Formation & Evolution of the Solar/Planetary System

- ***Summary***
  - Planetary system formed during/shortly after formation of the Sun
  - Collapse of interstellar gas/dust cloud
  - Disk formation by gas friction
  - Cold disk to grow m size bodies and planetesimals
  - Runaway grow of planets
  - Clean-up by collision down-grinding, scattering, impacts (early & late heavy bombardment) and radiation pressure
  - Atmosphere evolving from magma gas release and impacts
  - Proto-planetary disk was full of organics including L/D aminoacids
  - Sun will expand as red giant star to orbit of Mars

Dating of surface ages

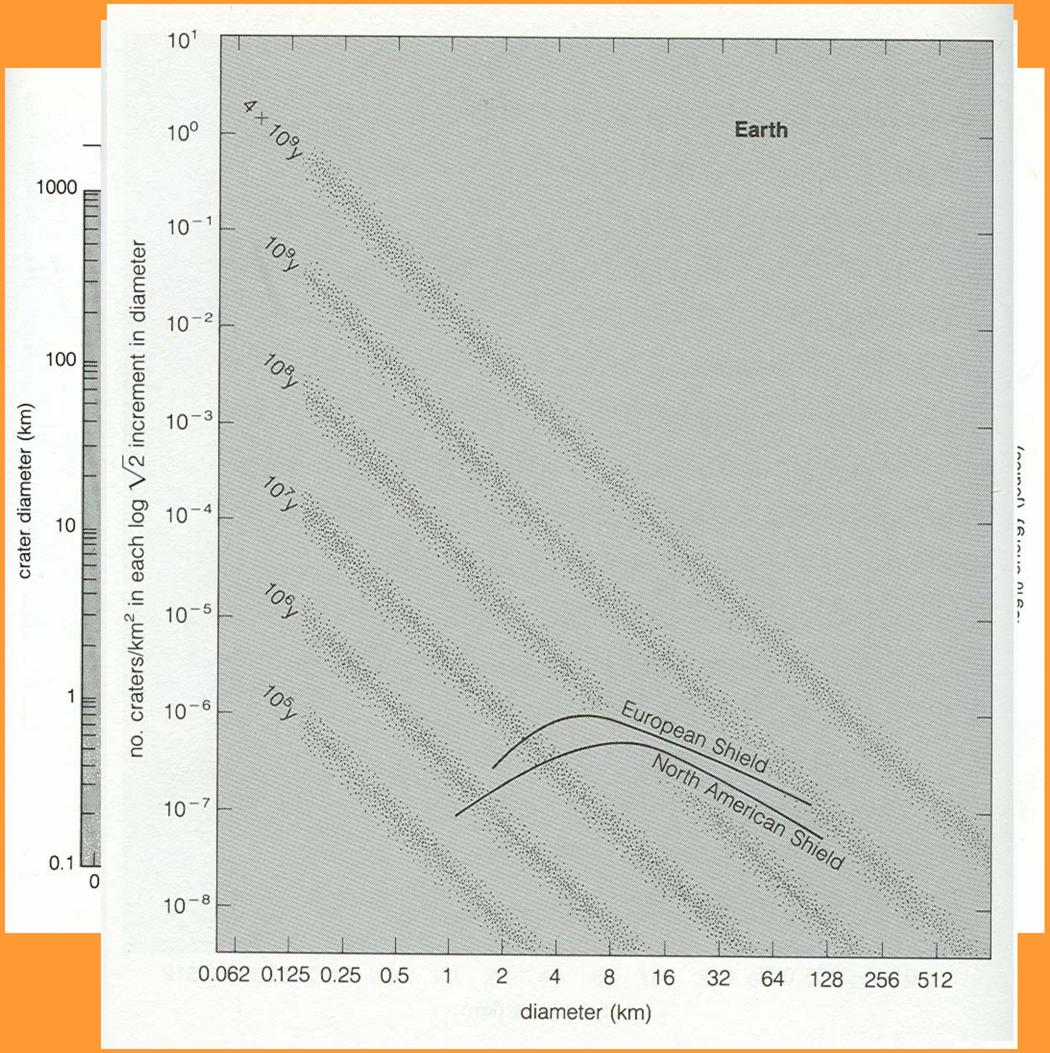
Recipe:

