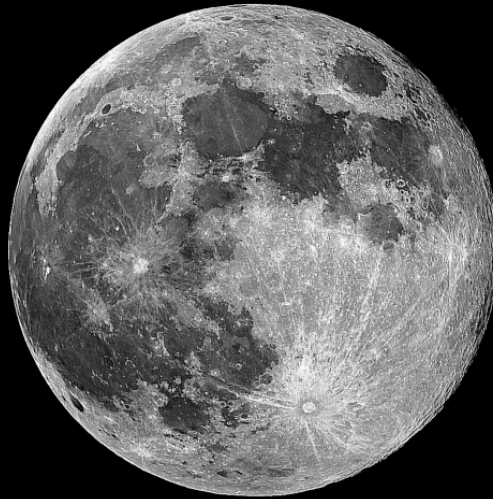# Origin of the Moon

Mark Wyatt

The Earth-Moon system
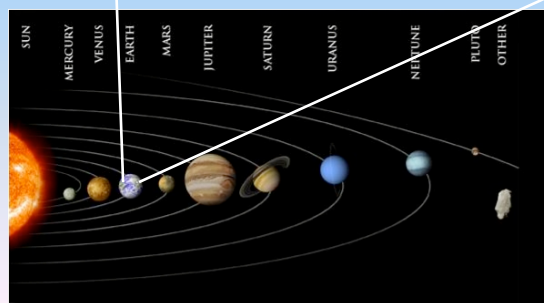
The Moon orbits the Earth at
a_{moon} = 385,000 km
with an eccentricity of 0.05, inclination to ecliptic of 5°

The Earth orbits the Sun at
a_{earth} = 150,000,000 km

Earth's Hill sphere (the distance at which objects are no longer gravitationally bound) is at
$R_{hill} = a_{earth} (M_{earth} / 3M_{sun})^{1/3}$
     = 1,500,000 km

So Moon is well within this limit at R_{hill} / 4, though note that orbits beyond R_{hill} / 2 are unstable

384,000 km

12,740 km   3476 km

SUN MERCURY VENUS EARTH MARS JUPITER SATURN URANUS NEPTUNE PLUTO OTHER

Roche radius

The Roche radius is the distance at which tidal forces on a satellite are greater than its self-gravity and so would tear it apart
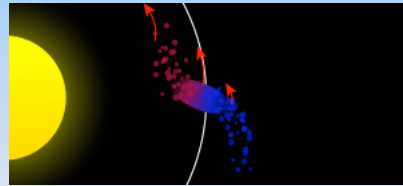
For a solid satellite

$$R_{roche} = 1.26 \, R_{earth} \, (\rho_{earth} / \rho_{satellite})^{1/3}$$
$$= 9,500 \text{ km}$$

For a fluid satellite
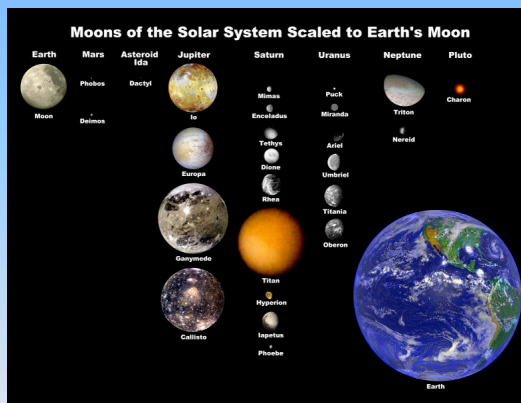
$$R_{roche} = 2.44 \, R_{earth} \, (\rho_{earth} / \rho_{satellite})^{1/3}$$
$$= 18,400 \text{ km}$$

The Moon is ~20x beyond these limits

The Moon compared with other moons

Moons of the Solar System Scaled to Earth's Moon

There are other moons that are bigger than our Moon, but these orbit giant planets that are much bigger than the Earth

Our Moon is large compared with the size of the parent planet: $M_{moon} = M_{earth} / 80$
Other moons all have mass ratios $< M_{pl} / 4000$
... apart from Charon which is half the size of Pluto (and $M_{charon} = M_{pluto} / 8$)

