Intelligent leven in het Heelal

crowded skies, lonely planet or rare earth?

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SETI: The Search for Extraterrestrial Intelligence

Are we alone?

So many stars... so many galaxies.

$$10^{11} \times 10^{12} = 10^{23}$$

- It is often stated that the vastness of the Universe and the enormous number of stars it contains, ensures that there must be numerous places in the Universe suitable for life to exist.
- The 'Copernican Cosmological Principle' (or the assumption of mediocrity) states that we are not special in any sense.
- So, obviously, the Universe must contain lots of planets with (carbon-based) life, including many instances of intelligent life like on Earth.

- It is certainly possible there are many planets where conditions are favorable for life to originate, so that primitive life would be prolific.
- But is it so obvious that this will *unavoidably* evolve into complex and intelligent forms of life?
- Maybe very special conditions are required for this.
- Arthur C. Clarke (1917–2008):
  'Sometimes I think we're alone; sometimes I think we're not. In either case, the thought is staggering.'

SETI, the Search for Extraterrestrial Inteligence

- There is a long history that I have no time to review.
- The first serious publication was by Guiseppe Cocconi & Philip Morrison in a paper in *Nature* in 1959[1].
- They proposed to use the frequency of the 21-cm neutral hydrogen line as the most natural one.
- After the Project Ozma in 1960 many more efforts have been made to detect radio signals from nearby, sun-like stars.
- Also messages have been sent.

[1] 'Searching for interstellar communications'; www.coseti.org/morris_0.htm

Current situation

- Currently the efforts are concentrated in the privately funded SETI Institute[2] in Mountain View, California (founded 1984).
- *"The SETI Institute's Mission is to explore, understand and explain the origin, nature and prevalence of life in the universe."*
- Prominent scientists are Jill Tarter and Seth Shostak.

[2] www.seti.org

- Seth worked for a number of years in Groningen as a radio astronomer at the Kapteyn Institute.
- He started a computer animation company DIGIMA.
- In 1988 he won the Wubbo Ockels Prize of the city of Groningen.
- He was particularly known for his original use of language and puns.

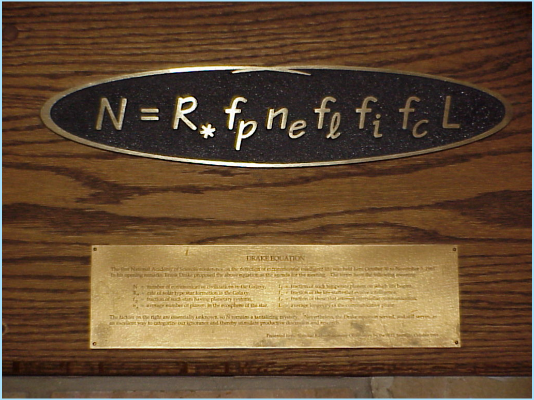
- The SETI Institute operates with the University of California at Berkeley, the Allen Array[3] at Hat Creek Observatory in Northern California.
- Currently it has 42 6-meter elements.
- The idea was ultimately 350 elements, but funding is difficult.

[3] Named after Paul Allen, co-founder of Microsoft, who provided 25M$.

Crowded skies or lonely planet?

Drake equation

Plaquette in the National Radio Astronomy Observatory (Charlottesville, VA) on the wall where Drake first wrote this equation in 1961 on a blackboard.



The Drake equation estimates the number of civilizations in the Milky Way that want to communicate.

- Take the number of (suitable) stars that are being formed in the Galaxy per year and multiply by:
  - fraction that has a planetary system;
  - number of habitable planets in a system;
  - fraction on which life originates;
  - fraction on which then intelligent life develops;
  - fraction of these civilizations that are interested in communication.
- That leaves you with the number of new civilizations per year that send out radio messages.

- The number if (suitable) stars forming in the galaxy is usually taken to be between 1 and 10 per year.
- The other factors are completely unknown but are assumed to be of order 0.1 to 1.
- Then there are between 0.1 and 10 new civilizations per year starting sending out signals.
- Multiply that by the mean lifetime (how long they keep doing that) and you get the number of such civilizations in the Galaxy.
- Drake, Sagan, etc. used to assume values of 10^5 to 10^6 years.
- *The nearest civilization then is of order (a few) hundred lightyears away.*

How realistic is all this?

- I will come back to the question of frequency of (habitable) planets later.
- Probably primitive life (archaea, prokaryotes, single-cell eukaryota) originates under many circumstances and is therefore abundant in the Universe.
- But evolution into life on land, animals and even mammals may require very special conditions.
- Even if intelligent life forms, it may not develop into technological civilizations.

Drake equation: conclusions

Intelligent life, that SETI searches for[4] is abundant in the universe:

- if most stars have planets suitable for life to occur;
- if life will inevitably form on these planets and as a matter of course will develop into intelligent life; and
- if civilizations interested in communication will survive for very long times.
- The equation expresses only our ignorance and does not tell us anything new.

[4] Christopher McKay: *'Intelligence is now defined as having the ability to build a radio telescope.'*

Fermi paradox

- The story goes that, around 1950 in Los Alamos, Enrico Fermi, Edward Teller and a few atomic scientists were discussing extraterrestrial life over lunch.
- They conjectured that advanced civilizations should be able to colonize the Galaxy (self-replicating robots?) in 10^5 to 10^6 years.
- Fermi is supposed to have asked: *"So, where is everybody?"*
- If there are that many habitable planets and intelligent civilizations, why has none of these visited Earth?
- This is Fermi's Paradox.
- It has been made more prominent by Michael H. Hart.

- He earned a Ph.D. at Princeton with Lyman Spitzer in 1972 at age 40 (on treatment of convection in stars).
- Became a Carnegie Fellow at the Hale Observatories (Mt. Wilson and Palomar) in Pasadena, CA.
- There he turned his interest to planetary atmospheres and life in the Universe.
- I was a Carnegie Fellow at the same time and the matter was discussed extensively at Hale Observatories.
- He published *'Explanation for the Absence of Extraterrestrials on Earth'* in 1975[5] (after his fellowship ended).
- Later he became interested in history and an ultra-conservative Republican, and he even proposed racial segregation.