- count surface density of craters

- plot surface density versus diameter of craters

- compare with isochrone lines

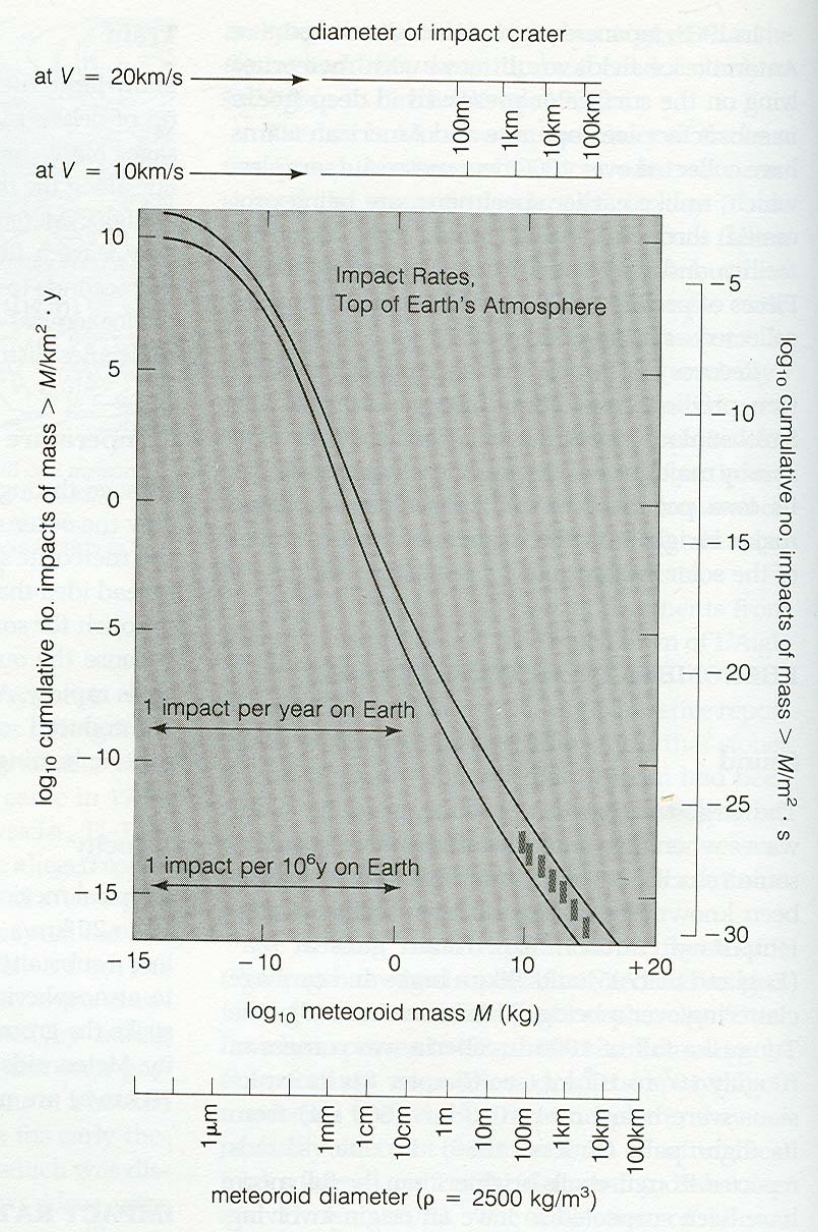
- calibration of isochrone lines mostly from sample analysis of Apollo moon missions

