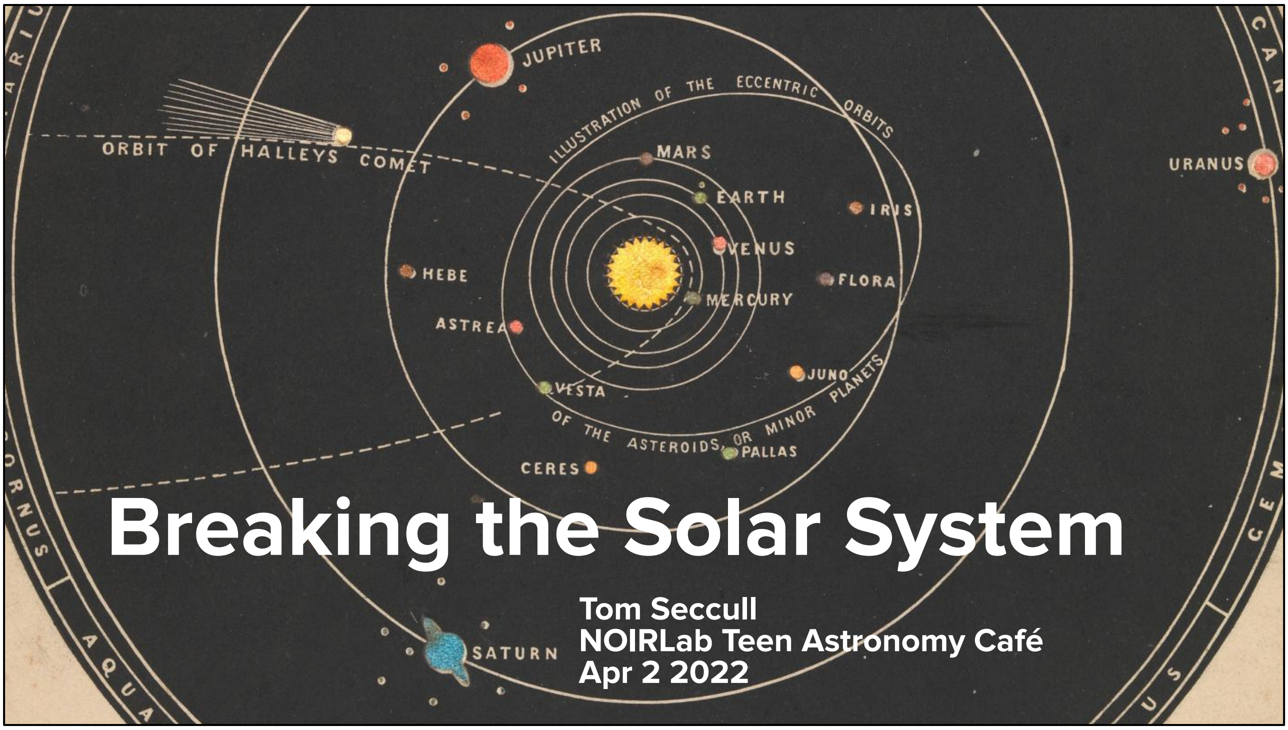
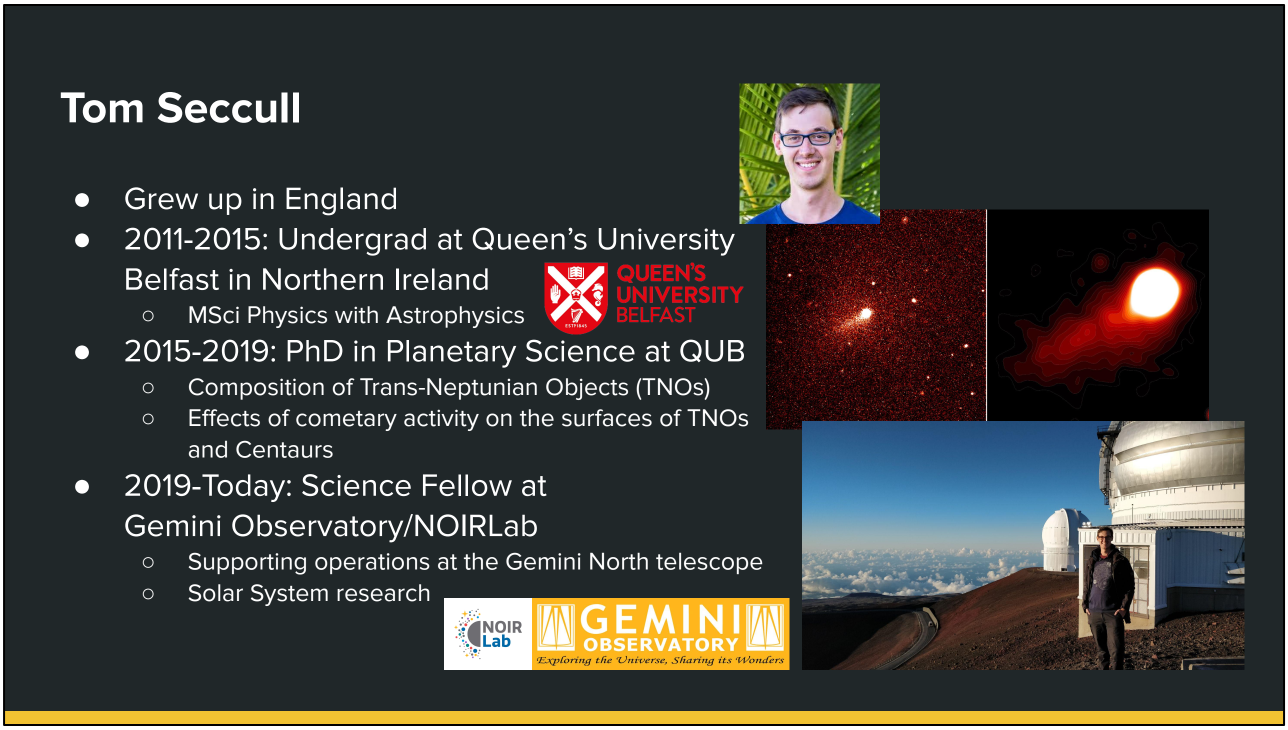