[5] adsabs.harvard.edu/abs/1975QJRAS..16..128H

Fermi(-Hart) paradox: implications

"The Fermi paradox is the apparent contradiction between high estimates of the probability of the existence of extraterrestrial civilizations and the lack of evidence for, or contact with, such civilizations."[6]

Although ways out have been suggested (e.g. zoo hypothesis[7]), the implication of the paradox would be that intelligent extraterrestrial life is extremely rare.

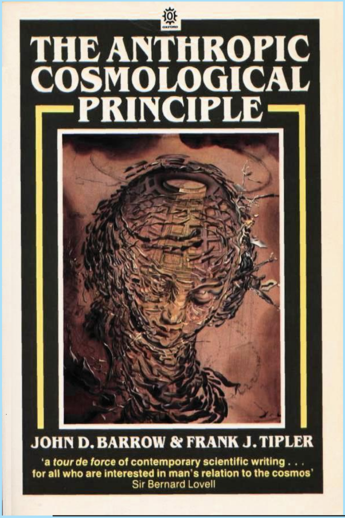
[6] From Wikipedia

[7] Or the 'Prime Directive' of *Space Trek*: *"There can be no interference with pre-warp civilizations"*.

Anthropic cosmological principle

- The anthropic principle originated in physics and cosmology.
- We live in a universe that is fine-tuned in the sense that fundamental constants in physics have to have values in a small range for life as we know it to exist.
- An example of 'fine tuning' is the existence of a semi-stable, resonant excited state of otherwise very unstable beryllium-8 (^{8}Be) that
  - allows 'helium burning' ($3\,^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C}$) at just the temperature and density that occurs during late stages of stellar evolution,
  - but which does not work in the early universe such that cosmological nucleosynthesis stops at He (except for a tiny bit of Li).
  - Without this coincidence life would not be possible.

The anthropic principle was introduced by Brendon Carter[8] in 1974.



- It has been extensively treated in a book by Barrow & Tipler and extended to various variants.
- *"The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirements that the Universe be old enough for it to have already done so."*

[8] adsabs.harvard.edu/abs/1974IAUS...63..291C

- Barrow & Tipler show that the order of magnitude of the lifetime of a star that radiates through 'hydrogen-burning', can be expressed in terms of fundamental physical constants[9]:

$$T_\star \sim \frac{\alpha \hbar}{\alpha_{\mathrm{G}} \beta^2 m_{\mathrm{p}} c^2} \sim 10^{10} \text{ years.}$$

- So the fundamental physical constants *dictate* that stars like the Sun must live for billions of years.
- It is then no surprise that we live in a Universe that has a size of billions of lightyears and contains an enormous number of stars.

[9] Here α is the fine-structure constant, α_{G} the gravitational coupling constant (defined as $Gm_{\mathrm{p}}^2/\hbar c$), G Newton's gravitational constant, $\hbar$ the reduced Planck constant, c the speed of light, m_{p} the proton-mass and β the proton-electron mass ratio.

- Currently the anthropic principle is quoted often in connection with string theory and the existence of the 'Multiverse' or 'Cosmic Landscape'.
- This has to do with the fact that Theories of Everything fail to predict the values of the physical constants.
- Only those universes in the Landscape with very special values for the constants allow observers[10].
- Tipler has gone further and deduced from the anthropic principle that 'extraterrestrial beings do not exist'[11].

[10] Leonard Susskind: *The Cosmic Landscape: String theory and the illusion of intelligent design* (2005).

[11] adsabs.harvard.edu/abs/1980QJRAS..21..267T; see also adsabs.harvard.edu/abs/1983RSPTA.310..347C

- Aspects of nature that are necessary for intelligent life to develop imply timescales of billions of years and therefore a Universe that measures billions of lightyears.
- This in turn implies the existence of 10^{20} stars, so it is no surprise if it has been realized only once.
- The anthropic principle has been criticized as being unscientific (not falsifiable).
- Its appeal is that it emphasizes the unity in nature and the intimate connection between the structure of the universe and the presence of humankind.

Anthropic principle: implications

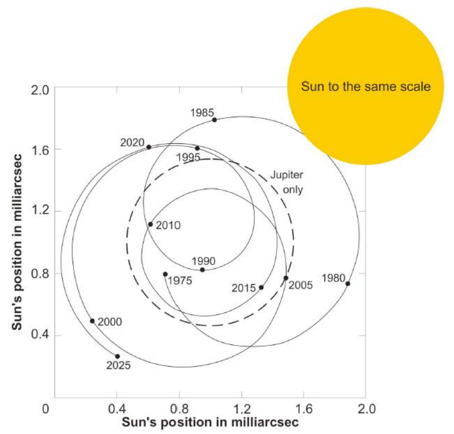
- According to the anthropic principle we must be in a very special position that allowed the development of intelligent life.
- This is the opposite of the Copernican principle.
- Intelligent life does not have to be abundant and could even be rare.