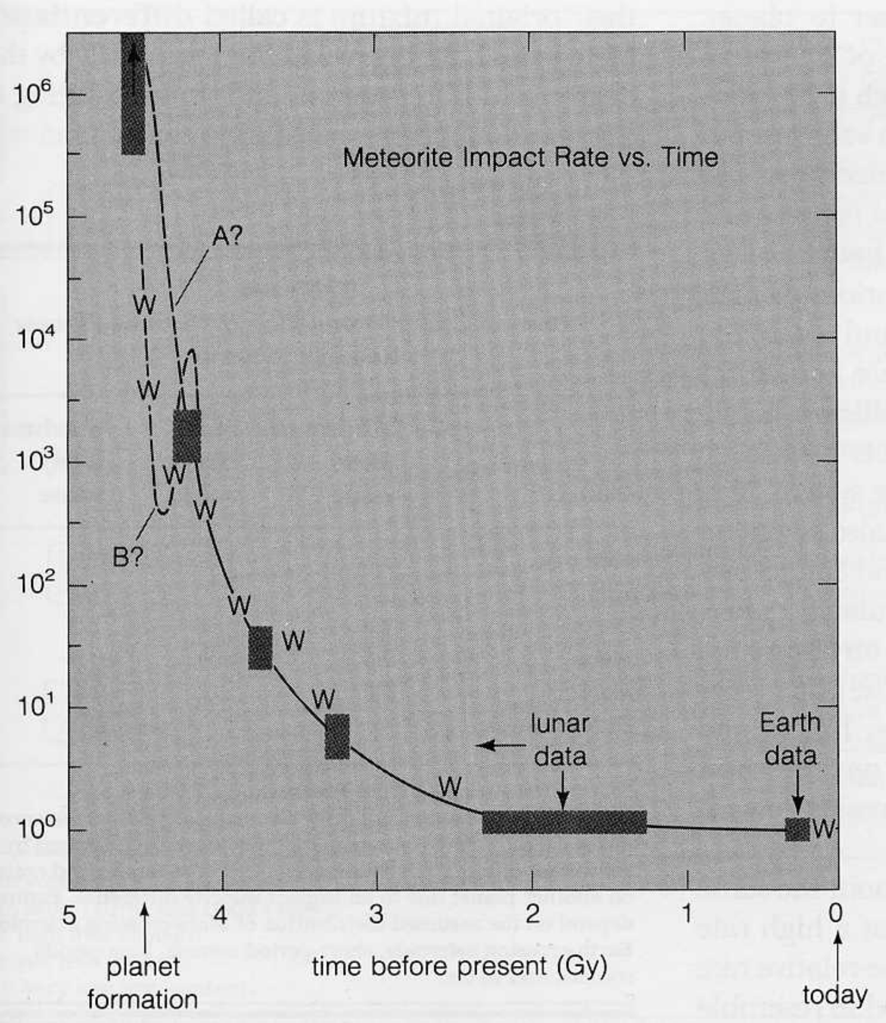


<u>Moon:</u> old surface modeled by early and late heavy bombardment

<u>Earth:</u> young surface due to tectonics, erosion, life

Cratering and planetary system formation





Observational Indications

- Primitive asteroids, comets, TNOs: primordial = remnants from formation period of planetary system (planetesimal state and before)
- For the Formation and its environment:
  - Environment: star forming regions
    - Dense interstellar clouds
  - Formation temperature: relatively cold
    - Organics in meteorites (T<300K)
    - Not from cooled Sun material: deuterium is lost in nuclear reactions within 10^6 y D/H(giant planets)>>D/H(sun)
    - Isotopic ratios Sun to Meteorites/Comets identical (for heavier elements)
    - Mixing of H and He in Jupiter/Saturn as in Sun
  - Ingredients: stellar formation regions
    - Interstellar gas with most abundant elements H, He
    - Interstellar gas that can form volatile ices (H_2O, CO, CO_2, NH_3, CH_4 etc.)
    - Interstellar dust, strongly shocked or enriched in supernova produced elements

      (diamonds=shocked C, ^{26}Mg from ^{26}Al in chondrites higher than in current neighbourhood)
  - Mass: > 1.02 solar mass

- For the Formation time:
  - Meteorites ➔ 4.56 10^9 a

    ➔ not necessarily in present stellar neighbourhood, but probably in star cluster (Gallactic rotation and differential motion of stars, proper motion of the Sun)
- For formation time scales:
  - Meteorites, i.e. cm→m size bodies +/-10 10^6 y around formation time
  - Oldest impact craters (on moon) ~4.3 10^9 y

    ➔ planet (moon!) formation widely ‚finished‘ within 100 10^6 y from chondrite formation
- For the typical size and geometry (some times during formation process):
  - Kuiper Belt extension ~ 50 AU at one time (maybe even smaller: Nice model and Neptune migration)
  - Ecliptic-orientation of planets and the belts and analogy to circumstellar disks and proplydes in star formation regions

    ➔flat disk-shape geometry
  - Mass concentrated in Sun, angular momentum in planets
- Objects produced:

– Sun (star)	1 solar mass
– Terrestrial planets	10^{-5} solar mass
– Gas giants	10^{-3} solar mass
– Icy planetesimals and fragile comets	10^{-3} solar mass

all appeared quasi-simultaneously

Formation Scenario

- Step 1 - Protostellar collapse:
  - Jeans criterion for collapse of gas clouds: self-gravitation energy > thermal energy in cloud

    self-gravity ~ $GM^2/R \sim GM\rho R^2$

    (M,R = mass/radius of cloud, G = grav. Const)

    thermal energy ~ $Mv_s^2 \sim k^2MT^2$ (v_s/T = speed of sound/temperature in cloud)

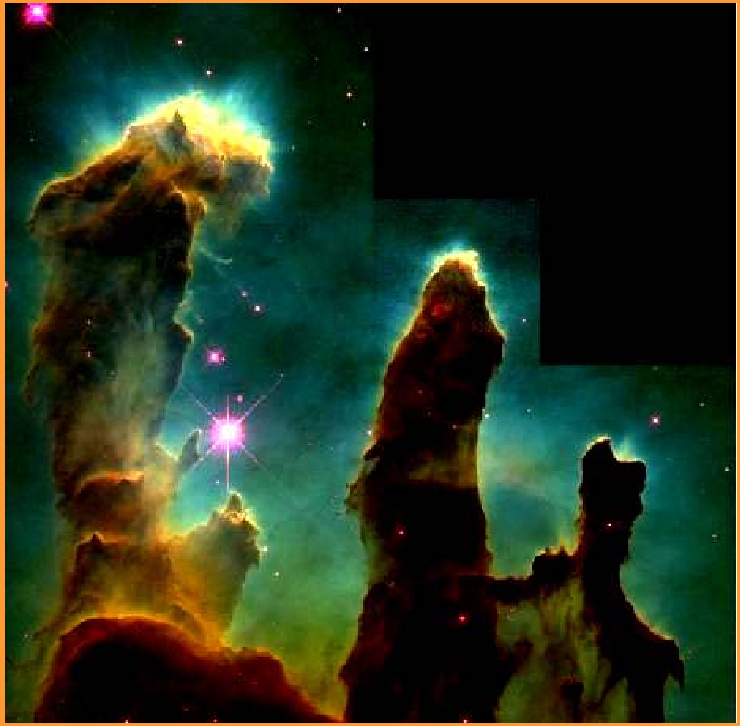
    $R = (\pi v_s^2 / G\rho)^{1/2}$ (Jeans criterion)