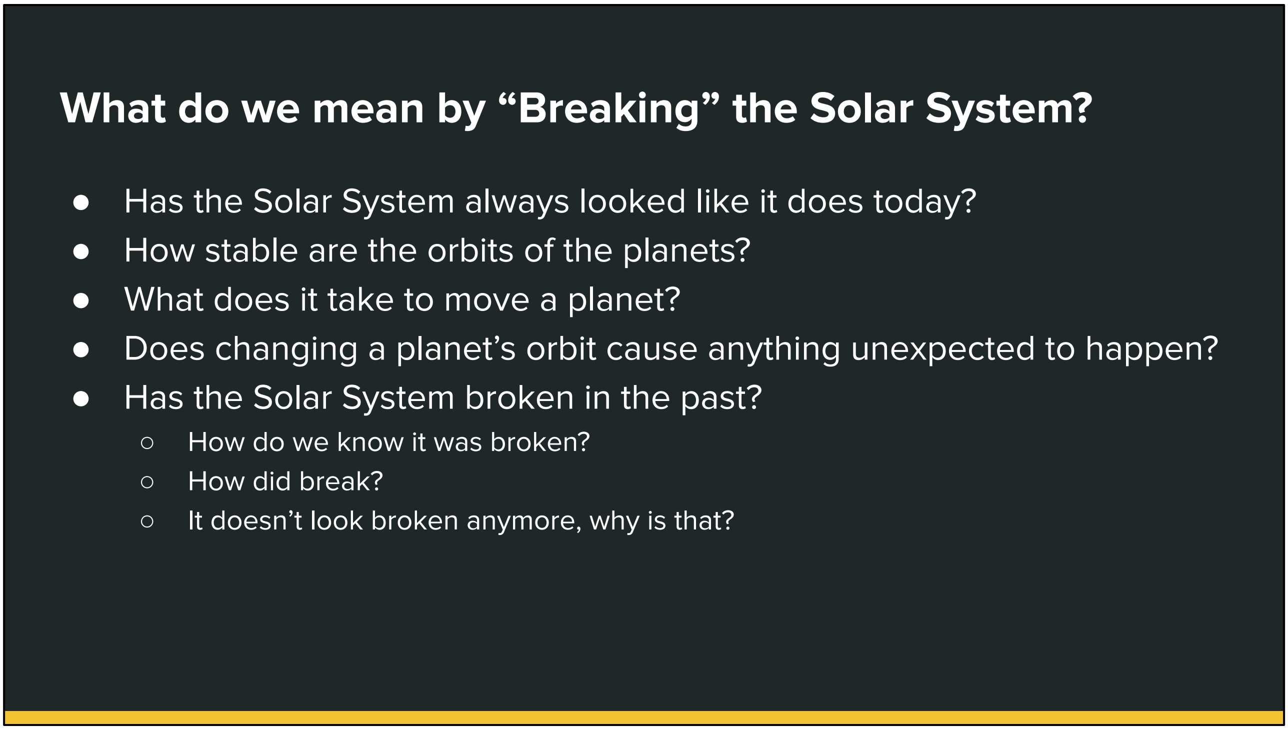
Breaking the Solar System

Tom Seccull
NOIRLab Teen Astronomy Café
Apr 2 2022



Tom Seccull

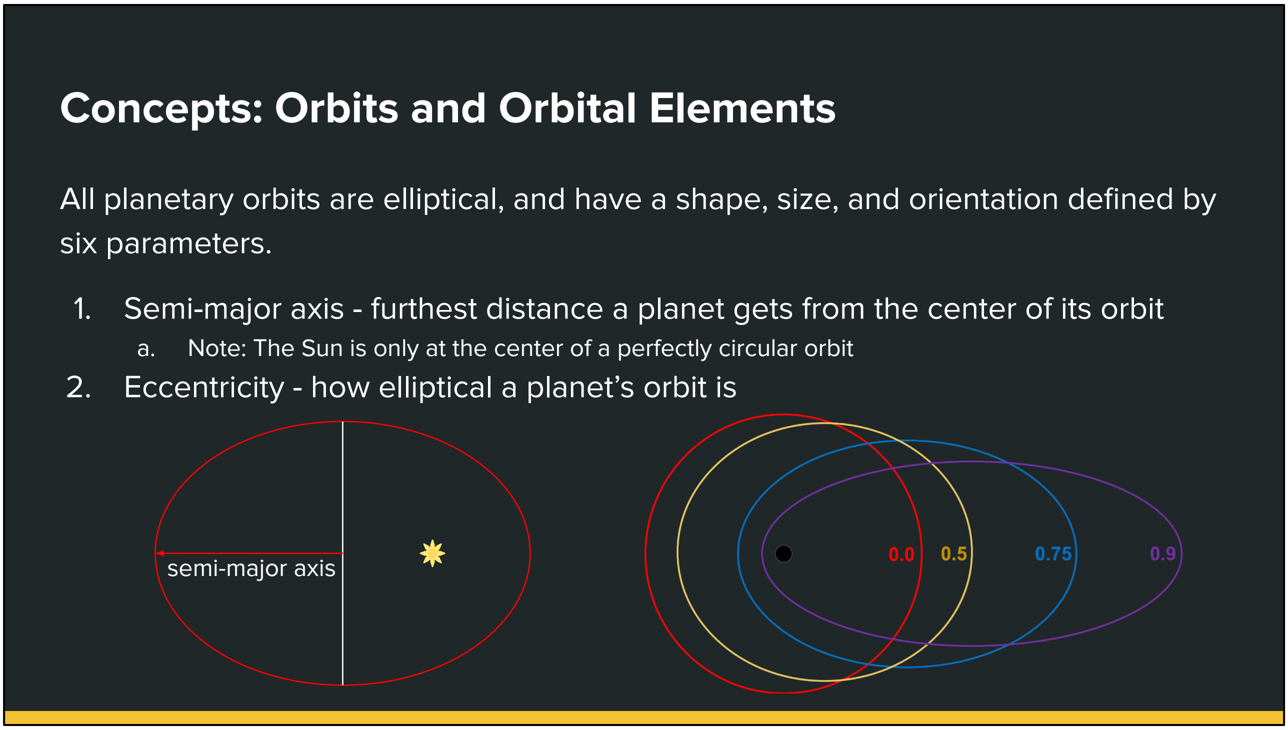
- Grew up in England
- 2011-2015: Undergrad at Queen’s University Belfast in Northern Ireland
    - MSci Physics with Astrophysics
- 2015-2019: PhD in Planetary Science at QUB
    - Composition of Trans-Neptunian Objects (TNOs)
    - Effects of cometary activity on the surfaces of TNOs and Centaurs
- 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?

When talking about “breaking the Solar System” we’re talking about the dynamical structure of the Solar System and the configuration of the orbits of the planets.



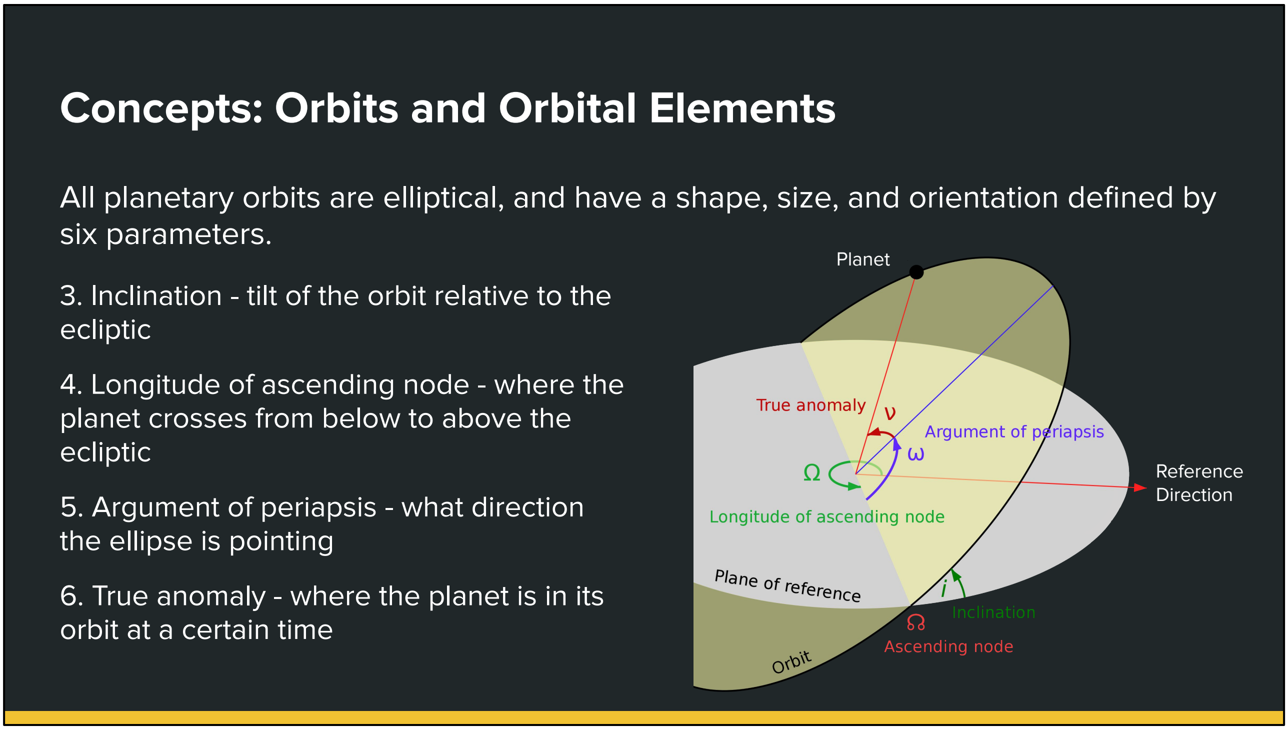
Concepts: Orbits and Orbital Elements

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

Semi-major axis can be taken as a proxy for the size of an orbit, and in orbital mechanics is noted by the letter *a*. In the Solar System semi-major axes are measured in Astronomical Units (au, or AU). 1 au is the average distance between the Earth and the Sun throughout the Earth's orbit, and is equivalent to 1.495 x10^11 m, ~150 million km, or ~93 million miles.

In orbital mechanics eccentricity is noted by the letter *e*. Eccentricity for objects that are gravitationally bound to the Sun falls between values of 0 and 1. Some Oort cloud comets have eccentricities a tiny bit higher than 1, which means that they may become unbound from the Solar System the next time they pass the Sun and will fly off into interstellar space. Interstellar objects that enter the Solar System from outside like 1I/'Oumuamua and 2I/Borisov have what are called hyperbolic orbits; these are completely unbound from the Sun so these objects fly into the Solar System, scatter off the Sun, and leave. 1I and 2I have very high eccentricities of 1.20 and 3.35, respectively.



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

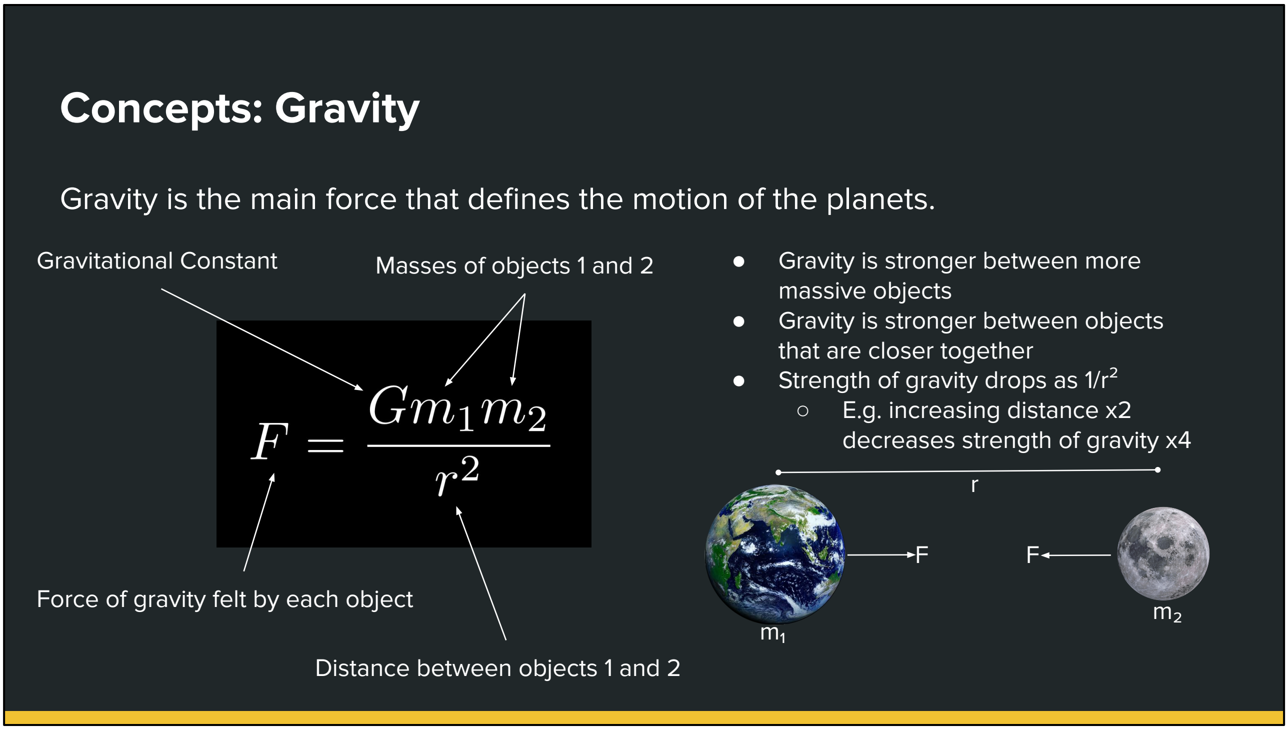
5. Argument of periapsis - what direction the ellipse is pointing

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

In orbital mechanics inclination is noted with the letter *i*, and is typically measured relative to the ecliptic plane (i.e. the plane of the Earth's orbit); by definition Earth's orbit has an inclination of 0 degrees relative to the ecliptic.

Longitude of ascending node and argument of periapsis note the orientation of an orbit in space. Changing the longitude of ascending node twists the orbit around the pole of the ecliptic. Changing the argument of periapsis twists the ellipse of an orbit through its own orbital plane.

True anomaly describes the location of a planet relative to its location at a reference point in time.