Exoplanets: Search methods[12]

Direct imaging

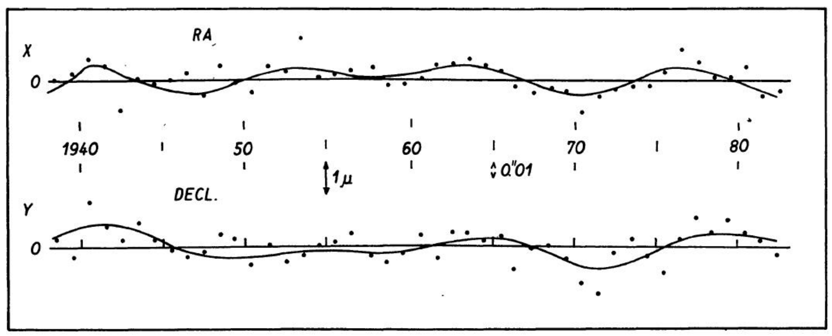
- At 10 pc (1 parsec = 3.26 lightyears) Jupiter is 0.5 arcsec from the Sun and 19.6 mag (factor 7×10^7) fainter.
- At this distance the Earth is 0.1 arcsec from the Sun and 22.4 mag (factor 9×10^8) fainter.
- This makes this method unpractical at the moment.
- It is expected that the European Extremely Large Telescope that is being considered may be able to do this using conjugate adaptive optics together with coronography.[13]

[12] See e.g. Jones, adsabs.harvard.edu/abs/2008IJAsB...7..279J
[13] See www.eso.org/sci/facilities/eelt/science/index.html



- Here we see the motion of the Sun around the center of gravity of the Solar System seen from a distance of 10 pc (32.6 lightyears).
- Both due to Jupiter alone (dashed circle) and to all planets.
- Amplitude is of order milliarcsec for Jupiter.
- This is extremely difficult to measure.

Peter van de Kamp claimed two planets around Barnard's Star[14].



- From long-term project from Sproul Observatory (Penn., USA).
- Van de Kamp (1901–1995) was an famous astrometrist.

[14] adsabs.harvard.edu/abs/1982VA.....26..141V

- The planets had periods of 12 and 20 years.
- Barnard's star is high-velocity star at 6.0 lightyears with mass 0.15 $M_\odot$.
- Planets are at 2.4 and 3.4 AU[15] and masses are 0.5 and 0.7 $M_{\rm Jup}$.
- Detailed study has shown that deviations correlate with times of maintenance and modifications to the objective lens of the (refractor) telescope.
- At present no planets have been found around this star.

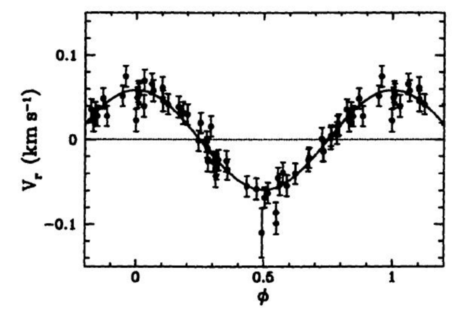
[15] Astronomical Unit = mean distance Earth – Sun

Radial velocity

- If we would be in the plane of the Solar System its radial velocity of the Sun would have a wobble
  - Jupiter: amplitude 12.5 m/sec with period 11.9 years.
  - Earth: amplitude 8.9 cm/sec with period 1.0 years.
- The inferred mass is dependent on inclination i if the orbit.
- This method requires high accuracy and stability.
- The accuracy attainable now is about a m/sec.
- This means the measurement of the wavelength of a spectral line accurate to one part in 300 million.
- The High Accuracy Radial Velocity Planetary Search (HARPS)[16] instrument of Geneva Observatory on the ESO 3.6-meter La Silla telescope is very prominent.

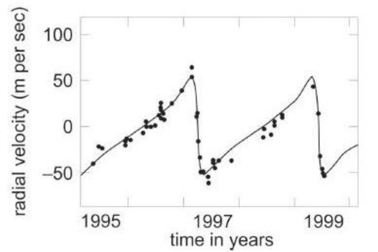
[16] obswww.unige.ch/Instruments/harps

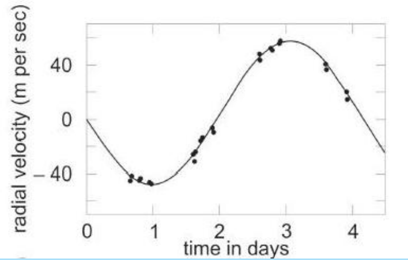
First detection of an exoplanet in 1995.[17]



- 51 Pegasi is a solar-type star ($M = 1.06 M_\odot$) at about 50 lightyears.
- It somewhat more metal-rich than the Sun.
- Planet mass is $0.47/\sin i \ M_{\mathrm{Jup}}$.
- Roughly circular orbit of 4.23 days and radius about 0.05 AU.
- First example of a 'hot Jupiter'.

[17] M. Mayor & D. Queloz: *A Jupiter-mass companion to a solar-type star*, adsabs.harvard.edu/abs/1995Natur.378..355M.

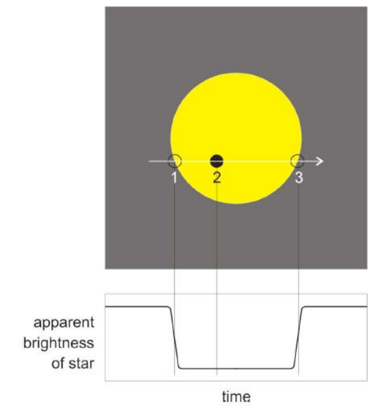




The form can be used to determine the eccentricity[a] of the orbit.

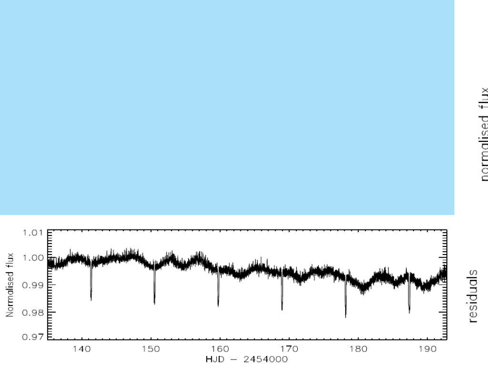
[a] Often spelled eccentricity

Transits



- Transit of Jupiter: Dip of 1.1% for maximum 36.6 hours and repeating every 11.9 years. No more than 0°.05 from plane of orbit.
- Transit of Earth: Dip of 0.0083% for maximum 13.1 hours and repeating every 1.0 years. No more than 0°.25 from plane of orbit.