Angular momentum in Earth-Moon

Orbital angular momentum:

$J_{orbEM} \sim M_{moon} [G\, M_{earth}\, a_{moon}]^{1/2}$ (plus M_{moon}/M_{earth} terms)
$= 2.9 \times 10^{34}$ kg m^2 / s

Rotational angular momentum of solid homogeneous body:

$J_{rotE} \sim 4\pi\, M_{earth}\, R_{earth}^2 / 5\, P_{rot}$ (but most objects have higher density cores)
$= 7.1 \times 10^{33}$ kg m^2 / s

$J_{rotM} \sim J_{rotE} / (80 * 3.7^2 * 27) = J_{rotE} / 30{,}000$ so is negligible

So, most of the angular momentum of the Earth-Moon system is in the orbital motion, which is in contrast to other moons in the solar system (e.g., for Jupiter's moons $J_{orb} < J_{rot} / 100$)

Tides

Rotation period is exactly equal to its orbital period of 27 days

Synchronous rotation means Moon keeps same face to us, and is the result of tidal evolution

Tides dissipate energy which causes orbit to recede at a rate 38mm/year

Angular momentum is conserved

$J_{tot} \sim J_{orbEM} + J_{rotE}$ and $dJ_{tot}/dt=0$

so Earth's spin is also slowing (days are lengthening by 23µs/year)

Where did the Moon start?

In past Earth was spinning faster and Moon was closer to the Earth;
constant recession over 4.5Gyr would imply Moon started at 214,000 km

Actually dissipation would have been faster
when closer, with simple model of a bulge
leading the motion of the Moon giving
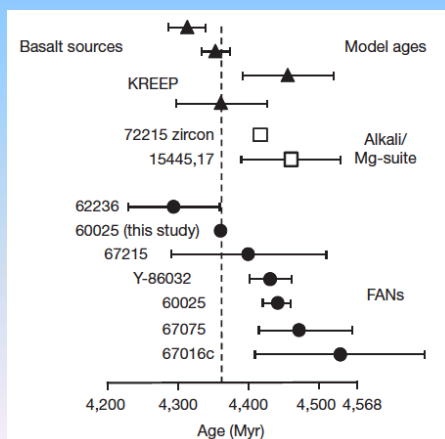
$$da/dt \sim a^{-7} (P_{orb}/P_{rotE} - 1)$$

leading to tidal catastrophe

Also tidal energy loss comes out as heat
(which is why Io is so volcanic), so tidal
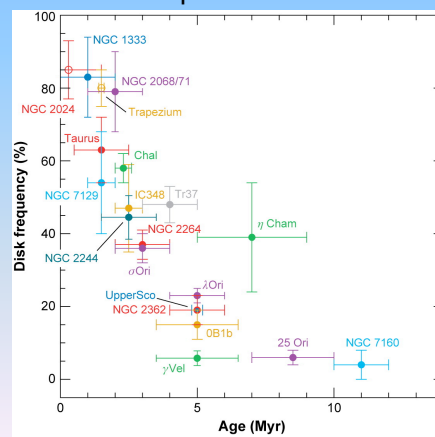dissipation would have melted Earth
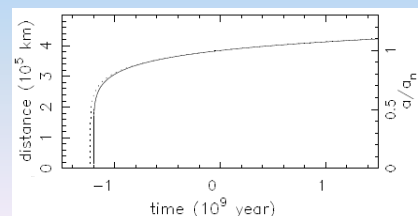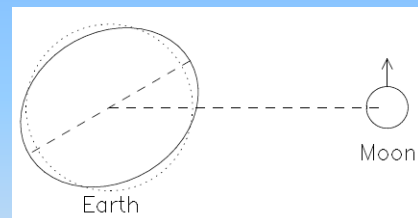
When did the Moon form?