Concepts: Gravity

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

Gravitational Constant

Masses of objects 1 and 2

$$F = \frac{Gm_1m_2}{r^2}$$

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

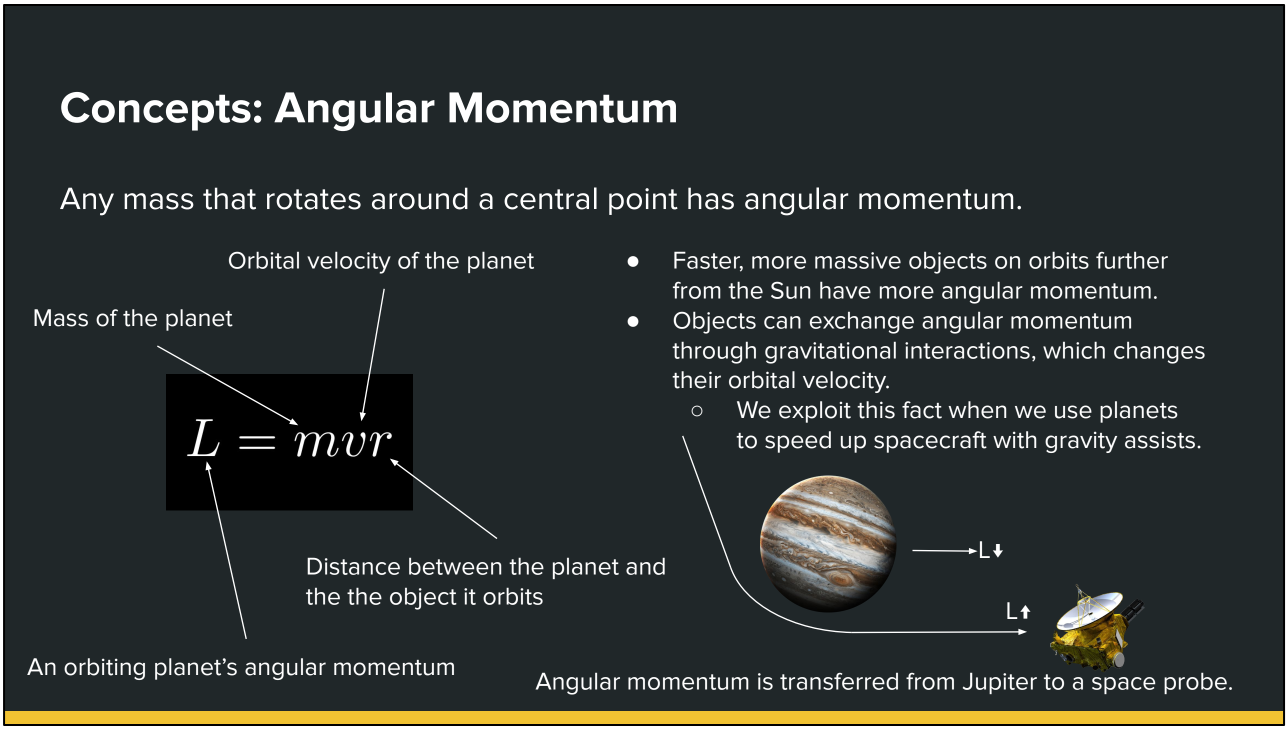
The equation for Newtonian gravity in this slide is simplified to calculate only the magnitude of the force felt by two masses due to gravity. Of course gravitational forces also have a direction, so in a complete version of the equation F and r are both vectors with a directional component. When considering the gravitational force on a planet due to the mass of the Sun, the vector form of the equation can be simplified to F= -(Gm1m2)/r^2, where r is a positive distance from the Sun, and the negative sign denotes that the gravitational force felt by the planet is toward the Sun in the negative radial direction.

G, the gravitational constant has a value of 6.67408x10^-11 (m^3)(kg^-1)(s^-2).

Note that every object in the Solar System has a gravitational effect on every other object, even if that effect is tiny. This means that the Sun is moved a small amount by the planets too and has its own orbit. All the planets and the Sun orbit around the common center of mass of the Solar System, known as the barycenter. Most of the Sun's motion is caused by the most massive planet, Jupiter. Stars in other planetary systems are also moved slightly by the planets that orbit them, and we can measure this motion with spectroscopy. When this motion is observed, we can infer the presence of exoplanets orbiting a star even if we cannot see them directly; this method of discovering exoplanets is known as the Radial Velocity, or RV method.

Similarly to the planets and the Sun, planets and moons orbit each other around a common center of mass. In some extreme cases the center of mass can be offset from the center of the planet by a fairly large distance. For example Earth's moon is the largest Moon in the Solar System relative to the planet it orbits. The center of mass of the Earth-Moon system is still inside the Earth, but it is closer to the Earth's surface than Earth's core, at a depth of 1700 km (about 25% of the distance from the surface to the Earth's center). This means that the Earth-Moon system is almost a binary planet system.

Pluto and its moon Charon form a true binary system, because their center of mass is outside of Pluto completely, at about 950 km above its surface.



Concepts: Angular Momentum

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

$$L = mvr$$

Orbital velocity of the planet

Mass of the planet

Distance between the planet and the the object it orbits

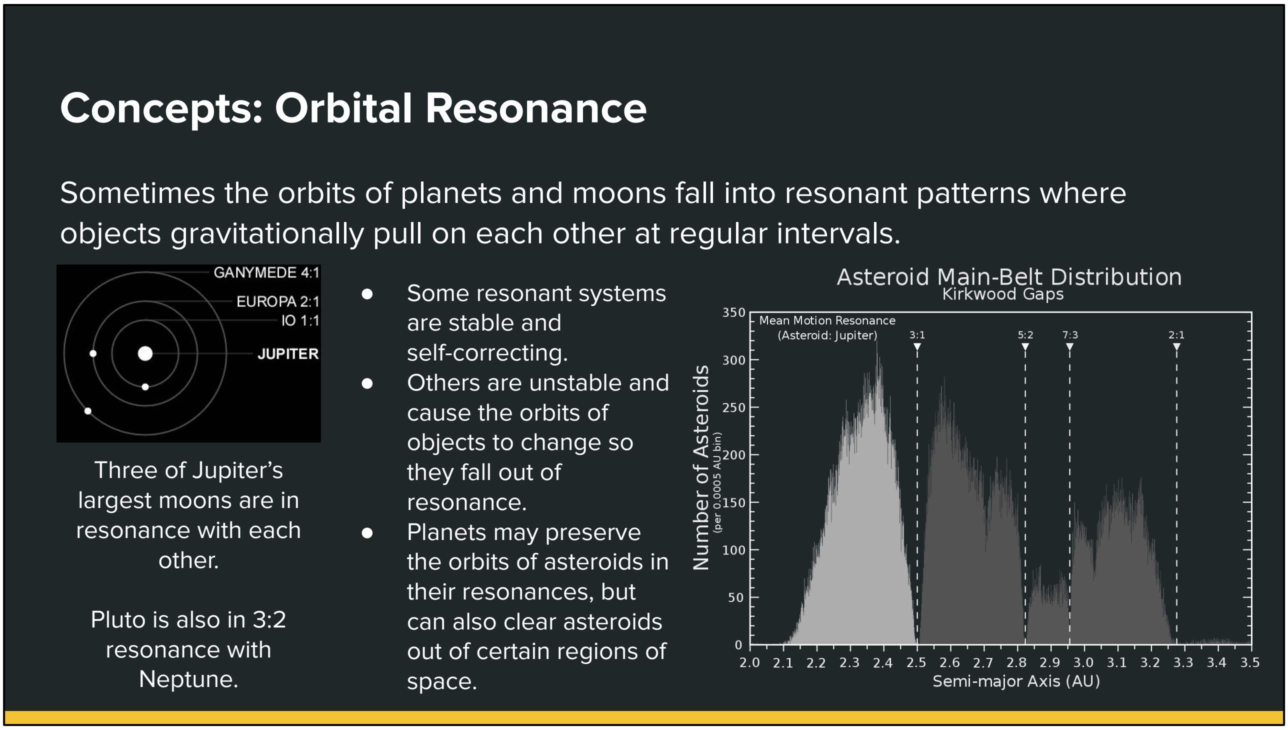
An orbiting planet's angular momentum

- 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.

Again, this slide oversimplifies angular momentum somewhat. L, v, and r in the equation are all vectors with direction; an object on a circular orbit has L and v pointing in the same direction, while r is the radius vector that points outward from the center of the circle.

While the Sun contains the majority of the mass of the Solar System, the planets contain most of the Solar System's angular momentum due to their distance from the center. Because of its huge mass, Jupiter contains the most angular momentum. If, however, planet 9 is real it will likely have the most angular momentum of all the planets due to its vast distance from the Sun.



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.

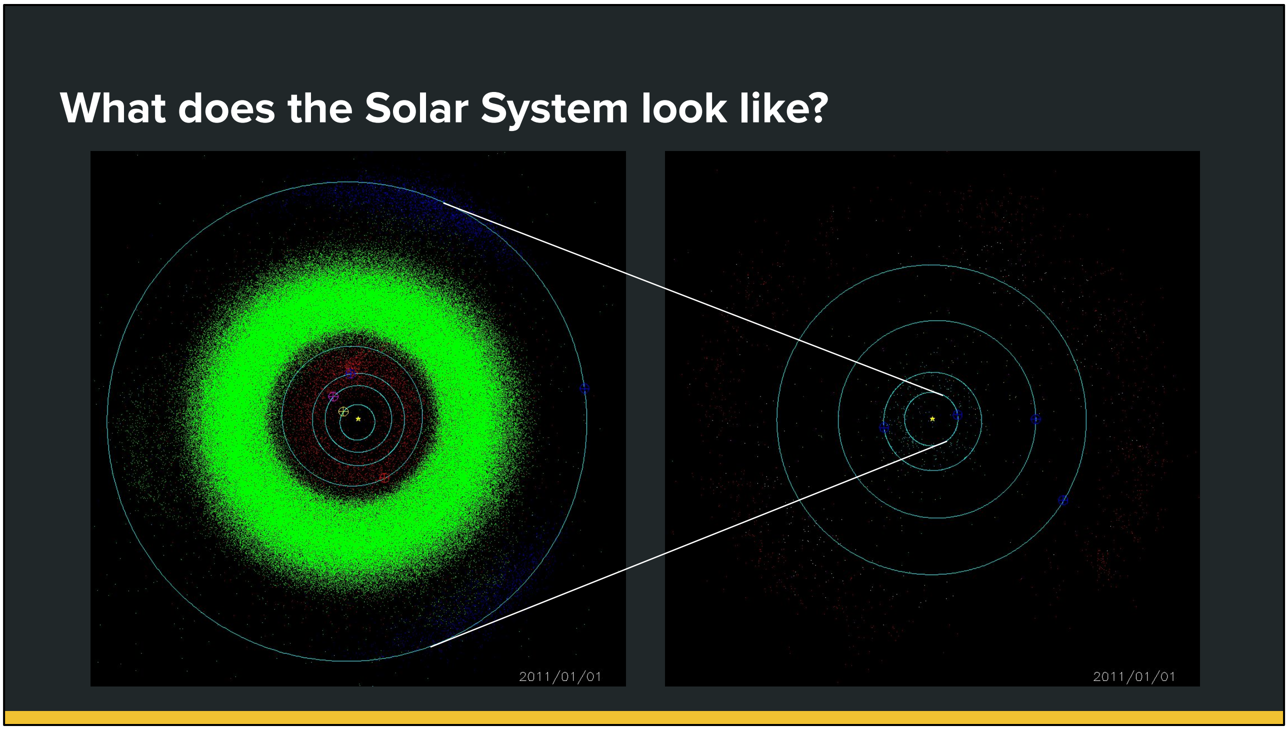
Pluto is also in 3:2 resonance with Neptune.