- This can be done with a large accuracy from space.
- The satellites CoRoT[a] (France/Europe) and Kepler[b] (USA) are discovering large numbers of planets.
- Figure show data from CoRoT (CoRot-exo4; 1.17 R_{Jup}, 9.2 days).
- Follow-up is needed to determine eccentricity.

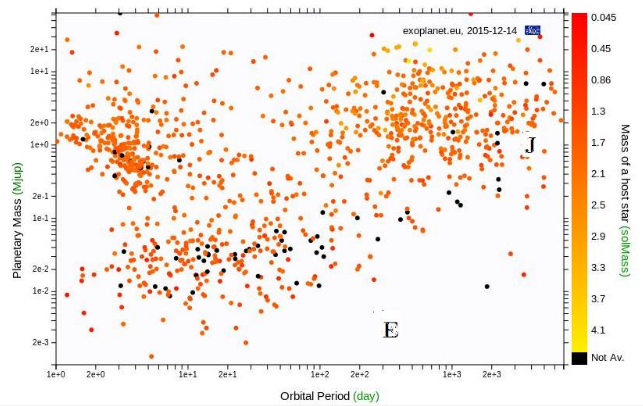


[a] smsc.cnes.fr/COROT and www.esa.int/esaMI/COROT/index.htm
[b] kepler.nasa.gov

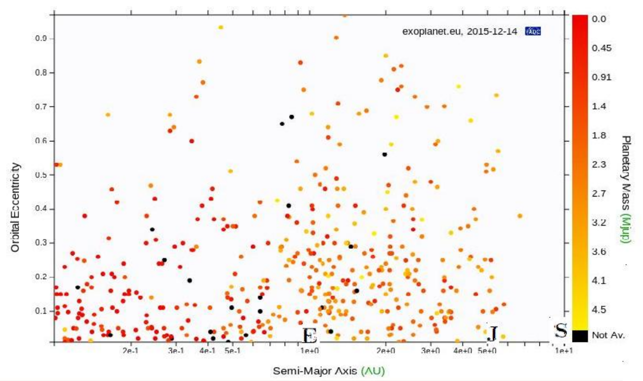
Exoplanets: Results of searches

The following applies to December 14, 2015.

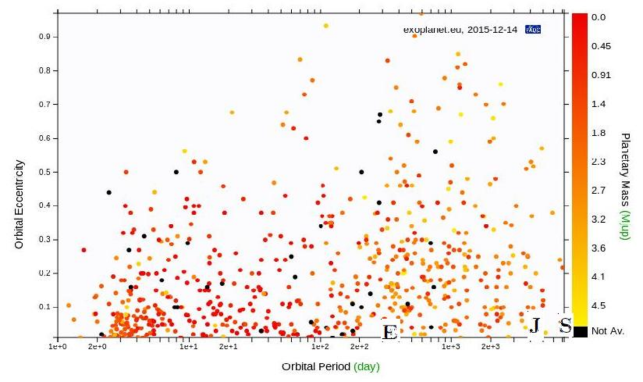
- In exoplanet.eu and exoplanet.org there are 2030 exoplanets around 1288 stars.
- Of this 803 have measured eccentricities.
- There are 502 multiple planet systems.
- There is a long list of candidates by Kepler that need confirmation.



Orbital period versus planetary mass.
Earth and Jupiter have been added.

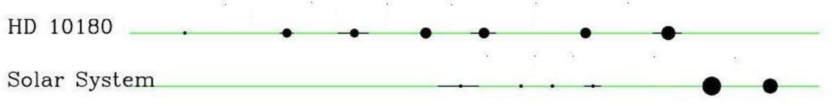


Semi-major axis versus eccentricity.
Earth, Jupiter and Saturn have been added.



Orbital period versus eccentricity.
Earth, Jupiter and Saturn have been added.

Here is a comparison of some systems with large number of planets, compared to the Solar System.



HD10180 ($1.06 M_\odot$, $\sim$8 Gyr, [Fe/H]$\sim$0.1) has 7 known planets.

Kepler-11 ($0.95 M_\odot$, $\sim$7 Gyr, [Fe/H]$\sim$0.0) has 6 known planets.

These systems are still very different from the Solar System.

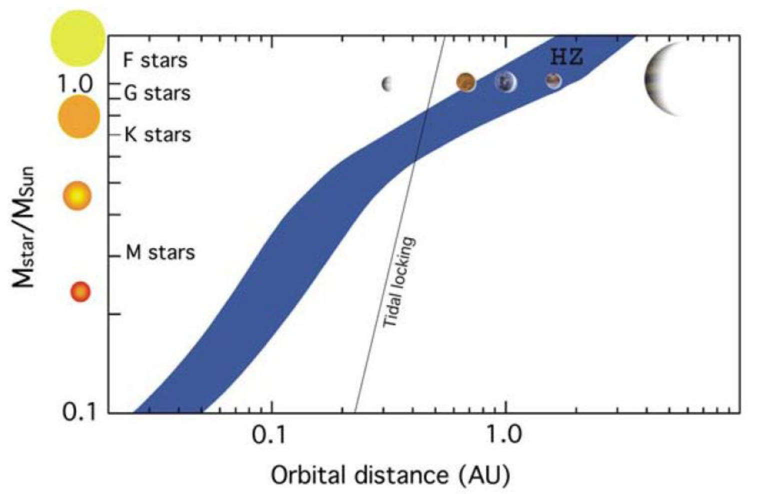
Exoplanets: conclusions

- Many stars have exoplanets.
- Often these systems contain large planets close to the star.
- The orbits are generally very eccentric.