    → from star forming regions:

    $R \sim 0.1$ pc ($3\ 10^{15}$ m), $T \sim 10$K

    collapse time scale: $t \sim R/v_s \sim 10^6$ y

    min. mass involved for protosolar nebula ~ 1.02 solar mass (Sun+planets)



- Step 2 – Disk formation:
  - Radial collapse & conservation of angular momentum

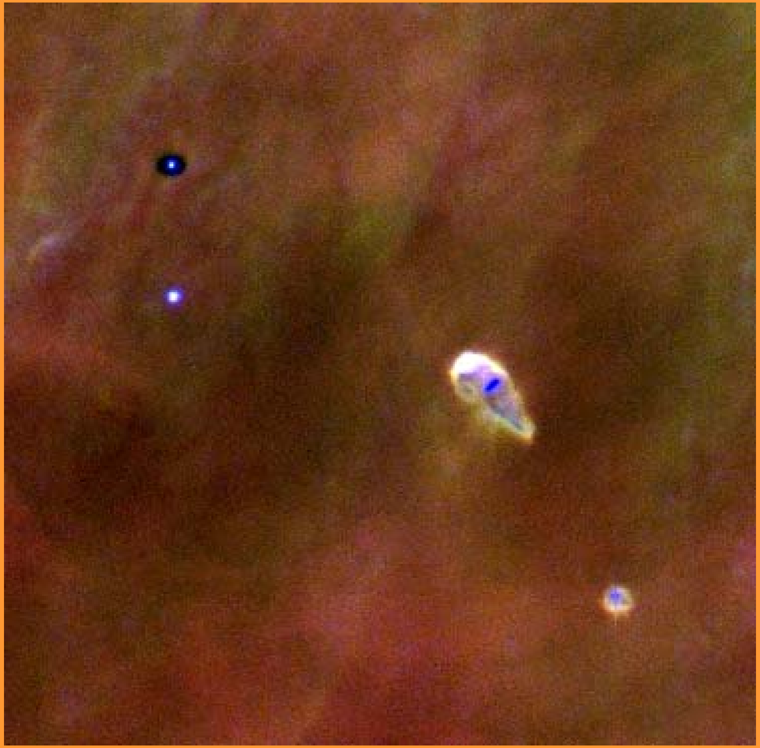
    ➔ flat disk is formed

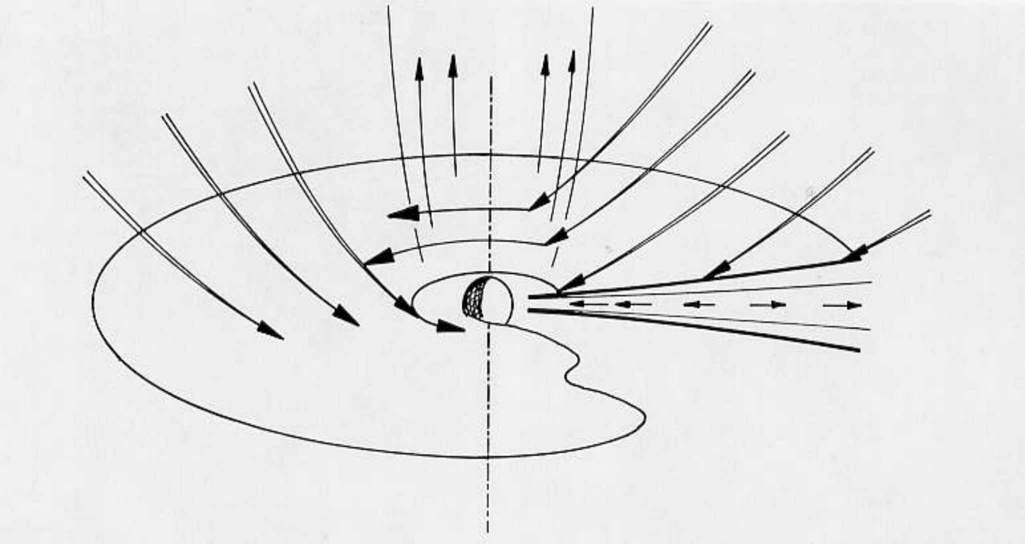
    Collapse along rotation axis of cloud continues, inside disk has to overcome centrifugal forces

    ➔ Angular momentum in disk is transformed into thermal energy via friction

    ➔ Heating, towards center stronger, i.e. more efficient friction, better angular momentum transfer

