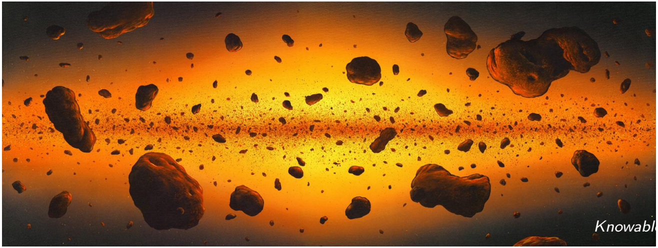
Formation of habitable planets by pebble accretion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CELS Welcome Meeting, September 2021

European Research Council
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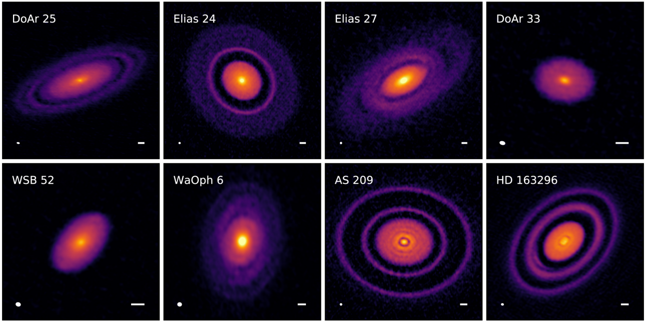
Protoplanetary discs around young stars

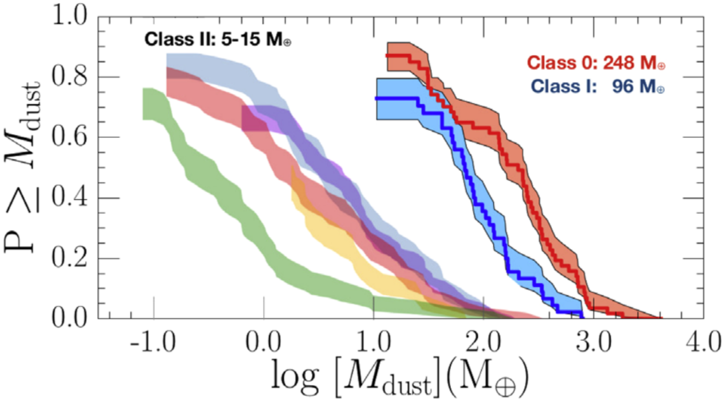


(DSHARP survey: *Andrews et al.*, 2018)

- Planets form in protoplanetary discs of gas and dust
- Protoplanetary discs reveal themselves from the thermal emission from cold pebbles of millimeter sizes
- Typical sizes of 100 astronomical units
- Contain 99% gas (transparent) and 1% dust and ice (opaque)
- Typical disc masses between 1% and 10% of the mass of the central star

Planet formation is a race against time

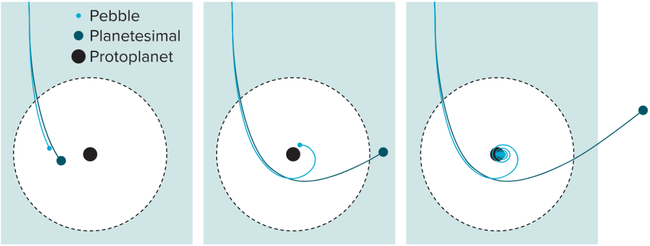
(*Tychoniec et al.*, 2018)



- The gas and dust in protoplanetary discs is accreted onto the star
- Discs around very young stars contain several 100 Earth masses of dust
- Dust mass falls to $\sim$10 M_{E} after a few million years
- Protoplanetary discs typically live for 2-3 million years
- Dust must grow rapidly before the disc is emptied onto the star

Planetesimal accretion and pebble accretion

(*Johansen & Lambrechts*, Annual Reviews, 2017)



SOURCE: M. LAMBRECHTS & A. JOHANSEN

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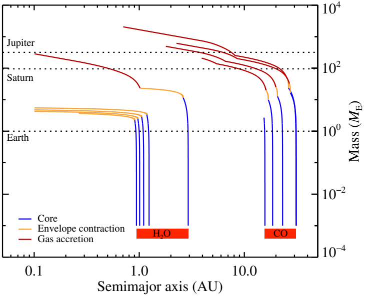
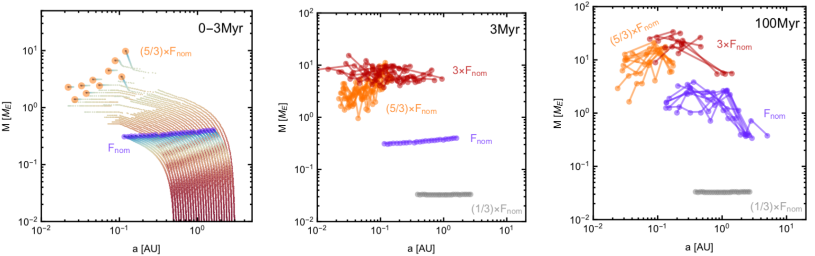
- Planet growth by planetesimal accretion is very inefficient (*Johansen & Bitsch*, 2019)
- Most planetesimals are scattered by a growing protoplanet, yielding very long growth time-scales (*Tanaka & Ida*, 1999)
- Pebbles are accreted much faster due to energy dissipation by gas friction (*Johansen & Lacerda*, 2010; *Ormel & Klahr*, 2010; *Lambrechts & Johansen*, 2012)
- Planetary growth by pebble accretion outperforms migration (*Bitsch et al.*, 2015; *Johansen et al.*, 2019)