Rare Earth

Habitable Zones

- The Habitable Zone (HZ) around a star is the range in radius over which liquid water can be present on a terrestrial planet.
- At the inner edge of the HZ runaway greenhouse effects will vaporize the water reservoir.
- At the outer edge greenhouse effects are unable to to keep the surface above freezing temperature.
- In the Solar System, Venus ($\sim M_\oplus$; mass of Earth) is just out of the HZ. Mars is within the HZ, but its mass ($\sim 0.1 M_\oplus$) is too low to hold on to the water.
- Tidal locking: tidal forces keep the same side turned to the star, so uneven temperatures .


F stars
G stars
K stars
M stars
1.0
0.1
Mstar/MSun
HZ
Tidal locking
0.1
1.0
Orbital distance (AU)

- The star has to have a sufficiently long life-time.
- The relevant phase is the hydrogen-burning phase that astronomers call Main Sequence stage.
- For the Sun this stage lasts of order 10 Gyr. For a star of 1.5 $M_\odot$ this is 3.5 Gyr.
- We then have to exclude stars more massive than about 1.5 $M_\odot$.
- Red dwarf stars may be too variable (due to starspots).
- We then also have to exclude stars with mass less than 0.5 $M_\odot$ or so.
- Stars in the range (0.5–1.5) $M_\odot$ are called F, G and K-stars.

- If this is true, we are left with some 10% of all stars.
- The Milky Way Galaxy has about a few $\times 10^9$ FGK-stars in its disk.
- Maybe half of these have insufficient amounts of 'metals' and roughly half are younger than the Sun.
- Estimates are that one-third of FGK stars have terrestrial size planets
- This still leaves of order 10^8 suitable stars in the Galaxy.
- We can look in more detail in the immediate Solar Neighborhood.

- For the range (0.5–1.5) $M_{\odot}$ (FGK-stars) we have the following statistics.
- According to RECONS[18] we have within 10 pc (=32.6 ly):

stars	FGK	M	systems	single
369	70	247	256	174

- Among the 100 nearest systems (out to 6.6 pc = 21 ly) there are 8 single FGK stars.
- Of these 8 single stars, 1 G-star (Sun) and 1 K-star (ϵ Eri) are known to have planets.
- So of order 10% of stars are of suitable type and are not part of multiple systems.

[18] Research Consortium on Nearby Stars; www.chara.gsu.edu/RECONS

Timescales[19]

- The Earth is 4.566 ± 0.002 Gyr old.
- For the first 0.5 ± 0.4 Gyr life was impossible.
- Life exists now for $4.0^{+0.4}_{-0.2}$ Gyr.
- Therefore the genesis of life took place $0.1^{+0.5}_{-0.1}$ Gyr after it was possible.
- This extremely rapid appearance of life indicates that it may appear almost immediately as soon as it is possible.
- This suggests that life is present on all suitable planets around stars near the sun and must be abundant.

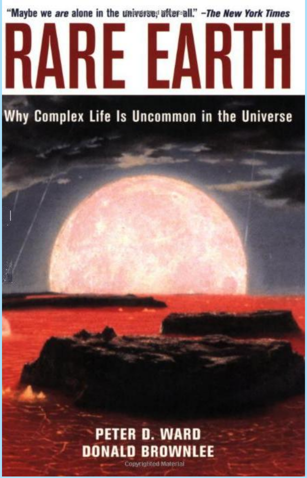
[19] See Lineweaver & Davis: adsabs.harvard.edu/abs/2002AsBio...2..293L

- Land animals (first footprints) are only $\sim$ 500 Myr old; mammals appeared only about 200 Myr ago.
- Intelligent life like ours took on Earth about 4.5 Gyr to emerge.
- The median age of solar type stars in the Solar Neighborhood is 5.4 Gyr, so that more than half the stars are older than the sun.
- These statistics suggest that there are many stars that are old enough to harbor intelligent life, <u>if conditions are suitable</u>.

Habitable zones and timescales: conclusions

- *Habitable planets seem to be possible only around FGK stars in the GHZ. That is only a few percent of all stars, but many have planets in their HZ.*
- *Then there are many stars in the Universe that are potentially suitable to harbor planets with* **some form** *of life on it.*
- *The rapid appearance of life on Earth suggests this is a very common occurrence.*
- *However, complex intelligent life takes very much longer to appear. But the majority of nearby stars is older than the Sun.*

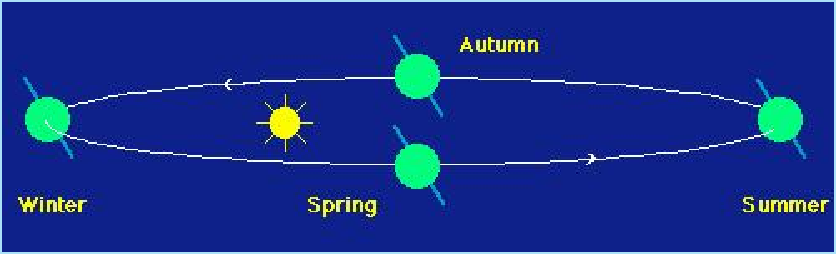
Tides, magnetic field, plate tectonics



- Ward & Brownlee argue in Rare Earth (2000) that it is necessary for intelligent life to form that the planet:
  - has continental drift, tides and a magnetic field, which requires a molten core and liquid H_2O.
  - is shielded from major impacts by asteroids and comets by a giant planet like Jupiter.
  - has a long-term stable climate, which requires a rather large Moon.
- They claim these things rare.
- I will not address the geological issues.

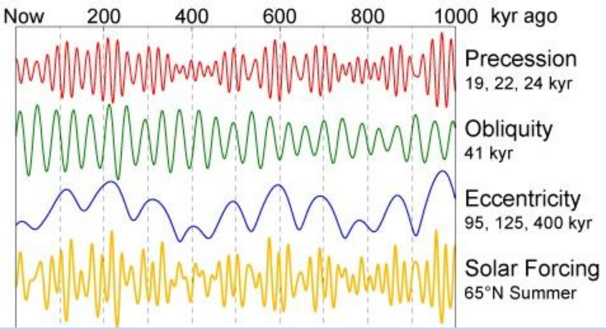
Earth's obliquity, Moon and Milankovitch Cycles

The seasons and the amount of sunlight received (the solar irradiation) depend on the characteristics of the Earth's orbit and orientation.