- 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.

Orbits that are in a stable resonance become locked together and their evolution is slowed down. For example, Pluto and many other objects on a similar orbit, are stabilised by their resonance with Neptune and have their orbits preserved. Meanwhile many non-resonant objects in the Kuiper Belt, thar form what is called the Scattered Disk, are frequently getting kicked around by Neptune's gravity. The orbits of scattered disk objects evolve relatively quickly; it's predicted that some of them get kicked into the inner Solar System where they become comets like 67P/Churyumov-Gerasimenko (the comet that ESA sent the Rosetta probe to).

Orbital resonances can also play a large role in clearing asteroids out of certain regions of space. The classic example of this is the Kirkwood gaps in the main asteroid belt. In these regions orbits around the Sun are resonant with Jupiter's orbit, and the frequent gravitational interactions with Jupiter experienced by objects on these orbits usually causes them to be scattered to other parts of the Solar System, or even out of the Solar System entirely.

There are multiple kinds of orbital resonance that have different effects in the Solar System. This slide is concerned only with mean motion resonances. Secular resonances are another main kind of resonance that are beyond the scope of this talk.

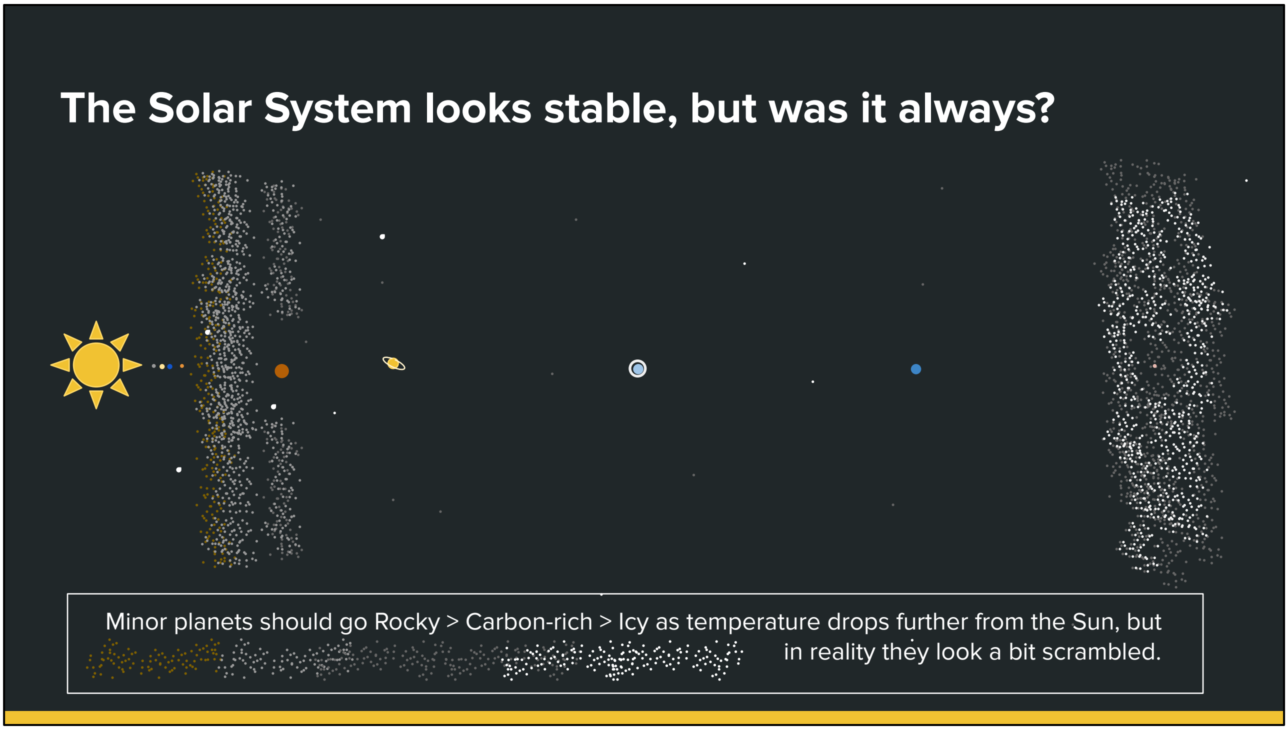


What does the Solar System look like?

In these animations from the IAU Minor Planet Center we see the orbits of real minor planets throughout the Solar System. The inner Solar System is shown on the left, with the orbits of Mercury, Venus, Earth, Mars, and Jupiter shown in light blue from the center going outwards. Red asteroids are Near-Earth Asteroids. The Main Belt asteroids are shown in green. Blue asteroids are Jupiter Trojan asteroids which oscillate around the L4 and L5 Lagrange points of Jupiter, which respectively lead and trail Jupiter in its orbit by 60 degrees; Jupiter trojan asteroids are also sometimes described as being in 1:1 mean motion resonance with Jupiter.

On the right the animation shows the outer Solar System. From the center outwards the orbits of Jupiter, Saturn, Uranus, and Neptune are shown in light blue. Light blue points are the centaurs and scattering objects with orbits that take them into the giant planet region. Some of these objects go on to fall into the inner Solar System and become comets when they heat up and start outgassing. The red points at the outer edge show the Kuiper Belt, where lots of icy primitive minor planets are found alongside icy dwarf planets like Pluto.

https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=pluto&view=VOP
The link above takes you to NASA’s orbit viewer.

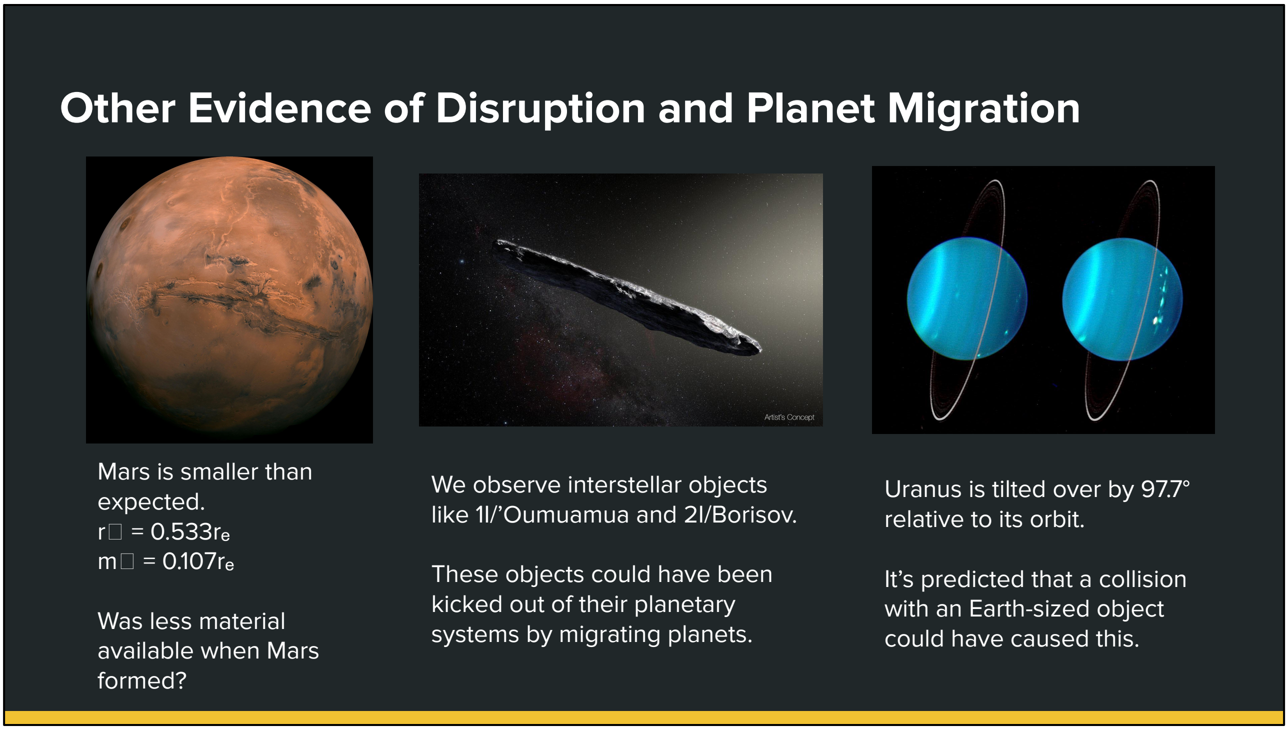


The Solar System looks stable, but was it always?

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

Based on what we know from physics and our observations of protoplanetary disks, we expect that there should be a steady change in the composition of minor planets as their temperature drops further from the Sun. The innermost asteroids should mainly be rocky as their surfaces are too hot to maintain water ice and other volatile substances. Further out, it's expected that some ices may have survived long enough to be irradiated by particles and UV light from the Sun. This irradiation drives chemistry on their surfaces that turns the ices into long chain hydrocarbons that are dark and reddish in colour. Even further out, the same chemistry occurs, but at a much slower rate due to the greater distance from the Sun and lower Solar radiation levels; this means that icy material and volatiles should last a lot longer on the surfaces of these objects.

