INTELLIGENT LIFE IN THE UNIVERSE

Crowded Skies, Lonely Planet or Rare Earth?

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INTELLIGENT LEVEN IN HET HEELAL

Bevolkte hemel of zeldzame aarde?

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This presentation is available on

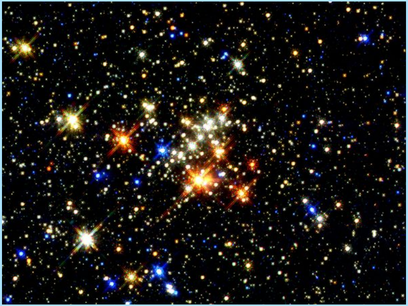
www.astro.rug.nl/∼vdkruit/jea3/homepage/KNG_SETI.pdf

At the end there is a list of 'suggestions for further reading'.

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.
- *"For all those who have thought the hard question a better companion than the easy answer, and the road better than the inn."*[1]

[1] Dedication in *'The Dawn of Life'* by J.H. Rush (1957).

- Maybe there are indeed 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.
- **Is intelligent life exceptional or abundant in the Universe?**
- Arthur C. Clarke (1917–2008):
  'Sometimes I think we're alone; sometimes I think we're not. In either case, the thought is staggering.'

- On two previous occasions I discussed the matter of intelligent life in the universe and the Cosmological Anthropic Principle (see later):
  My inaugural lecture 'Welke ster is nu de mijne'[2] and my J.H. van Oosbree-lecture 'Oorsprong'[3].
- I used to devote the final lecture of my course Sterrenkunde I for first-year students to this, until the 'herprogrammering'.
- Recently wrote a book review 'Dan zouden we het toch gehoord hebben' for the Dutch periodical *Academische Boekengids*.[4]
- I have an old interest in studies of the longterm stability of the Planetary System (lectures on 'Hemelmechanica' by Henk van de Hulst).

[2] www.astro.rug.nl/∼vdkruit/jea3/homepage/oratie.pdf
[3] www.astro.rug.nl/∼vdkruit/#J.H. van Oosbreelezing
[4] www.astro.rug.nl/∼vdkruit/jea3/homepage/SETIXL.pdf

History of SETI

- Speculations on the plurality of worlds go back to ancient times; e.g. Plutarch.
- The church has declared this idea at times heretical.
- Giordano Bruno was burned on the stake in 1600, among others for promoting the view of a universe full of inhabited planets.
- Kepler (1571–1630) in 'Conversations with the Starry Messenger' after having learned of Galilei's discovery of the moons of Jupiter:
  "Our Moon exists for us on Earth, not for the other globes. Those four little moons exist for Jupiter, not for us. Each planet in turn, together with its occupants, is served by its own satellites. From this line of reasoning we deduce with the highest degree of probability that Jupiter is inhabited."

- Later Kepler wrote a book 'Somnium' and described what the Earth would look like from the Moon.
- Late nineteenth and early twentieth century early radio technology was used to attempt listening to extraterrestrials, e.g. by Tesla and Marconi.
- The first serious publication was by Guiseppe Cocconi & Philip Morrison in a paper in *Nature* in 1959[5].
- They proposed to use the frequency of the 21-cm neutral hydrogen line as the most natural one.

[5] www.coseti.org/morris_0.htm

SEARCHING FOR INTERSTELLAR COMMUNICATIONS

By GIUSEPPE COCCONI* and PHILIP MORRISON†
Cornell University, Ithaca, New York

NO theories yet exist which enable a reliable estimate of the probabilities of (1) planet formation; (2) origin of life; (3) evolution of societies possessing advanced scientific capabilities. In the absence of such theories, our environment suggests that stars of the main sequence with a lifetime of many billions of years can possess planets, that of a small set of such planets two (Earth and very probably Mars) support life, that life on one such planet includes a society recently capable of considerable scientific investigation. The lifetime of such societies is not known; but it seems unwarranted to deny that among such societies some might maintain themselves for times very long compared to the time of human history, perhaps for times comparable with geological time. It follows, then, that near some star rather like the Sun there are civilizations with scientific interests and with technical possibilities much greater than those now available to us.

To the beings of such a society, our Sun must appear as a likely site for the evolution of a new society. It is highly probable that for a long time they will have been expecting the development of science near the Sun. We shall assume that long ago they established a channel of communication that would one day become known to us, and that they look forward patiently to the answering signals from the Sun which would make known to them that a new society has entered the community of intelligence. What sort of a channel would it be?

The Optimum Channel

Interstellar communication across the galactic plasma without dispersion in direction and flight-time is practical, so far as we know, only with electromagnetic waves.

Since the object of those who operate the source is to find a newly evolved society, we may presume that the channel used will be one that places a minimum burden of frequency and angular discrimi-

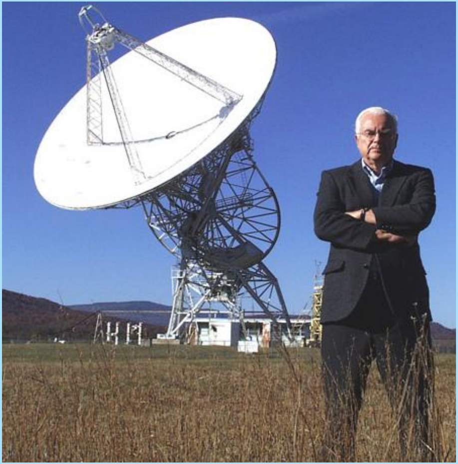
* Now on leave at CERN, Geneva.