Studies of lunar rocks give
oldest ages at 30-100Myr after
the Solar System formed

Protoplanetary disks disperse over
~5Myr, so Moon formed after disk
dispersal, and also after meteorites
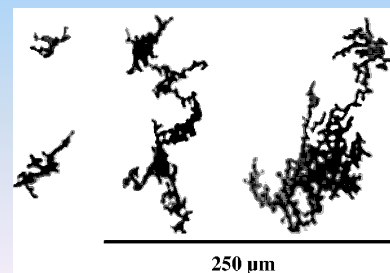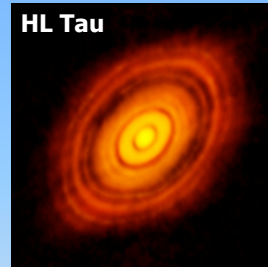and terrestrial planets formed

Terrestrial planet formation: stage 1

HL Tau

Stars are born with protoplanetary disks made of gas and µm-sized dust

Experiments show that dust grains stick to each other when they collide at anticipated velocities, and that growth to cm-size is easy

But growth beyond metre-sizes is prevented by bouncing and strong radial drift

250 µm

Terrestrial planet formation: stage 2

As soon as km-sized planetesimals form, it is easy to grow them into planets

They undergo runaway growth due to gravitational focussing, then oligarchic growth

Formation of something that looks like the Solar System's terrestrial planets is relatively easy, albeit with some restrictions (e.g., mass of Mars, low eccentricities)
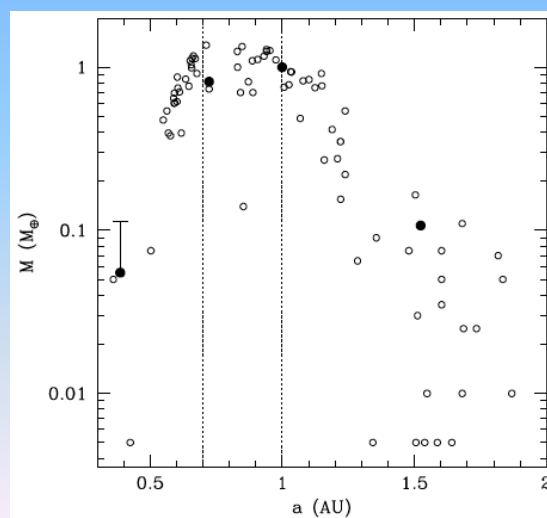
Constraints on Moon formation

Mass: $M_{moon} = M_{earth} / 80$

Angular momentum: High J_{EM} / M_{EM} compared with other planets

Age: ~50Myr

Lack of volatiles: very dry (no water except from comets?)

Lack of Iron: density is $3.3 g/cm^3$ implies 0.25x cosmic abundance of Fe, much less than Earth

Oxygen isotopes: ^{17}O / ^{18}O are identical to Earth, but these vary with position in the Solar System and so in protoplanetary disk

Magma ocean: Apollo rocks showed that Moon melted early in history forming a low density crust, denser mantle, maybe metallic core
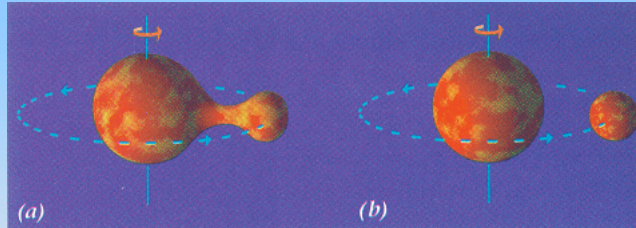
Formation scenarios: Co-accretion

Idea: During accretion of the Earth, a circumterrestrial disk of planetesimals was formed out of which the Moon accreted

(a)   (b)
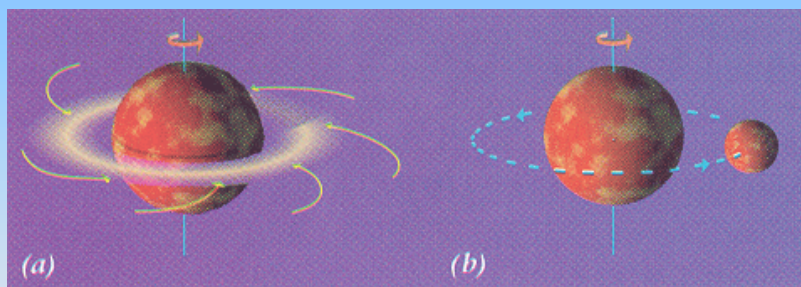
Problems: How could Earth acquire a disk with such high angular momentum? Age of Moon. Chemical composition would be same as Earth