    ➔ Proto-sun forms in disk center





- Time scale: 2 10^7 y
- Most of mass in Sun
- Disk thickness ~ 1/10 diameter
- Inner disk (~1 AU) is hot >1500K

  dust vaporizes, lighter molecules dissociates (not heavier ones)

  mass ~ 0.03 solar masses
- Outer disk (>2 AU) remains cool

  dust intact, more molecular gas

- Step 3 – Growth of cm/m size grains (meteorites):
  - Inner disk: rapid cooling through IR radiation

    ➔ stony molecules crystallize rapidly to µm grains

    Outer disk: gas freezes on dust grains

    ➔ dust grains start to agglomerate

    dm/dt ~ $a^2 v \rho_{dust}$ (a/ρ_{dust} = radius/density of dust)

    v ~ speed of dust settling towards disk plane

    Important: works only for relative velocities of dust < 10 cm/s

    ➔ ***dust aggregates only in dynamically cold disk***

    dynamically cold = dust grains have similar orbits (e,i), otherwise destruction by collision

    ➔ dust sticking is supported by formation of inter-grain matrix through condensation and surface reactions of gas molecules

    ➔ larger grains grow in very thin (out-of-plane) disk

    Time scale: < 10^3 orbits ~10^3 10^5 y

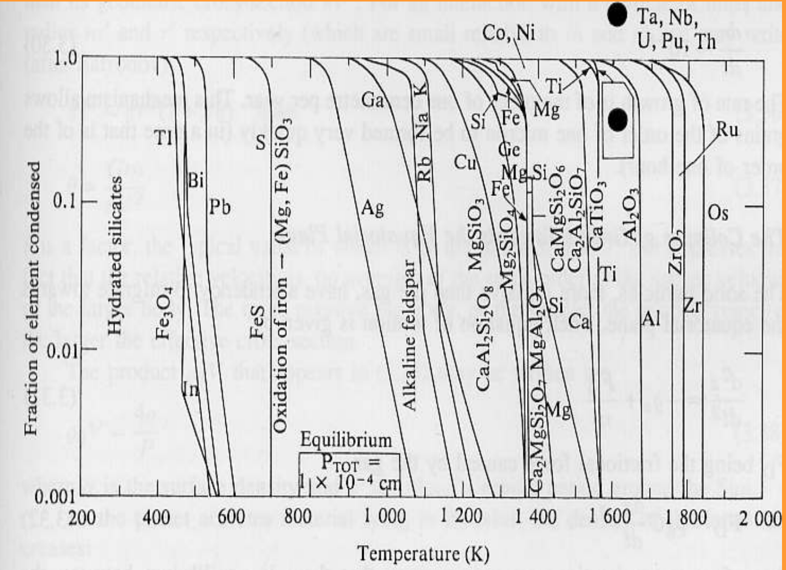


Fig. 3.1. The condensation sequence for a gas with solar composition. [After L. Grossman J.W. Larimer: Review of Geophysics and Space Physics **12**, 71 (1974)]

- Step 4 – Growth of planetesimals:
  - continuous gentle collisions of m size bodies grow planetesimals (~1km size)

    sticking by self-gravity

    Time scale: similar to step 3

    ➔ cold disk gets slightly ‚excited‘ due grav. interaction of planetesimals

- Step 5 – Runaway accretion of planets:

  planetesimals continue to collide and grow

  simulations ➔ 10^6-10^7 y few planet size bodies form, random behaviour for distances of planets

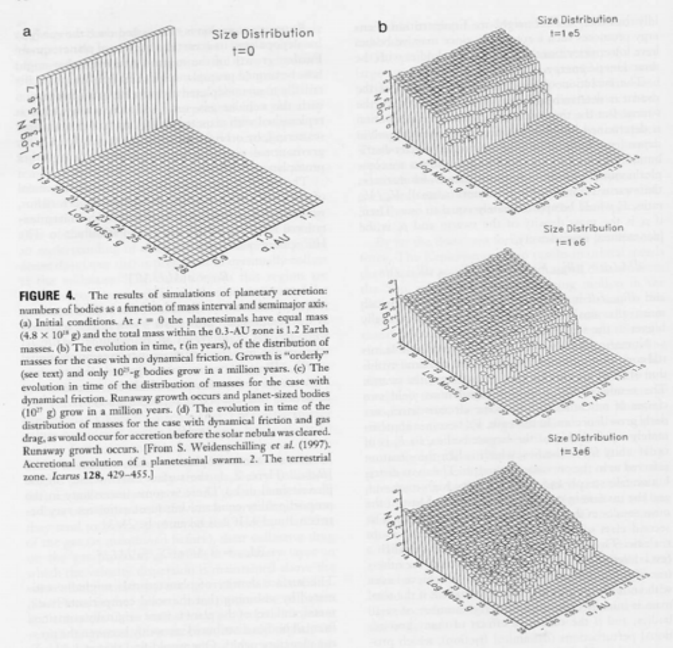
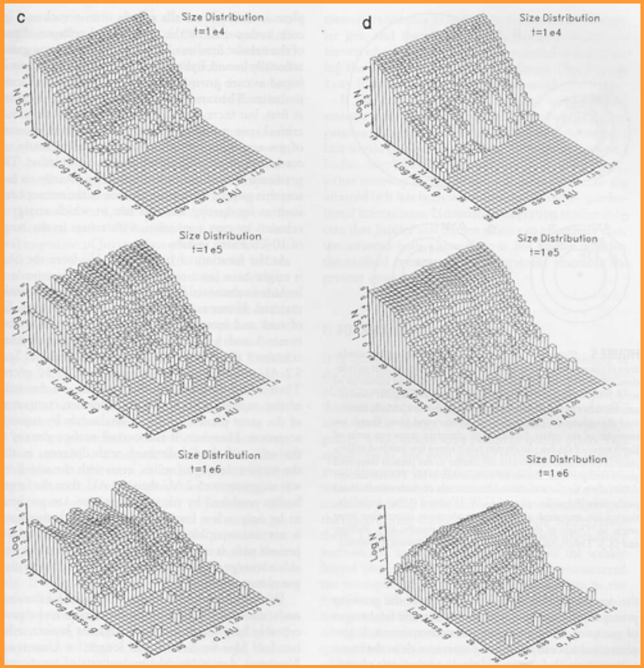