The formation of super-Earths and terrestrial planets

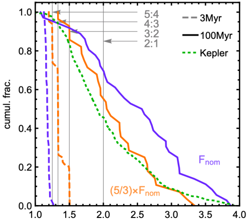


(*Lambrechts et al.*, 2019)

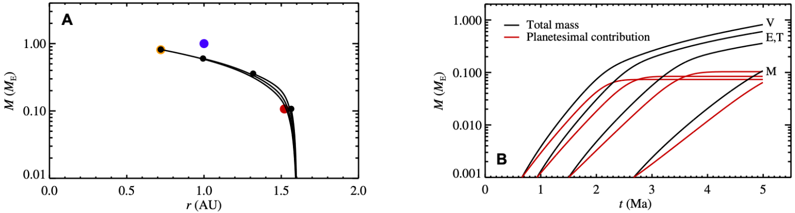
- Pebbles drift through the protoplanetary disc at a rate of approximately 100 M_E per Myr
- A nominal pebble flux leads to Mars-mass embryos, colliding over 100 Myr to form terrestrial planets as in the classical model (*Izidoro et al.*, 2015)
- A high pebble flux leads to the formation of super-Earth systems

⇒ The formation of super-Earths and terrestrial planets are connected processes

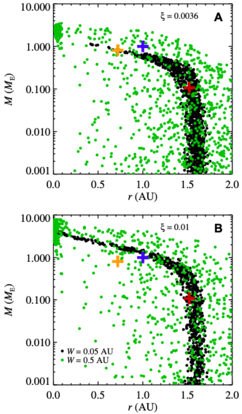
  - Planetary instability breaks the resonant chains (*Izidoro et al.*, 2017)



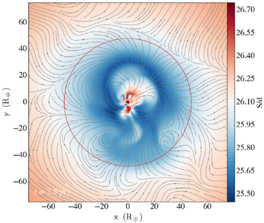
Terrestrial planet formation with pebble accretion

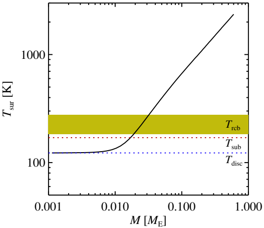


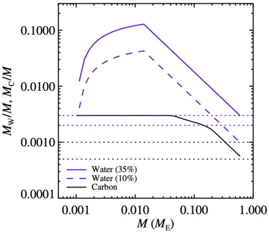
- The orbits and masses of Venus, Earth and Mars can be matched by forming a planetesimal belt at 1.6 AU and growing the planets by pebble accretion (*Johansen et al.*, 2021)
- We also match the isotopic composition of the Earth with this model (*Schiller et al.*, 2018; 2020)
- We must form an additional planet Theia that collides with Earth later to form the Moon
- Pebble accretion can explain why the Earth and the Moon have similar isotopic compositions



Volatile delivery by “pebble snow”

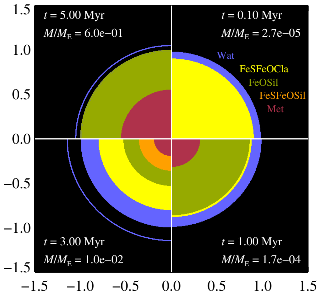


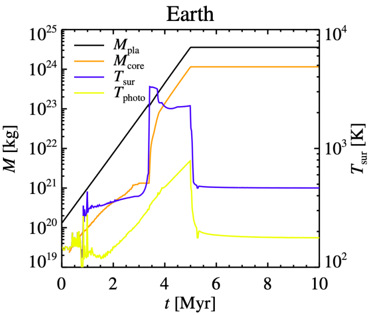




- Volatiles such as C and H_2O can be delivered to terrestrial planets by “pebble snow” (*Ida et al.*, 2019)
- The water ice line the solar protoplanetary disc was likely interior of 0.7 AU during most of the disc life-time (*Morbidelli et al.*, 2016; *Flock et al.*, 2017)
- The envelope ice line sits beyond the radiative-convective boundary (*Lambrechts & Lega*, 2017; *Popovas et al.*, 2019) and water vapour is transported back to the protoplanetary disc after the planet reaches $\sim 0.01 M_{\rm E}$
- Carbon in organics are sublimated and pyrolyzed between 325 and 425 K, while graphite burns at 1,100 K (*Gail & Trieloff*, 2017)
- Pebble accretion gives a good match to H_2O and C of Earth (*Marty et al.*, 2012)