Formation scenarios: Fission

Idea: Rapidly rotating Earth undergoes fission, perhaps triggered by Solar tides, whereupon Moon receded from Earth due to tides

Problems: Dynamically implausible, viscosity damps resonant motion supposed to trigger fission

Formation scenarios: Capture

Idea: The Moon was a planetary embryo formed in a different (but nearby) part of the Solar System which was captured into orbit around the Earth
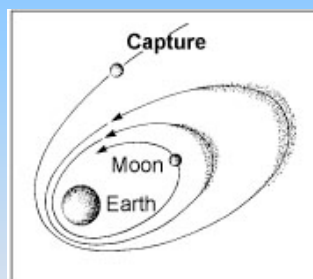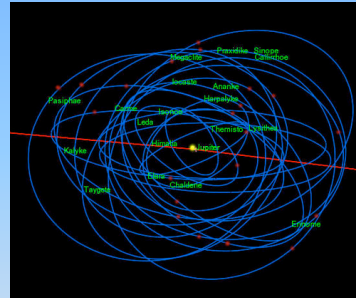

Problem: Low Fe of Moon, more likely to be captured on wide orbit (and requires third body to take energy away), no heating of Moon
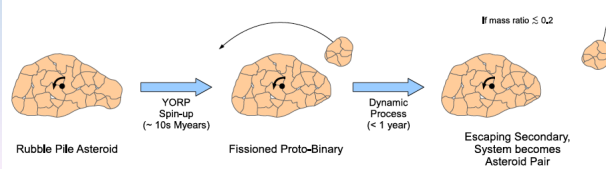
All scenarios have precedents

Jupiter's regular moons thought to have formed in a proto-jovian disk

Its irregular satellites are thought to be captured asteroids and comets

Binary asteroids may have formed by fission

If mass ratio ≲ 0.2

YORP Spin-up (~ 10s Myears)

Dynamic Process (< 1 year)

Rubble Pile Asteroid

Fissioned Proto-Binary

Escaping Secondary, System becomes Asteroid Pair

But these are different to the Moon

Formation scenarios: Giant Impact

Idea: Solve the problems of the co-accretion scenario by creating a circumterrestrial disk in a collision with a Mars-sized impactor (Theia) when Earth was 90% of its current mass
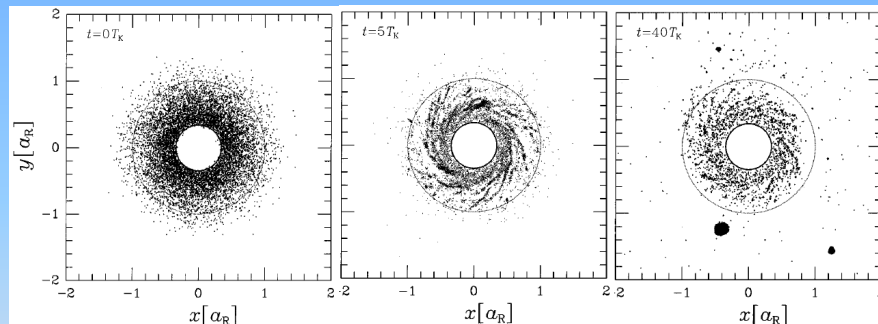
If Earth was differentiated then explains lack of Fe in Moon since this formed from mantle