FIGURE 4. The results of simulations of planetary accretion: numbers of bodies as a function of mass interval and semimajor axis. (a) Initial conditions. At $t = 0$ the planetesimals have equal mass (4.8×10^{18} g) and the total mass within the 0.3-AU zone is 1.2 Earth masses. (b) The evolution in time, t (in years), of the distribution of masses for the case with no dynamical friction. Growth is "orderly" (see text) and only 10^{25}-g bodies grow in a million years. (c) The evolution in time of the distribution of masses for the case with dynamical friction. Runaway growth occurs and planet-sized bodies (10^{27} g) grow in a million years. (d) The evolution in time of the distribution of masses for the case with dynamical friction and gas drag, as would occur for accretion before the solar nebula was cleared. Runaway growth occurs. [From S. Weidenschilling *et al.* (1997). Accretional evolution of a planetesimal swarm. 2. The terrestrial zone. *Icarus* **128,** 429–455.]



- Step 6 – Disk clean-up:
  - Proto-planets in environment of planetesimals, meteorites, dust and gas

    all planets: perturbation on orbits in neighbouring disk environment

    ➔ cold disk gets excited

    ➔ collisions more energetic, i.e. impacts and scattering of planetesimals occur

    ➔ planetesimal collisions causes down-grinding of objects to dust grain size

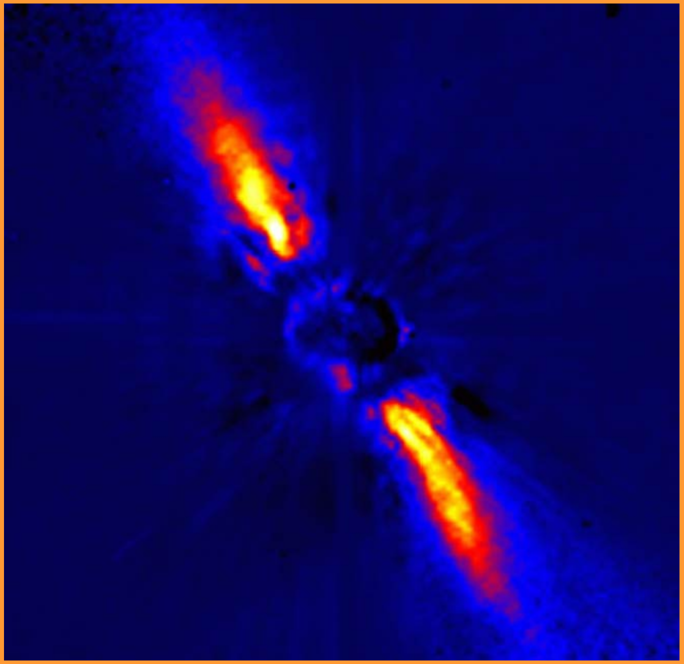
    ➔ dust removed by radiation pressure

    ➔ proto-planets grow further, disk looses mass towards Sun and outer solar system (interstellar space)

    terrestrial planets: H_2, He disk gas to hot and planet mass too small to allow accretion by condensation, only heavier molecule (H2O, CO2, CH4, NH3) can be accreted.

    giant planets: Earth size protoplanet is capable of accreting H_2, He gas since in colder environment

    Time scale: 10^7-10^8 y



Debris disk around β Pictoris

  - Oort cloud formation:

    during period of disk clean-up scattering from region of gas giants towards outer solar system

    ➔ ‚thermaliziation' of scattered comets by neighbouring stars and galactic molecular clouds

    ➔ distribution in spherical cloud at the edge of the solar system

    Arguments: ‚temperature-tracer ices' present/absent in Oort cloud comets

    ➔ matches expected temperature range for formation in giant planet regions, Kuiper Belt too cold

- End of the spectaculum:

  ~ 4 10^9 y from now

Planet Evolution (first 10^9 y)