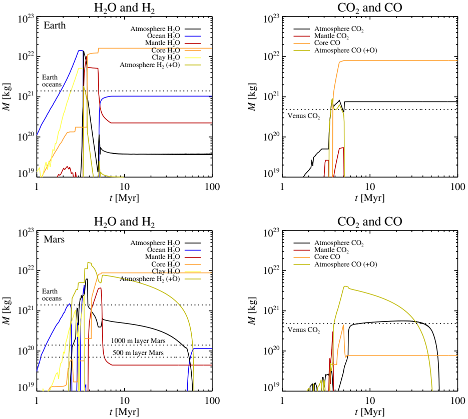
Differentiation and magma ocean

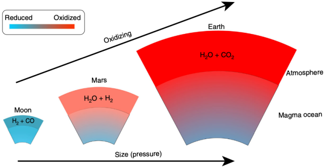




- Results of ADAP interior structure code (*Johansen et al.*, submitted)
- Accretion heat leads to a run-away greenhouse effect that heats the surface to form a magma ocean (*Matsui & Abe*, 1986)
- The planet differentiates from the surface and down, with the energy released by the falling metal contributing to the heating
- Results in a fully molten mantle magma ocean
- The planet settles with a CO_2 greenhouse atmosphere after accretion

The outgassed atmosphere

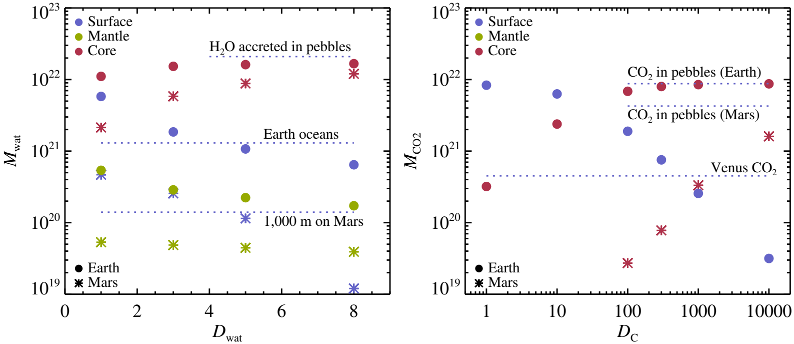




(*Deng et al.*, 2020)

- The composition of the outgassed atmosphere depends on the oxygen fugacity of the magma ocean (*Ortenzi et al.*, 2020)
- The canonical oxygen fugacity yields a strongly reduced atmosphere that experiences significant mass loss by XUV from the young Sun
- More massive planets experience mantle oxidation at high pressures, this leads to outgassing of an oxidized atmosphere (*Armstrong et al.*, 2019)

Dependence on partition coefficients



- The partitioning of water and carbon between mantle and core is a key process that determines the atmospheric composition
- Partition coefficient varies with pressure and temperature (*Fischer et al.*, 2020)
- We get good agreement with Earth and Mars water for $D_{\rm wat} \sim 5$
- We get good agreement with Earth and Venus atm+mantle for $D_{\rm C} \sim 300$
- Pebble snow model gives predictable amount of volatiles delivered to terrestrial planets, but mantle oxidation state, core-mantle partitioning and atmospheric loss lead to (predictable) diversity in volatile budgets

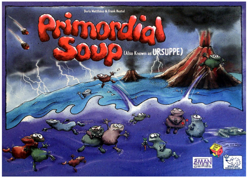
Prebiotic chemistry and the origin of life

What was the origin of organic molecules on Earth?

- The magma ocean phase must have destroyed all organic molecules delivered before the moon-forming giant impact
- The young Earth likely held 100 bar of CO_2 atmosphere (like Venus) that would allow meteorites to land unharmed
- Carbonaceous chondrite meteorites contain nucleobases, amino acids, sugars and peptides that assembled in their warm and wet interiors
- Did life take its first steps towards molecular complexity inside of planetesimals whose fragments fell on the young Earth?

Was the early atmosphere oxidized or reduced?

- A reduced atmosphere consists mainly of H_2 and CO and allows assembly of complex organic molecules through Urey-Miller processes
- An oxidized atmosphere has significant H_2O and CO_2 that attack and oxidize organic molecules
- Life could then originate at hydrothermal vents at the ocean floor
- Alternatively, wet-dry cycles in warm little ponds at the surface could lead to increasing molecular complexity



Is life common in our galaxy?

- Life established itself on Earth over 4 billion years ago (*Rosing*, 1999)
- James Webb Space Telescope (to be launched October 2021) and the Extremely Large Telescope (planned first light 2025) will characterize the atmospheres of nearby potentially habitable planets
- Possible to search for biosignatures such as O_2 and CH_4 and measure day/night albedo cycles to map continent and ocean coverage