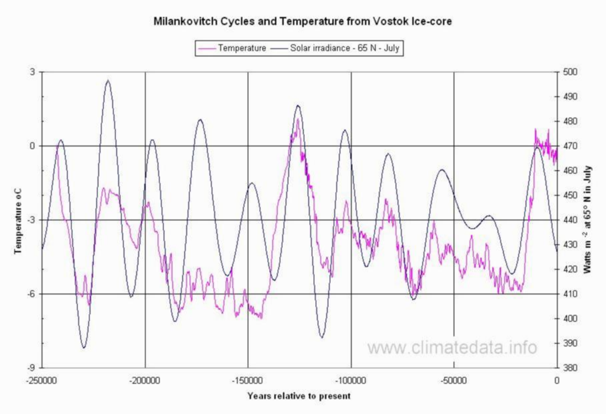
- The Earth moves around the Sun in an elliptical orbit with eccentricity $e = 0.017$ and with the aphelion occurring around January 3.
- The Earth's rotation axis makes an angle with the plane of the orbit (the obliquity) of $\epsilon = 23\overset{\circ}{.}44$.
- In the northern hemisphere the seasons last 89 (winter), 93 (spring), 93 (summer) and 90 days (fall).
- The solar irradiation in aphelion is about 7% larger than at perihelion.
- Most land mass (which reacts most quickly to such changes) at northern latitudes.
- Due to interaction with the Moon and other planets, the Earth's rotation axis precesses, while obliquity ϵ and orbit eccentricity e vary.

- Variations are $e = 0.005$ - 0.058, $\epsilon = 22\overset{\circ}{.}1$ - $24\overset{\circ}{.}5$ and precession has period ∼26,000 years.



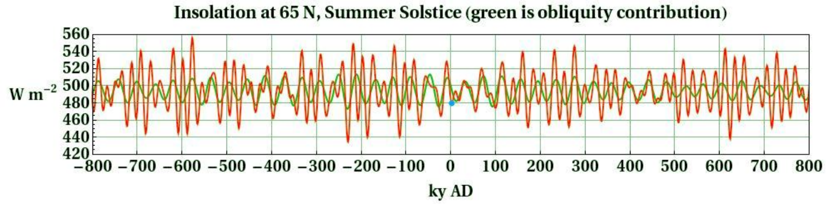
- The 'Milankovitch cycles'[20] force the temperature fluctuations and may be *'pacemakers of the Ice Ages'*.

[20] Milutin Milanković (1879–1958), a Serbian civil engineer and geophysicist.



Small changes in the Earth's orbit produce large effects in temperature.

The variations are relatively slow (order 10^4 yrs).



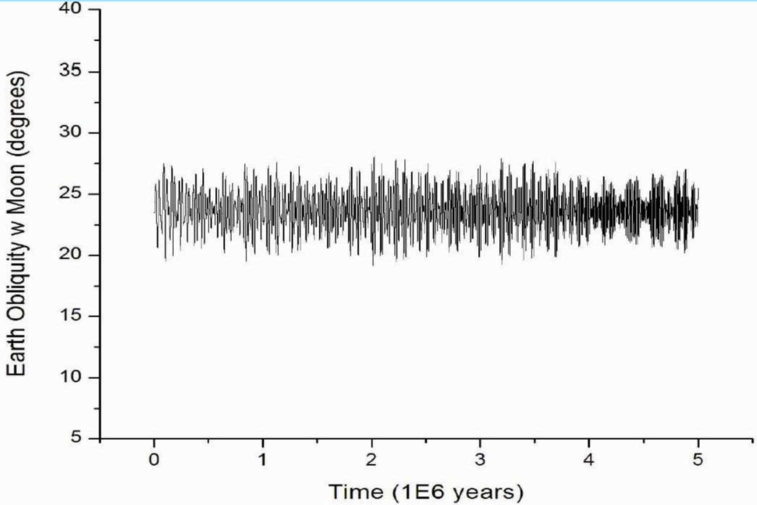
The obliquity of the Earth (green) is an important factor.

However, its variation ($\epsilon = 22\overset{\circ}{.}1$ - $24\overset{\circ}{.}5$) is small as a result of the stabilizing effect of the Moon.

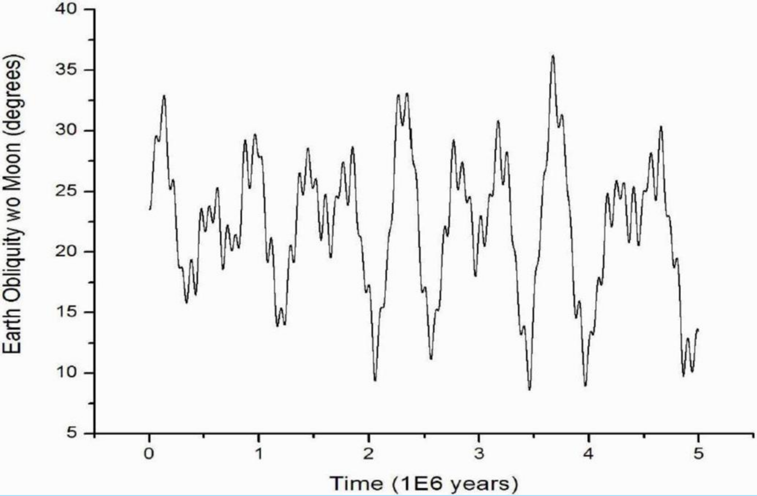
- It has been realized for some time that the presence of a large Moon stabilizes the Earth's rotation axis.
- If there were no Moon the dynamics of the obliquity would be chaotic and it would vary between 0° and 85°[21].
- This can be understood as the result of the larger angular momentum (factor about 3.5) of the Earth-Moon system than that of the Earth rotation alone.
- Here are some recent calculations over the last 5 million years[22].