- Heat-up by gravitational accretion: planets get hot during accretion due to ‚absorption' of impact / gravitational energy

  ➔ planet gets liquid, volatile molecules disappear to space or get distroyed in magma

  different density of metal and silicate materials causes differentiation

  ➔iron-core formation, silicate at surface
- Terrestrial planets: cooling of silicate forms crust of terrestrial planets, vulcanism releases solved magma gases, heavy bombardment deliveres further volatile gases

  ➔ original atmosphere (reducing character) forms
- Giant planets: hot core is surrounded by dense H_2/He atmosphere, i.e. efficient cooling of core, gets colder and solid again

  in parallel differentiation of gas atmosphere (H_2 fluid, He droplets)

Planet Evolution (Scenarios for next 10^{10} y)

- Some chaotic dynamics: planets may start migrating, colliding& scattering again
- Sun becomes red giant:

  photosphere growing to Mars orbit

  ➔ terrestrial planet will be gone

  ➔ gas giants will start evaporating their atmospheres

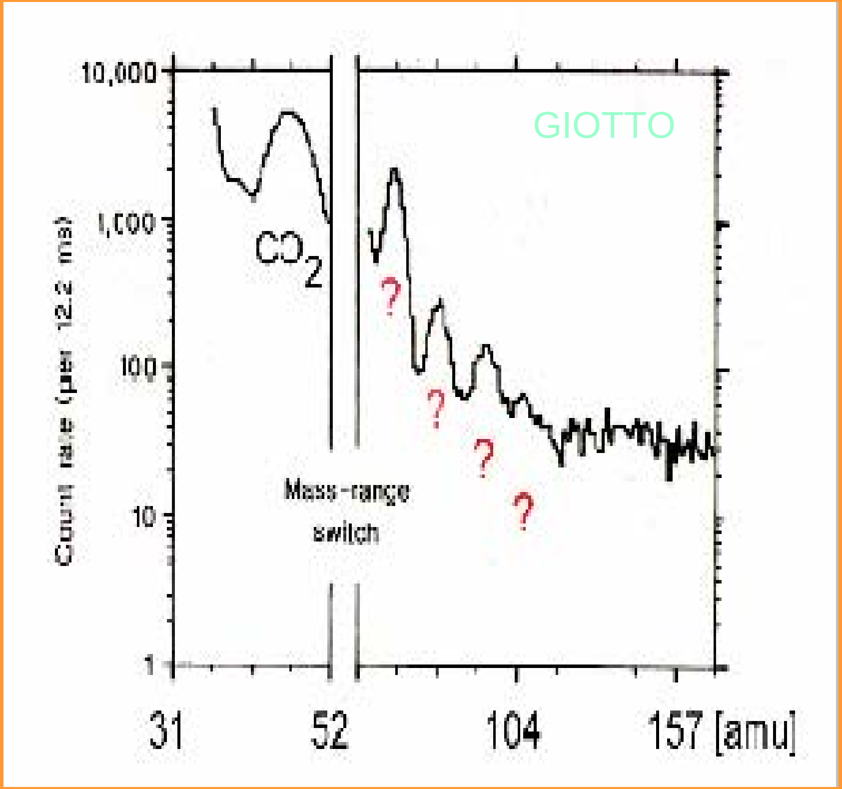
Bioastronomy in the Solar System

- Life on Earth (difficult to detect from space)
- Comets contain water ice (in part source of terrestrial water?; imported during late heavy bombardment)
- Existence of liquid water (oceans) is possible in large KBOs (like Pluto)

➔ KBO collision fragments = comets:

hence comets may contain relics from liquid phase

- Coma gas contains organic molecules (organic polymers?)



Bioastronomy in the Solar System

- Dust contains lots of CHON particles (GIOTTO at Halley)
- CI chondrites are suspected to contain primordial material from the formation period of the Sun
- CI chondrites are suspected to originate from comets
- Aminoacids exist in interplanetary space, i.e. found in some CI chondrites
- Murchinson CI contains aminoacids in non-racemic mixture (more L type)