Broadly, the above description is what we see in the Solar System, but sometimes we find objects mixed up where they shouldn't be or oddball objects that are in completely different part of the Solar System to where we'd expect them to be. For example, the asteroid belt is a mixture of rocky and carbon rich material, even though we expect that carbon-rich material should have formed further from the Sun. There's even some evidence of asteroids that experience cometary outbursts, which suggest the presence of icy and volatile material preserved in their subsurface layers. We have also observed rocky material in the Kuiper Belt and even objects from the Oort Cloud, at the very edge of the Solar System, that appear to have rocky surfaces. This suggests that the minor planets have been moved around a lot. Of course they cannot do this on their own; they need to interact with the gravity of something else before their orbits can evolve. This implicates the planets as a possible cause for the scrambling of the minor planets.



Other Evidence of Disruption and Planet Migration

Mars is smaller than expected.
r□ = 0.533r_e
m□ = 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.

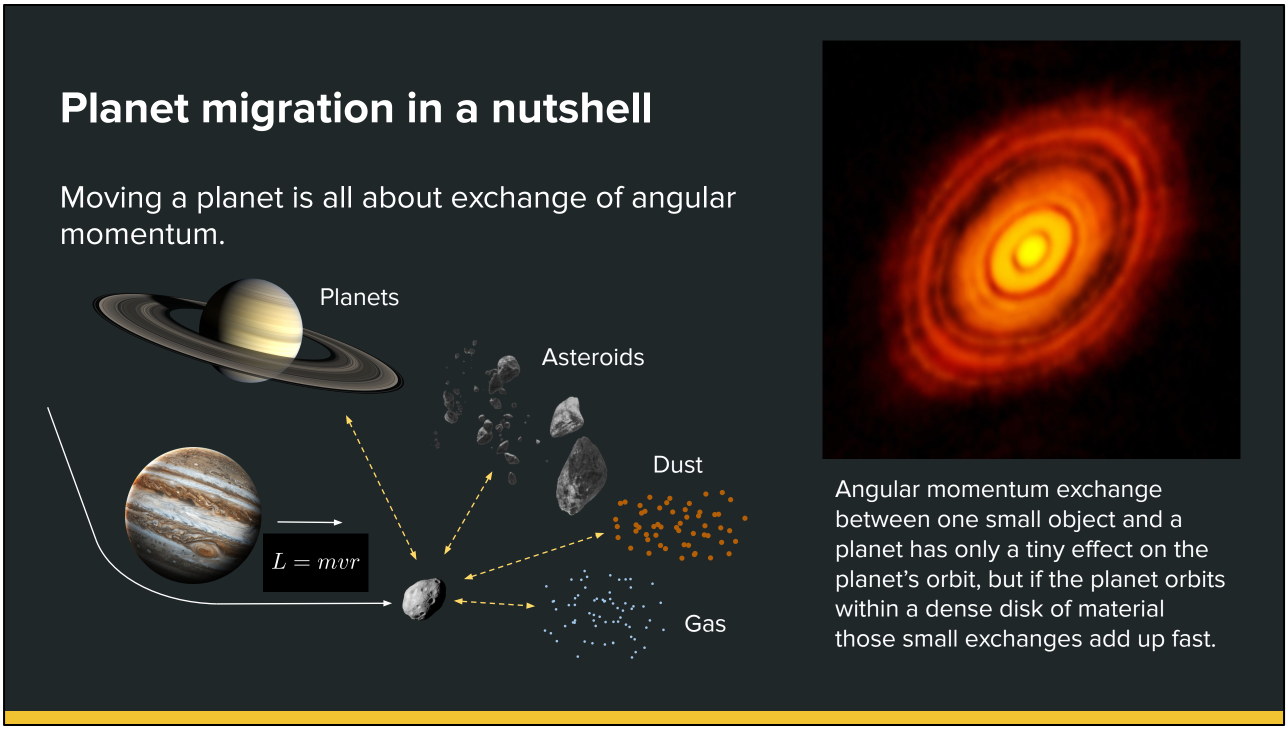
Uranus is tilted over by 97.7° relative to its orbit.

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

Mars is a lot smaller than we'd expect given that the amount of material in its region of the Sun's protoplanetary disk was probably enough to make a planet the size of Venus or Earth. It's possible that another planet could have cleared a lot of material out of the region Mars formed in before Mars had finished forming.

Interstellar objects are clear indications that minor planets are also moved around and kicked out of planetary systems pretty regularly. Scattering and migration of minor planets is not unique to the Solar System.

Uranus is basically on its side, which is difficult to explain without some sort of catastrophic disruption at some point in the past. Our best predictions suggest that Uranus was hit by an Earth-sized planet at some point, which tipped it over.



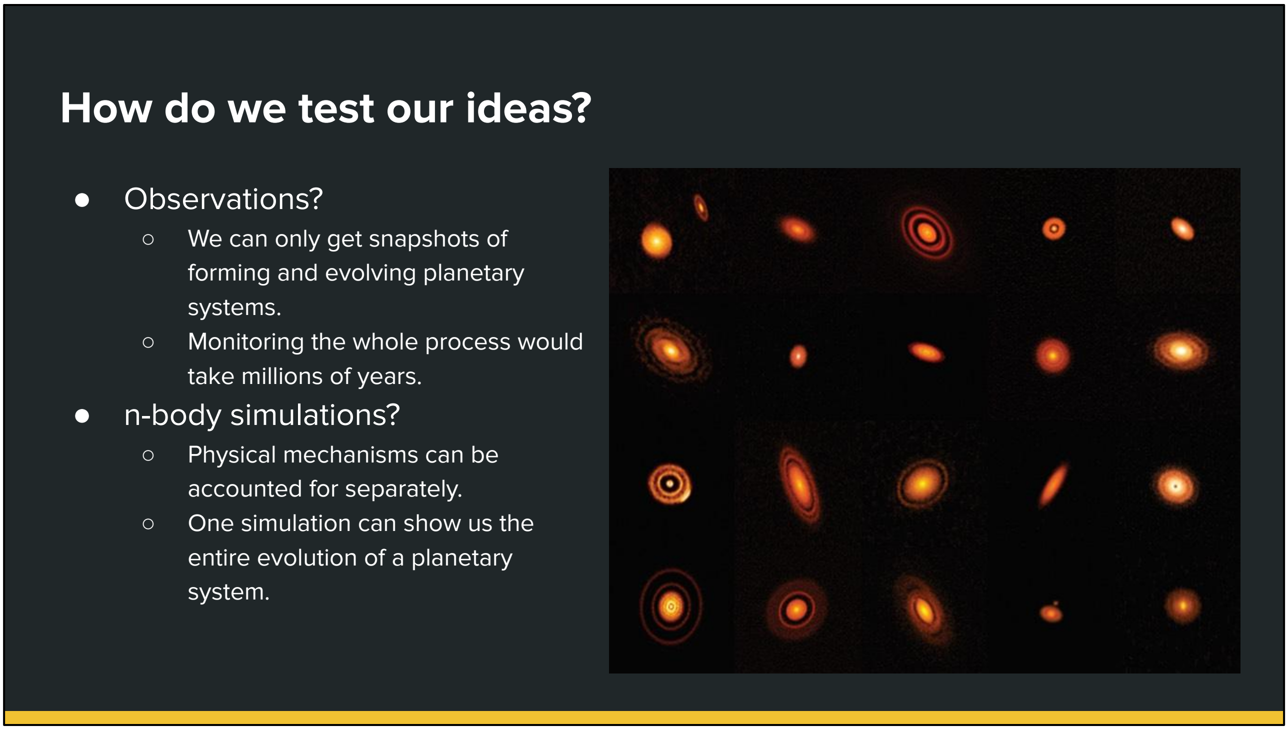
Planet migration in a nutshell

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.

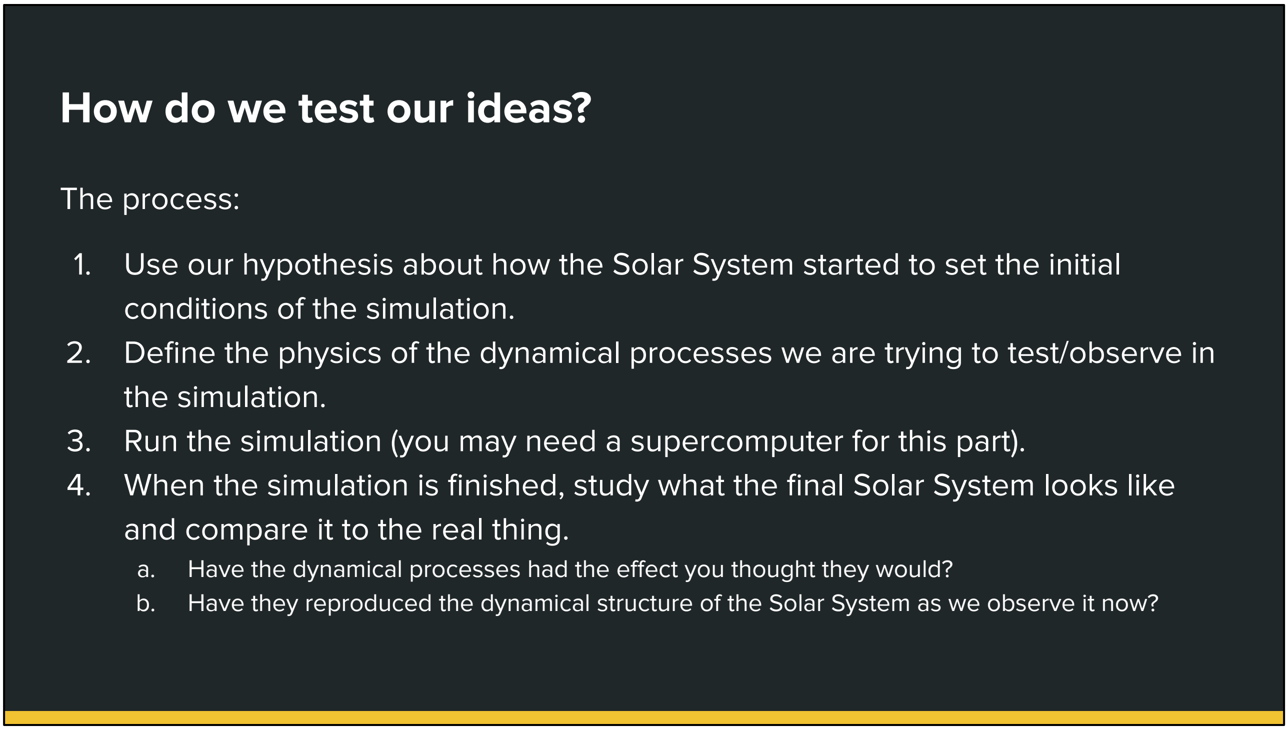
Planet migration is driven by exchange of angular momentum between a planet and something else with mass. This mass can be anything from another planet, to asteroids, to dust particles and gas molecules. The effect of one small mass on a planet like Jupiter is pretty inconsequential, but if a planet is forming in a dense disk af gas, dust, and planetesimals there is enough material to really get a planet moving. The dissipation of the Sun's protoplanetary disk is why the planets have stable orbits today; they don't have anything to push or pull them onto a different orbit anymore.