Smoothed Particle Hydrodynamics (SPH) simulations show that the formation of such a disk is plausible (Canup et al. 2001)
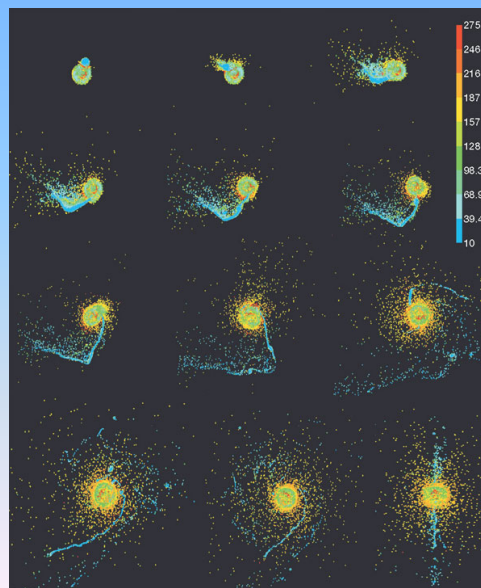
Evolution of circumterrestrial disk

Kokubo et al. (2000)

- Disk contracts through collisional damping
- Particle clumps grow inside R_{roche} but shear out to form spiral structure
- Gravitational torques push particles beyond R_{roche} where moonlets form
- Moonlets coalesce; lunar seed sweeps up all particles pushed $>R_{roche}$
- When Moon large enough, pushes inner disk onto Earth
- Formation timescale is ~1month (ignoring melting/vaporisation)

Plausibility of collision

As long as a circumterrestrial disk forms with 2-4 times lunar mass within the Roche radius, then an object like the Moon will coalesce out of it
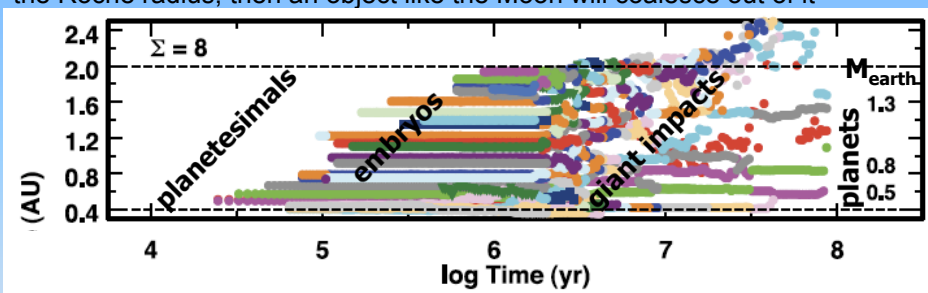
Collisions are expected during final stages of formation of terrestrial planets (e.g., Kenyon & Bromley 2006), but would have to be a high impact parameter and mass ratio to strip mantle, maybe ~1% chance?

Reasonable odds given we observe just one system, and maybe appeal to **anthropic principle** – if the Moon's existence favours the development of life then we would be more likely to be observing from a planet with a Moon

Niggling composition concerns

Part of the impactor always goes into the circumterrestrial disk

So why is isotopic composition of Moon so similar to that of the Earth?

Is it likely that even nearby embryo would have such similar composition? Perhaps 20% probability (Mastrobuono-Battisti et al. 2015)
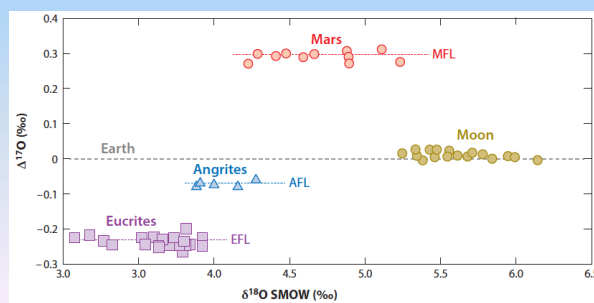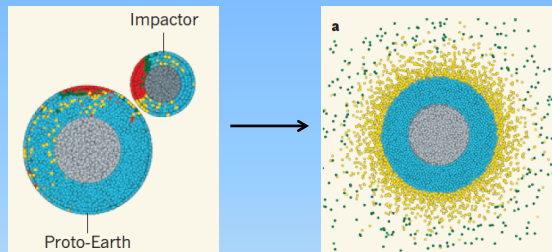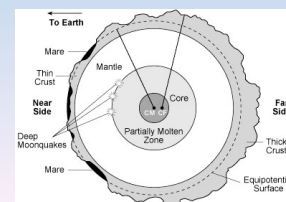