[21] Laskar *et al.*, adsabs.harvard.edu/abs/1993Natur.361..615L
[22] A.E. Girkin: etd.ohiolink.edu/view.cgi?acc_num=miami1133292203

The variation of the obliquity **with** Moon.



The variation of the obliquity **without** Moon.



So we find:

- Planets are common, but the systems that have been discovered are almost all very different from the Solar System.
- Complex life requires a terrestrial planet in the habitable zone of an FGK-star in the GHZ that is, moderately metal-rich and at least 4 Gyr or so old, and a relatively massive Moon to stabilize its axis.
- There are large numbers of stars that are suitable for life to appear, and many are old enough for evolution into intelligent, technological civilizations as on Earth.
- If Fermi's paradox is correct the latter must occurs very seldomly.

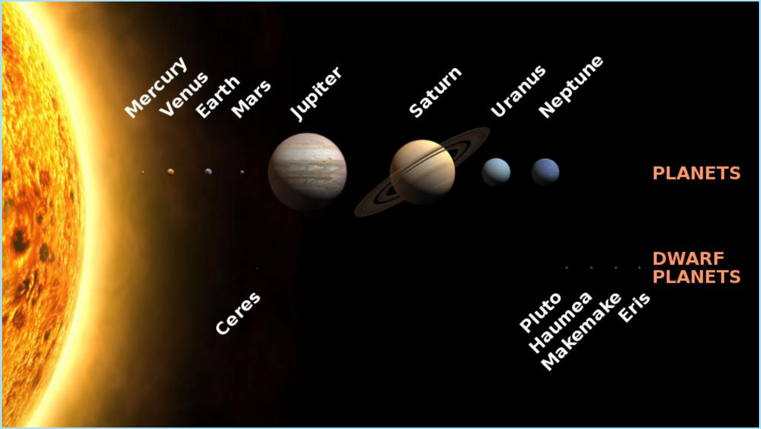
If intelligent life as on Earth is so rare, what then is so special about the Solar System?

Is the Solar System unique?

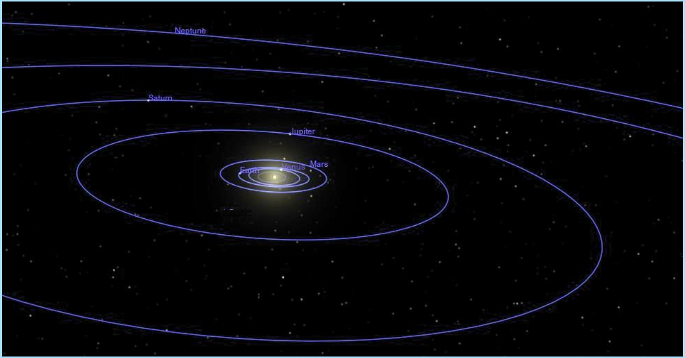
Characteristics of the Solar System

- The Solar System consists of eight planets.
  - The inner or terrestrial planets are small and rocky and consists mainly of metals and silicates.
  - The outer of Jovian planets are large and mostly gaseous (CH_4, NH_3, etc.), but are believed to have solid cores.
- The move around the Sun in elliptical, but nearly circular, nearly co-planar orbits, all going in the same direction.

This figure show their relative sizes.

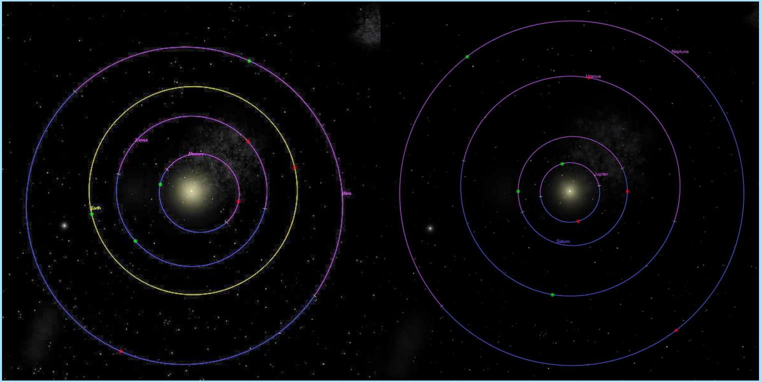


Here we see the orbits on relative scales.



Between Mars and Jupiter we find the asteroid belt with Ceres the largest.

Left the inner and right the outer planets.



Except maybe Mercury and Mars the orbits are not very eccentric.

- The Planetary System appears simple to describe. It consists of a point mass (Sun), with eight much smaller masses moving around it in nearly circular, nearly co-planar orbits.
- These orbits obey Kepler's laws and this is well understood in terms of Newton's laws of gravity.
- But there are gravitational interactions between the planets (ignoring all other bodies as comets, asteroids, etc.).
- Can this be stable over Gyrs? Say for order 10^9–10^{10} orbits?
- Many physicists (Newton, etc.) wondered about this. In particular Laplace and Lagrange thought they proved this to be the case.
- But is this also found in numerical experiments?

Resonances, stability and chaos

An old empirical 'law' is that of Titius-Bode (eighteenth century) for the semi-major axes:

$$a = 0.4 + 0.3 \times 2^m$$

for

$$m = -\infty, 0, 1, 2, ..., 6.$$

Planet	$a_{\rm real}$	$a_{\rm T-B}$
Mercury	0.39	0.4
Venus	0.72	0.7
Earth	1.00	1.0
Mars	1.52	1.6
Ceres	2.77	2.8
Jupiter	5.20	5.2
Saturn	9.54	10.0
Uranus	19.2	19.6
Neptune	30.1	38.8

- So, there is regularity in the sizes of the orbits.
- It is also a regularity in terms of the periods of the orbits through Kepler's third or harmonious law:

$$\frac{a^3}{T^2} = \frac{GM_\odot}{4\pi^2}.$$

- The ratios of subsequent planetary periods can be expressed in terms of a ratio of small integers and thus translate into resonances between these periods.