The image at top right is a real observation of the hot dust in the protoplanetary disk of HL Tau. The dark rings in the disk are regions that have been cleared by forming planets. This is exactly the sort of environment in which we expect planetary orbits are most likely to evolve.



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.

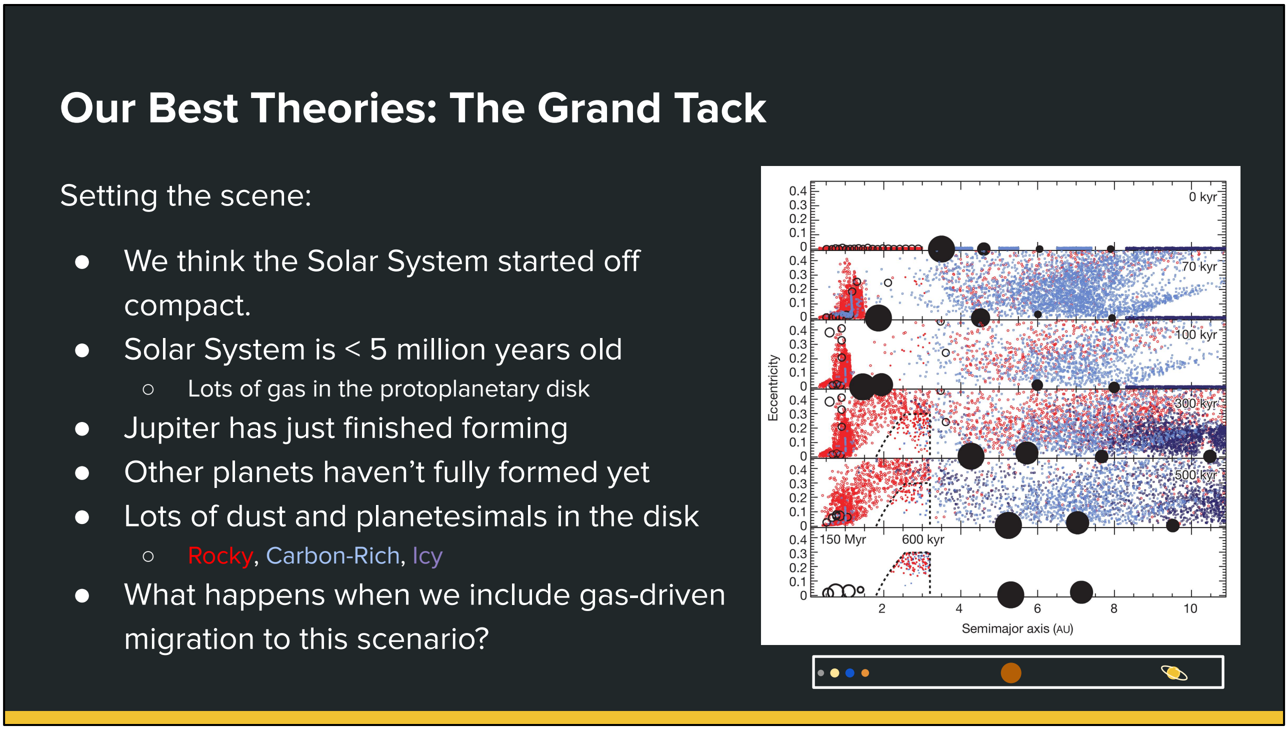


How do we test our ideas?

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?

It's often useful to run multiple simulations that have slightly different conditions to get a statistically useful idea of how certain dynamical processes affect the final configuration of the planets.



Our Best Theories: The Grand Tack

Setting the scene:

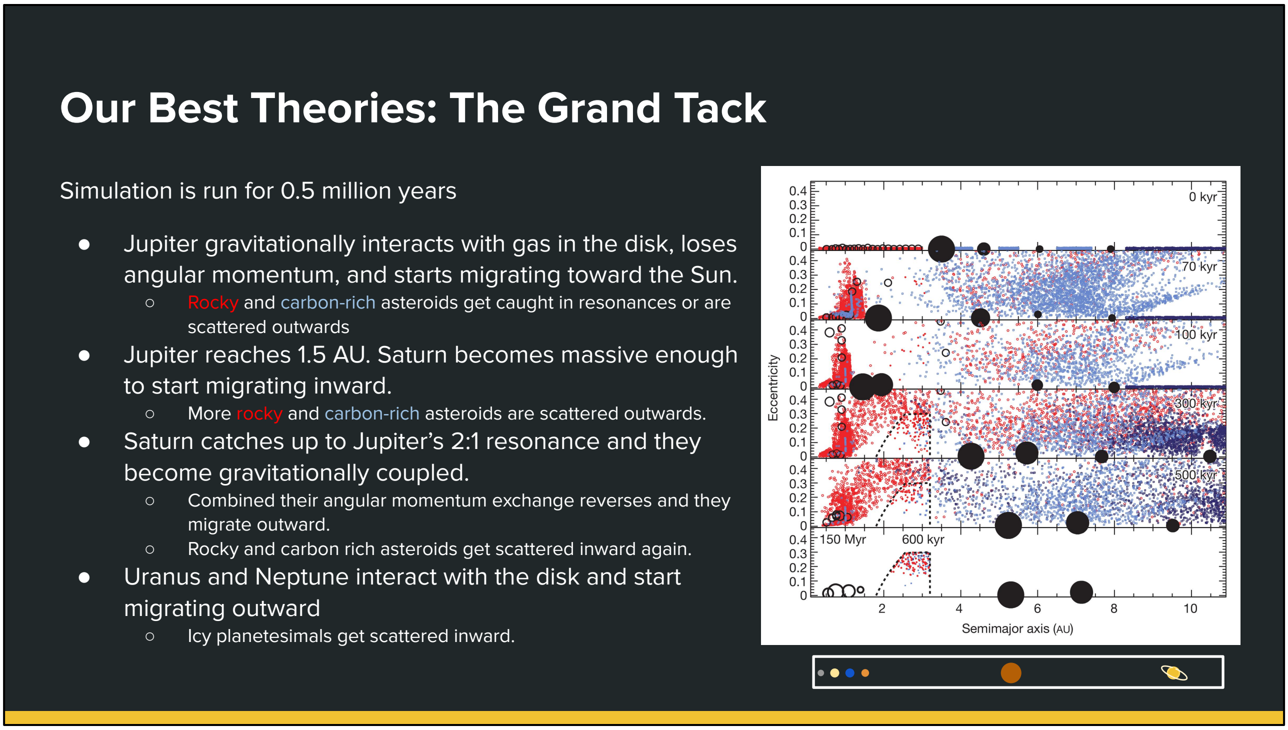
- We think the Solar System started off compact.
- Solar System is < 5 million years old
    - Lots of gas in the protoplanetary disk
- Jupiter has just finished forming
- Other planets haven't fully formed yet
- Lots of dust and planetesimals in the disk
    - Rocky, Carbon-Rich, Icy
- What happens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

~ 5 million years is about the maximum time the gas in a protoplanetary disk sticks around before it gets blown away by radiation emitted by the forming star. Gas giant planets form extremely quickly before the gas is gone. If the 4.5 billion year lifespan of the Solar system (from formation to today) is compressed into the space of 1 year, the gas giant planets formed by 9:30 am on January 1st. The rocky planets take a bit longer to finish forming, around 100 million years (or around a week on the example timescale).

The configuration of the Solar System as we see it today is shown in the cartoon below the plot on the right.

Panels in the plot step through time from top to bottom starting just as Jupiter finished forming.

The empty circles represent forming rocky planets. Many of these are lost, destroyed, or combine to result in the final rocky planets in the bottom panel.



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.

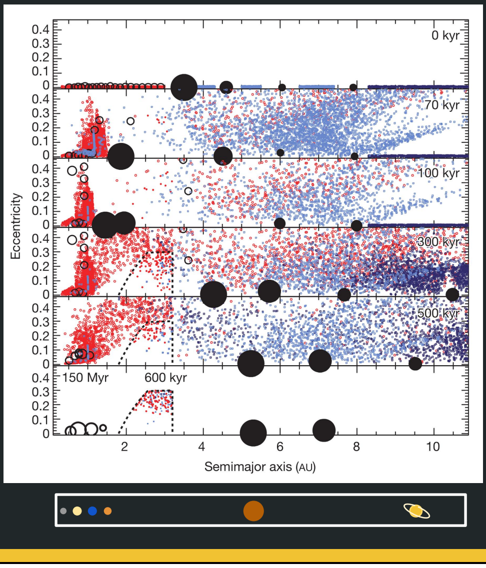
Point 1 refers to 70kyr panel
Point 2 refers to the 100 kyr panel
Points 3 and 4 refer to the 300kyr and 500 kyr panels together