Explanation 1: Protolunar disk physics

Diffusion of Earth and protolunar isotopic systems through disk atmosphere (Pahlevan & Stevenson 2007)
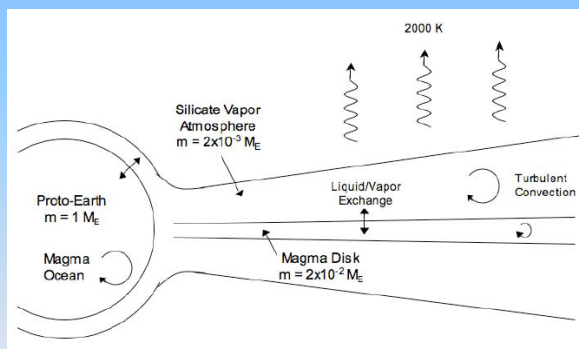
But, required diffusion may be self-limiting due to mass and angular momentum transfer, and highly refractory elements like Ti must also be homogenised (but not water)


Similar idea has only the equilibriation only occurring for the last moonlets accreted onto the Moon giving a late veneer of isotopically similar material (Salmon & Canup 2012)

Explanation 2: Different collision parameters

Not all collisions end up with Theia in protolunar disk, but most also end up with a system with too much angular momentum

Invoke capture of Moon in *evection* resonance (Cuk & Stewart 2012) which can halve angular momentum in Earth-Moon system by exchanging it within the Sun-Earth-Moon system
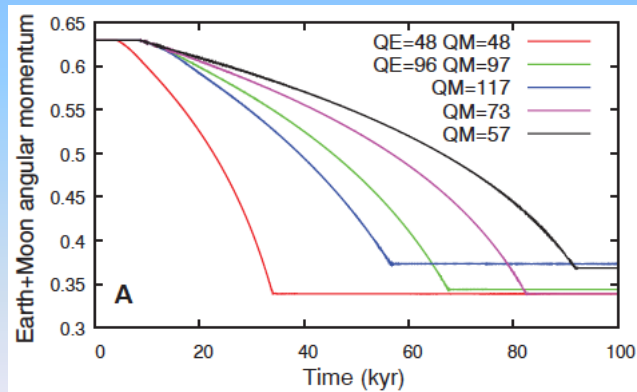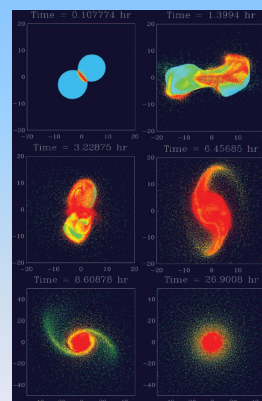

Evection resonance is between the Moon's orbital precession period and the Earth's orbital period

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Explanation 2: Different collision parameters

EG1: 20km/s collision of $0.05M_{earth}$ impactor onto proto-Earth spinning close to rotational instability at 2.5hr period (Cuk & Stewart 2012)
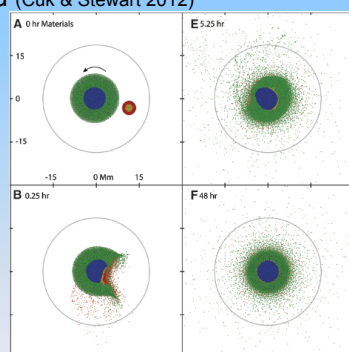
EG2: 4km/s collision of two $0.5M_{earth}$ planets (Canup 2012)

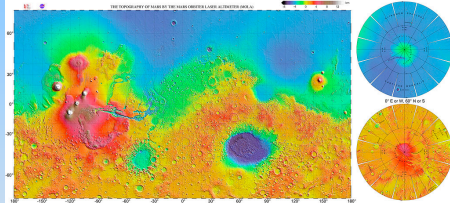

But could Earth be spinning that fast (probably requires previous giant impact), and would embryos be similar enough in mass?
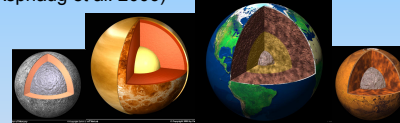
Other giant impacts in the Solar System