➔ Comets might be seen as carrier and bringer of pre-biotic material to Earth

Aminoacids: L and D Types

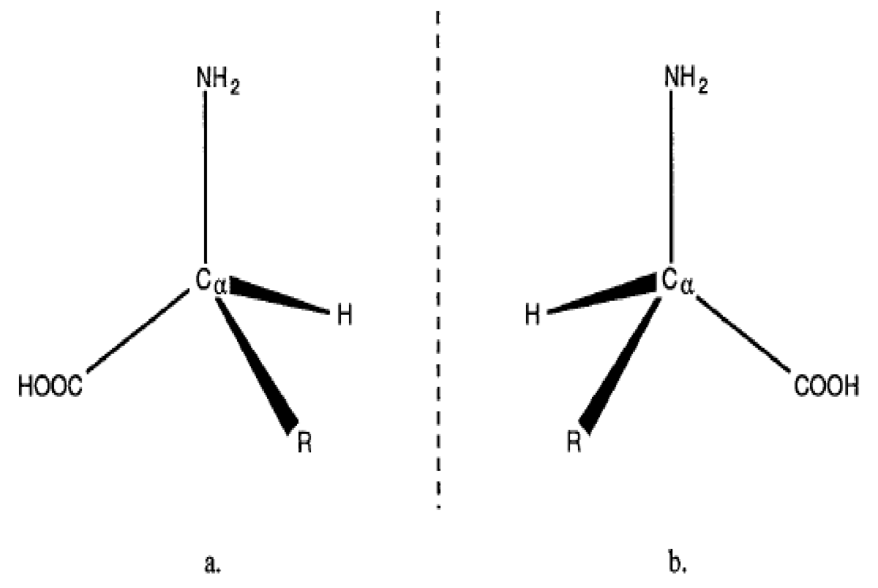


Figure 1. a. L-amino acid; b. D-amino acid

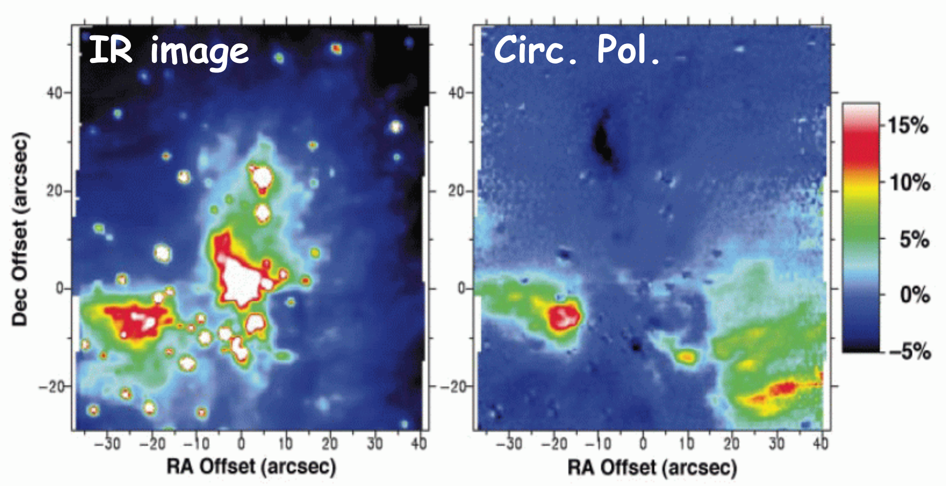
- Aminoacids: important pre-requisites for life formation on Earth
- Aminoacids come in two enantiomers: L and D type
- Terrestrial life built on L type aminoacids

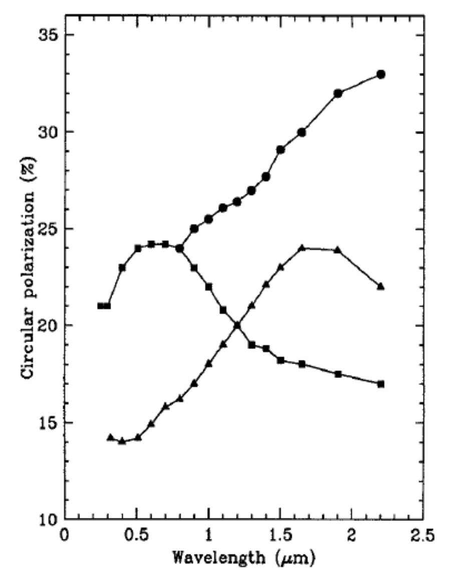
➔ Can this be produced in space?

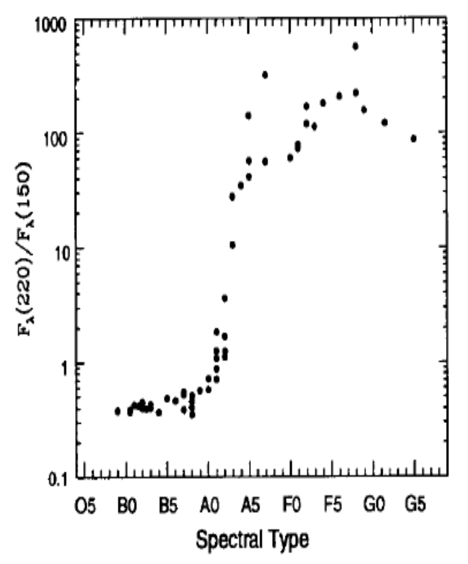
- L and D aminoacids show different optical activity: left and right-handed polarization

➔ Can this be used to detect them?

Polarized Light & Homochirality







- High (17% level) circular polarization measured in Orion dust clouds (Bailey et al. 1998)

- Photolysis of L/D molecules is affected by circ. pol. light

➔more efficient process than any other terrestrial fractionation effect for chiral molecules

- Homochirality of aminoacids through circ. pol. UV radiation from dust reflected star light

➔ most, but not all natural aminoacids on Earth are to be considered biogenic (Cref & Jorissen 2000)