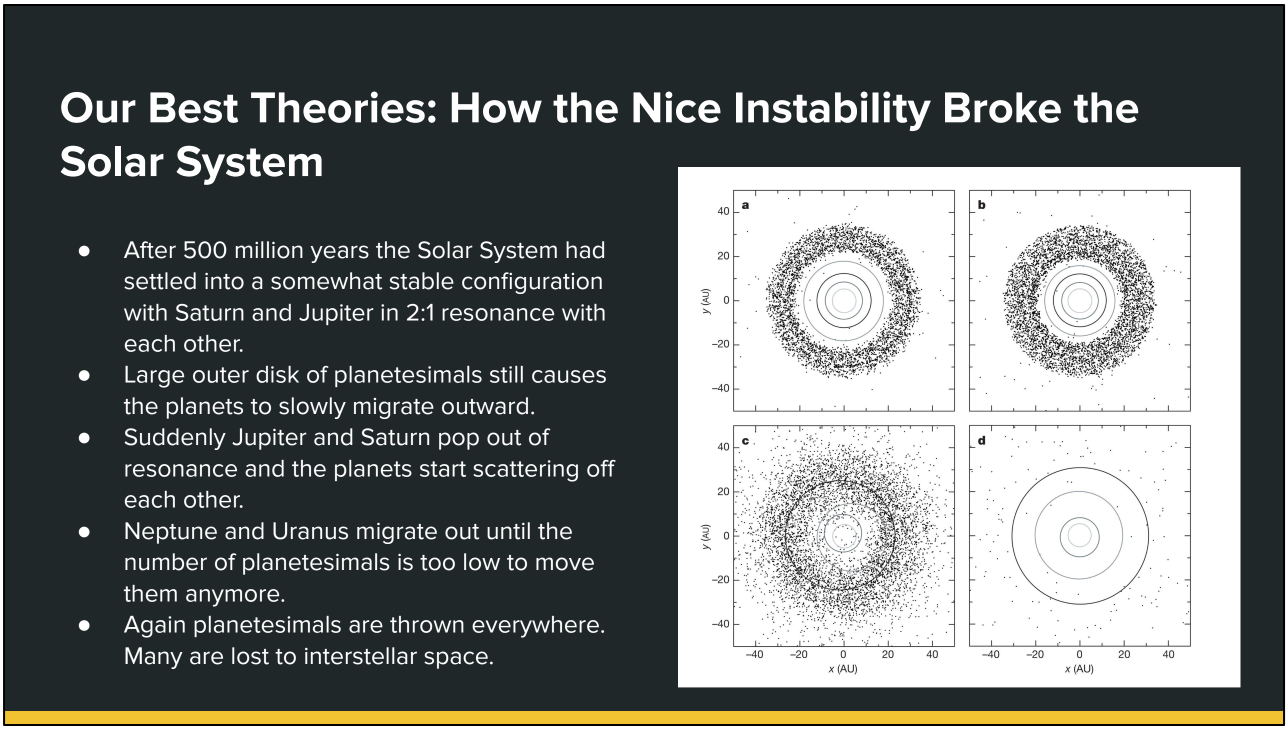
The 600 kyr panel shows what happens after you stop the planets from moving and let the rocky planets form. The little dashed box shows the dynamical extent of the modern asteroid belt.

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…



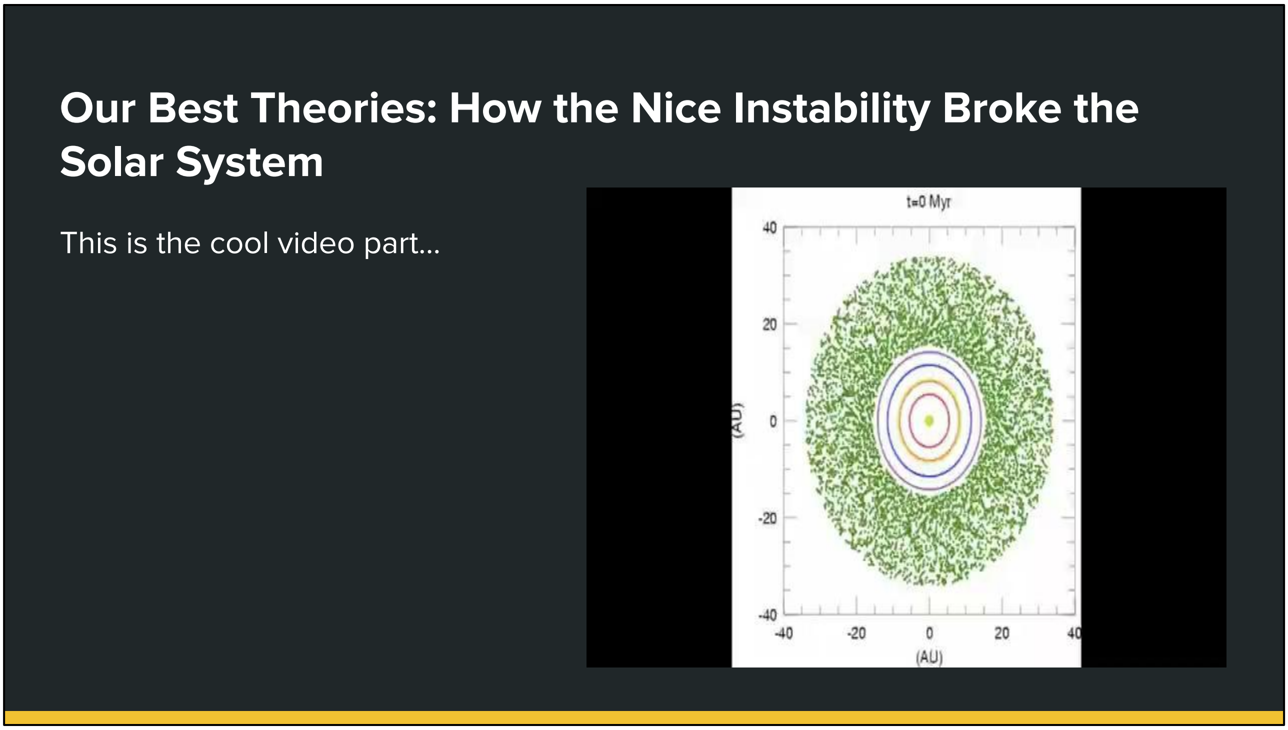


Our Best Theories: How the Nice Instability Broke the Solar System

- 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.

The main mechanism in the Nice instability scenario is that the planets start gaining angular momentum from the outer planetesimal disk and start to migrate slowly outward. Eventually Jupiter and Saturn pop out of their mutual stable resonance. Jupiter and Saturn are still close to resonance with each other though so they have a lot of gravitational interactions that ripple out and cause disruption for everything else. At this stage the main exchange of angular momentum is between planets as they scatter off each other. Many variations of this model have been tested through simulations and it is being continually revised over time as our understanding improves. Interestingly one of the simulations that is better at reproducing the real Solar System starts off with 5 giant planets instead of 4. This fifth mystery planet is typically kicked into interstellar space by Jupiter or Saturn, or alternatively it may collide with another of the planets. It seems far-fetched but it isn't beyond the bounds of possibility given that we've observed rogue planets before, that do not orbit a star.

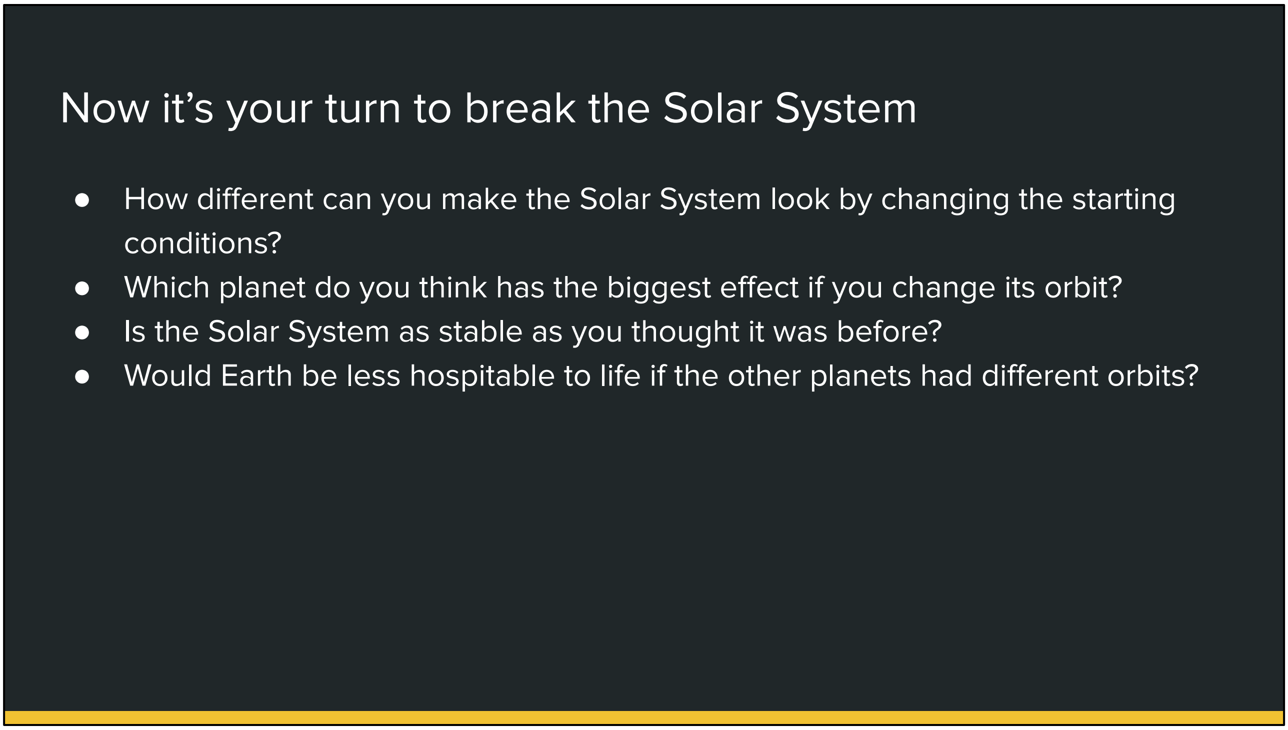
By the way, the Nice model is named after the city in France where the model was developed (pronounced like 'neese').