While origin of Moon is unsolved, all theories invoke a giant impact at ~50Myr, and giant impacts appear to be a common feature in the Solar System

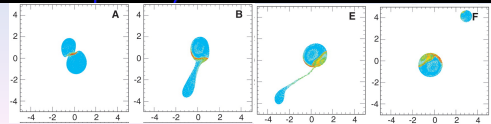Mars hemispheric dichotomy (Marinova et al. 2008)

Mercury Fe-rich composition
(Asphaug et al. 2006)

Uranus tilt (Parisi & Brunini 1997)

Pluto – Charon system (Canup 2011)

Are extrasolar giant impacts observable?

What do giant impacts do?	Evidence in Solar System	Potential extrasolar observable
Formation of moons	Earth – Moon and Pluto – Charon forming impacts	Transit timing variations from exomoons (Kipping, Nesvorny, et al.)
Modify internal planet composition	Mercury Fe-rich composition	Planetary densities from RV +transits
Modify planet surface	Mars hemispheric dichotomy	Too subtle?
Modify planetary atmosphere	Magma ocean?	Hot planet spectrum (Anic et al. 2007; Miller-Ricci et al. 2009)
Modify planetary spin	Uranus tilt	Exoplanet spins are measurable (Snellen et al. 2014)
Create debris	Hirayama asteroid families, dust bands	Infrared signature (Jackson & Wyatt 2012)

Dynamical evolution of impact debris

Take outcome of Moon-forming simulation and follow evolution of 1.6% of Earth mass of escaping debris using N-body (Jackson & Wyatt 2012)
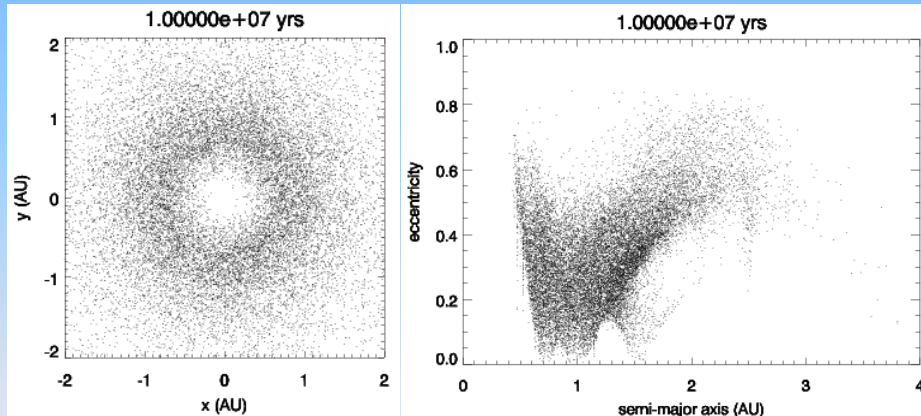

After 10Myr 45% of particles lost, of which: accretion onto Earth (45%), accretion by Venus (40%, so resurface to 10km), ejection by Jupiter (15%)
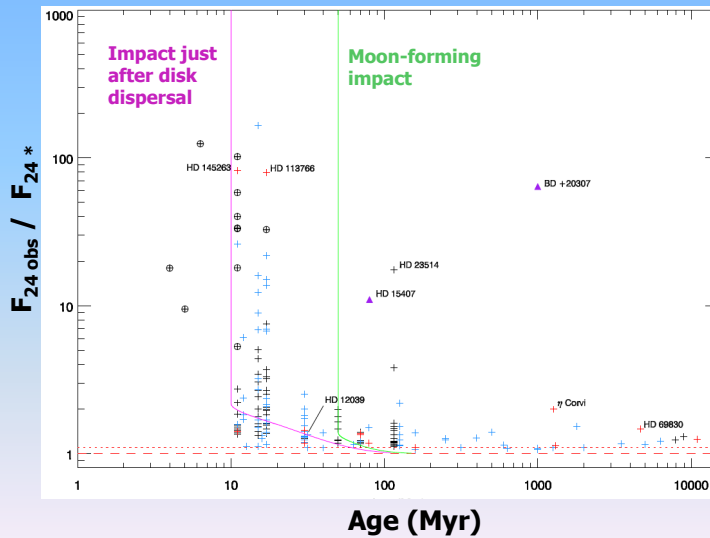
Detectability of Earth-Moon impact debris

