet Center - https://minorplanetcenter.net/iau/Animations/Animations.html
- Slide 10, Mars: NASA / JPL-Caltech
- Slide 10, Artist's impression of 1I/'Oumuamua: European Southern Observatory / M. Kornmesser
- Slide 10, Uranus: Lawrence Stromovsky, University of Wisconsin-Madison / W.M. Keck Observatory
- Slide 11, HL Tau dust disk observed with ALMA: ALMA Partnership et al. 2015, ApJ, 808, L3
- Slide 13, Twenty nearby protoplanetary disks observed with ALMA: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello
- Slide 15, 16, 17: Walsh et al. 2011, Nature, 475, 206
- Slide 18: Gomes et al. 2005, Nature, 435, 466
- Slide 19 videos: Gomes et al. 2005, Nature, 435, 466; Wes Fraser, NRC Herzberg Astronomy and Astrophysics Research Centre

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