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

This is the cool video part…

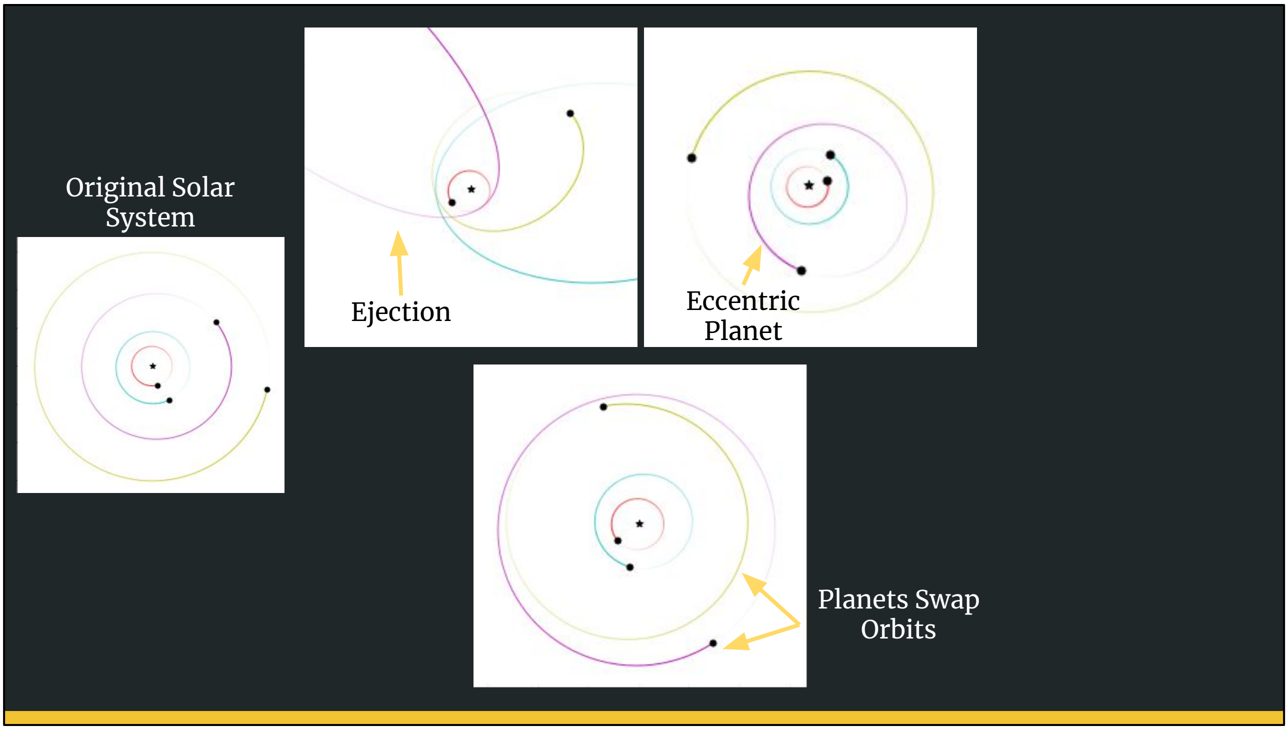
The video on this slide is an animation of the simulations plotted in the plot on slide 18. The Sun is in the center and the orbits of the four giant planets (Jupiter, Saturn, Uranus, Neptune). At the edge is a massive disk of planetesimals left over after the planets formed. As time runs forward the planets interact gravitationally with the outer disk of planetesimals, gain angular momentum, and start to migrate outward. Eventually (at the 850-900 million year mark), Jupiter and Saturn are pulled out of their stable 2:1 resonance and the Solar System becomes very unstable as the planets scatter off each other and move large distances in a short period of time. The planets later settle down once the planetesimal disk is scattered and the orbits of the planets end up roughly where we see them today.



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

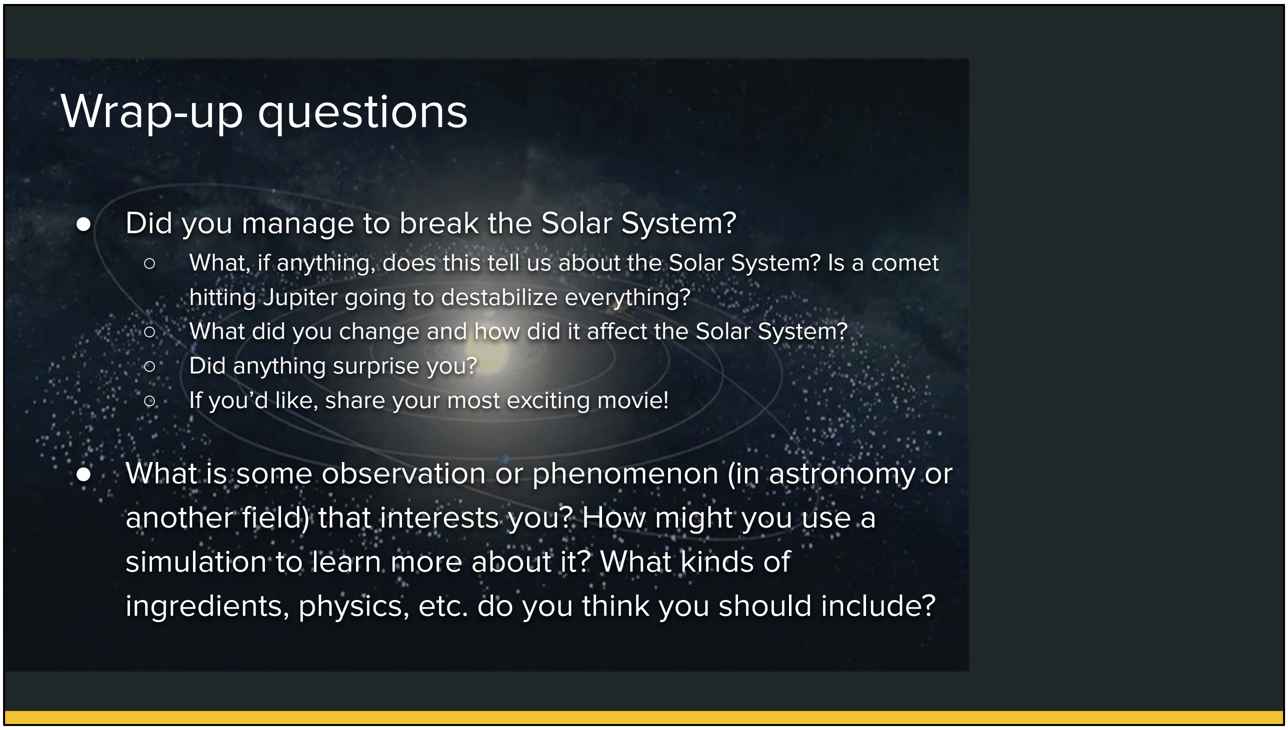


Original Solar System

Ejection

Eccentric Planet

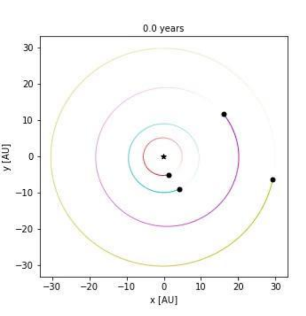
Planets Swap Orbits



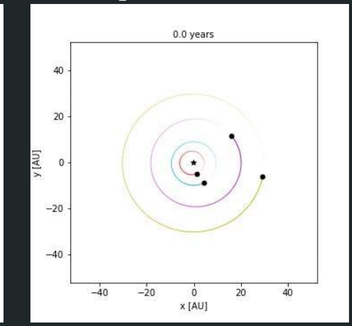
Wrap-up questions

- 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?

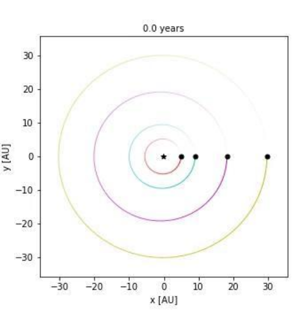
Sun’s mass=0.2



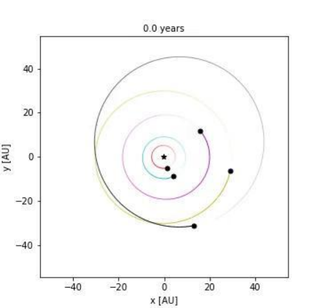
Jupiter ecc=0.15



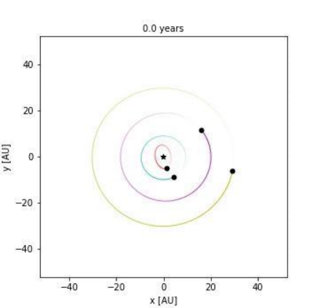
Planets start aligned



Pluto=Neptune’s mass



Jupiter i=50°



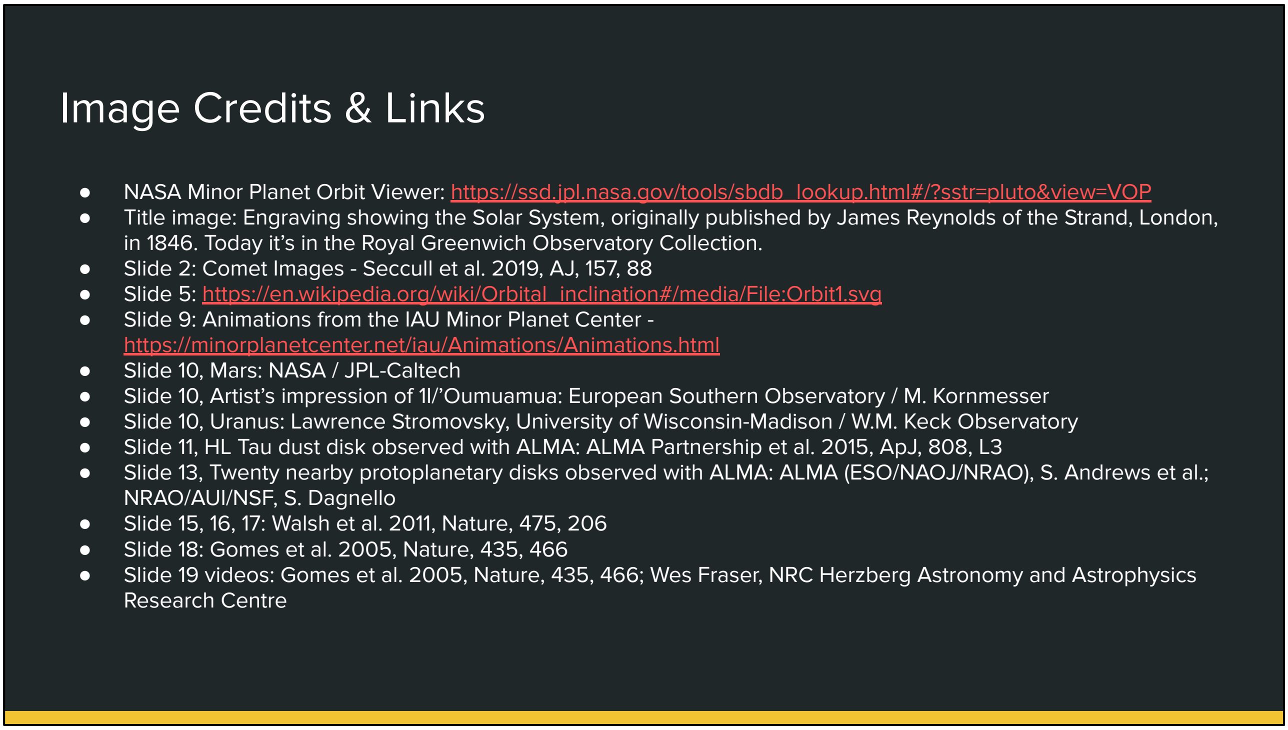


Image Credits & Links

- 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