Detectability depends on quantity of dust cross-sectional area (not mass), so size distribution is very important

Debris also depletes due to mutual collisions, the rate of which depends on the size distribution
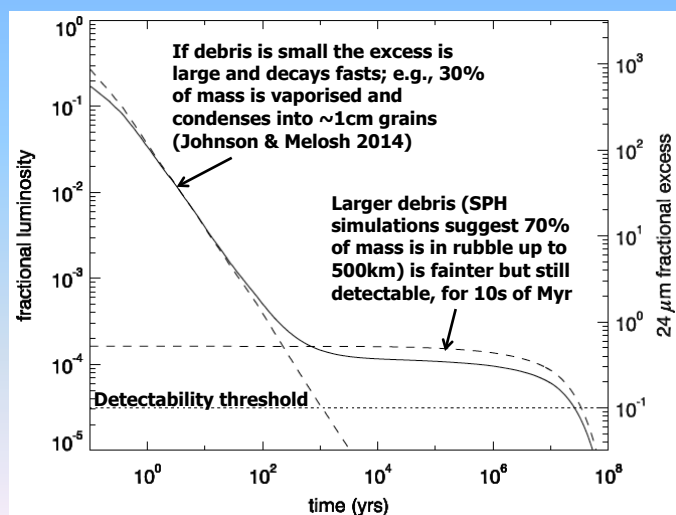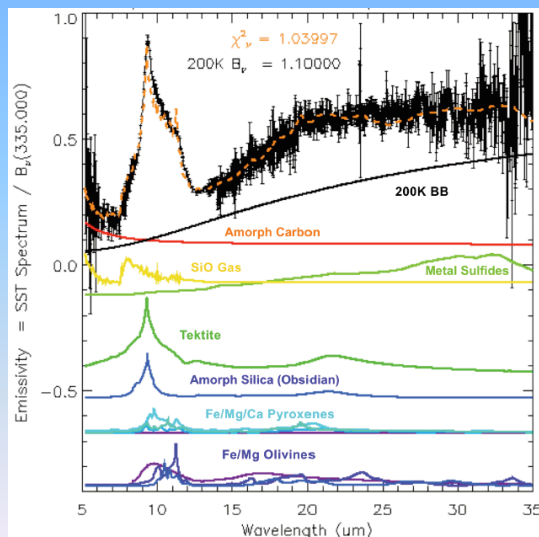
How does that compare with observed systems?

24μm excesses are observed around nearby predominantly young (<200Myr) stars, at a level and epoch consistent with expectations of giant impacts

HD172555: Compositional evidence for impact

Spectrum of this 12Myr A5V star shows dust composition dominated by silica (Lisse et al. 2009)

This points to recent collision at >10km/s between two massive (>Mars-mass) protoplanets; e.g., Earth-moon forming collision

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How common are Moon-forming impacts?

Fraction of 10-100Myr stars with 12μm emission at level expected from giant impacts (Kennedy & Wyatt 2013): ~ 3%

Fraction of those stars for which the emission is from giant impacts (not asteroid belts): <100%

Fraction of 10-100Myr period the Solar System exhibited detectable emission: ~30%

Thus, fraction of stars with similar evolution to the Solar System: <10%

So, either late giant impacts are rare (planetary systems emerge from the protoplanetary disk fully formed and stable), or terrestrial planet formation is rare, or we got something wrong!

Conclusions

(1) Moon likely formed from a giant impact; such impacts are expected in terrestrial planet formation models

(2) That giant impact had to have quite specific parameters to satisfy angular momentum and composition constraints, and our understanding is changing quickly (see Asphaug 2014, AREPS, 42, 551)

(3) Giant impact debris is detectable around nearby stars, but few stars exhibit such events suggesting that late-stage (10-100Myr) Moon-forming impacts are rare