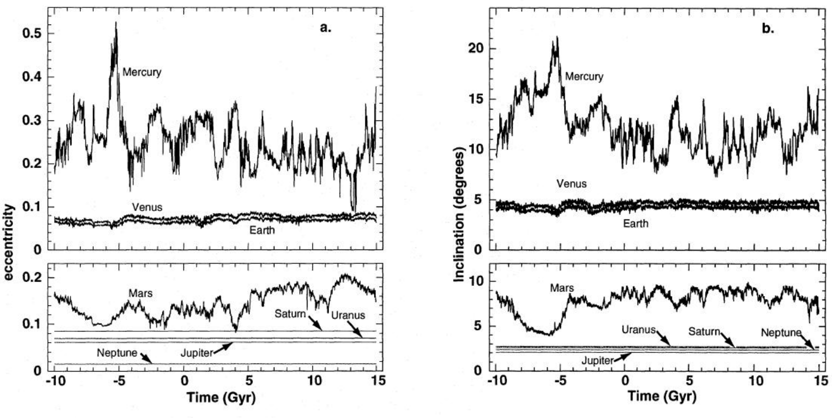
We have almost precise 'Mean Motion Resonances' (MMR):

Mercury – Venus	0.40	2 : 5
Venus – Earth	0.62	3 : 5
(Earth – Mars)	0.53	1 : 2
(Mars – Ceres)	0.41	2 : 5
Ceres – Jupiter	0.39	2 : 5
Mars – Jupiter	0.16	4 : 25
Jupiter – Saturn	0.40	2 : 5
Saturn – Uranus	0.35	1 : 3
Jupiter – Uranus	0.14	1 : 7
Uranus – Neptune	0.51	1 : 2

- Such Mean Motion Resonances are very common.
- E.g. de Sitter's model for the Galilean satellites of Jupiter was built on a basic model with 1 : 2 : 4 resonance between the orbits of the inner three.
- Resonances occur due to cyclic recurrence of mutual gravitational disturbances of the orbits.
- This 'locks' the planets in these resonant orbits.
- They also work in strongly elliptical orbits, but only when the directions of perihelia are very different.
- It is thought to provide stability to the Solar System.
- The classical study is the paper *'Large-scale chaos in the Solar System'* in 1994 by Jacques Laskar[23].

[23] adsabs.harvard.edu/abs/1994A%26A...287L...9L

This classical figure from Laskar (1994) shows the maximum values (in 10 Myr intervals) of e and i in a simulation (1 day CPU per Gyr) over 10 Gyr in the past to 15 Gyr into the future.



- The orbits themselves are relatively stable, but the motions are chaotic in the sense that positions of planets quickly become unpredictable.
- This is expressed by the Lyapunov time, which is the timescale of exponential growth of deviations.[24]
- If we change an initial position by $\Delta x_\circ$ and this gives rise to a change $\Delta x_{\rm t}$ after time t such that $\Delta x_{\rm t} \sim \exp{(\lambda/t)}\Delta x_\circ$, then the Lyapunov time is $1/\lambda$.
- The Lyapunov times of the planets range from a few to a few hundred Myrs.

[24] *Laskar: A shift of 150 m of the Earth's position 500 Myrs in the future corresponds to a change in the initial position of less than a Planck length ($l_J = \sqrt{\hbar G/c^3} = 1.6 \times 10^{-35}$ m), i.e. 38 orders of magnitude.*

Stability of Solar System: conclusion

- *The Solar System is chaotic with Lyapunov times between a few to some hundreds of Myrs, but the planetary orbits themselves are rather stable over very long timescales, up to Gyrs.*

Uniqueness of Solar System: conclusions

- An Earth-Moon system is exceptional, but with slow precession like in our case is extremely rare.
- Our Solar System appears to have an architecture that is the exception rather than the rule.
- The existence of giant planets like Jupiter and Saturn in almost circular orbits, locked in Mean Motion Resonance provides a Solar System that is stable over Gigayears.
- Milankovich cycles in our Solar System are exceptionally slow due to the precise location of the planets.

Conclusions

- *Fermi's paradox suggests that intelligent life in the Universe is highly exceptional.*
- *The anthropic principle is consistent with this.*
- *Planetary systems discovered up till now are almost all very different from the Solar System.*
- *Life as on Earth is probably possible only around stars with a mass between 0.5 and 1.5 times that of the Sun, a metallicity similar to of the Sun, an age of billions of years and at moderate distances from the Galactic Center.*
- *There are probably many Earth-like planets in Habitable Zones around such stars, although many on exccentric orbits.*
- *Primitive life may then be abundant in the Universe.*

- *Complex and intelligent life may require stable conditions over long timescales and the Solar System is exceptional in providing that.*
- *The Solar System is unusual in providing long-term stable orbits, resulting from by the presence of a few giant planets in almost circular orbits, locked in orbital resonances.*
- *The long-term stability of the Earth's climate derives from the presence of the Moon.*
- *The stable conditions on Earth for possible evolution towards complex life requires unusually slow Milankovitch cycles, which derive from both the precise properties of the Earth-Moon system and the detailed architecture Solar System.*
- *The chance of success of SETI will be extremely small, but it remains important to pursue it.*

Thank you for your attention

Deze presentatie zal enige tijd beschikbaar zijn als ‘blinde link’ op

www.astro.rug.nl/∼vdkruit/SETI@Assen.pdf,

en een meer gedetailleerde versie met literatuurverwijzingen op

www.astro.rug.nl/∼vdkruit/jea3/homepage/KNG_SETI.pdf

Zie ook mijn boekbespreking in de ‘Academische Boekengids’: *‘Dan zouden we het toch gehoord hebben’* op

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