† Now on leave at the Imperial College of Science and Technology, London, S.W.7.

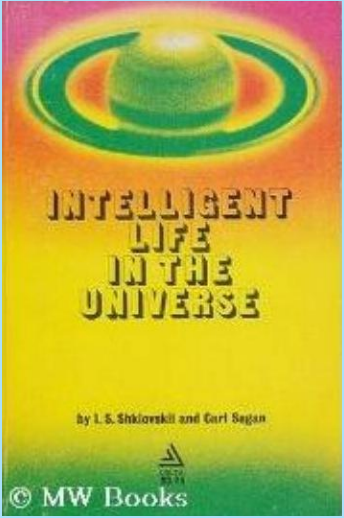
No. 4690 September 19, 1959 NATURE

Project OZMA[6]

- In 1960, Frank Drake used the 85-ft radiotelescope at Green Bank (W-Virginia) to study two nearby stars similar to the Sun (τ Tauri and ϵ Eridani).
- He found nothing (but a signal from military air traffic).

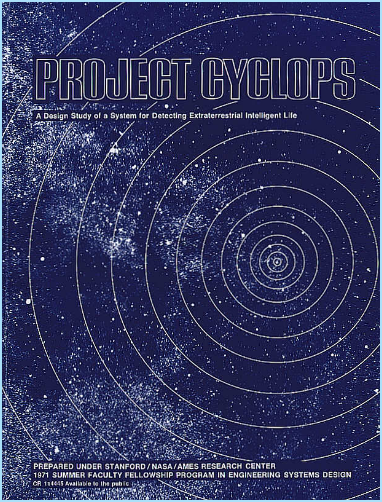


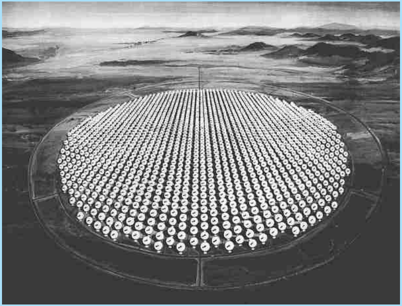
[6] www.bigear.org/vol1no1/ozma.htm

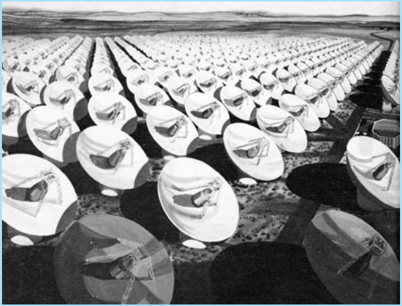


- In 1962 Iosif S. Shklovsky published a book in Russian.
- In 1966 he & Carl Sagan published a much more extended English version.
- It has drawn very much attention and started the discussion among a broad audience.
- There have been many reprints (the one shown here is the version I own from the seventies).

- The Project Cyclops of 1971 was a NASA-funded feasibility study.
- It envisioned an array of 1000–1500 100-meter radio telescopes to search for radio signals of intelligent life comparable to ours at distances of up to 1000 light-years.





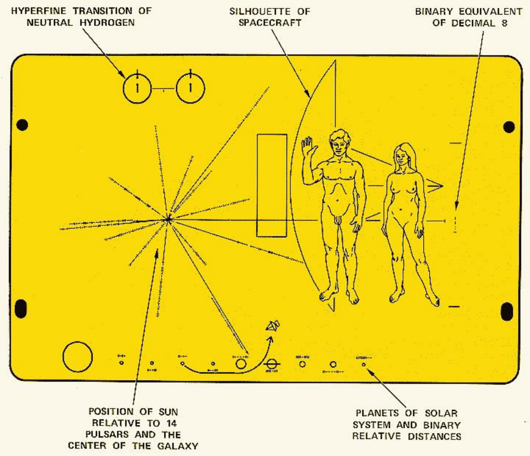


It would have cost billions of dollars, but that was comparable to what the Apollo program to the Moon had cost.[7]

[7] For a full electronic copy of the report see ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19730010095_1973010095.pdf

he Pioneer 10 (1972)and Pioneer 11 (1973) spacecrafts, that visited Jupiter (and P11 Saturn) and then left the Solar System, were outfitted with a plaque holding a message about us.

It was designed by Carl Sagan, who shows it here.


HYPERFINE TRANSITION OF NEUTRAL HYDROGEN
SILHOUETTE OF SPACECRAFT
BINARY EQUIVALENT OF DECIMAL 8
POSITION OF SUN RELATIVE TO 14 PULSARS AND THE CENTER OF THE GALAXY
PLANETS OF SOLAR SYSTEM AND BINARY RELATIVE DISTANCES

The 300-m Arecibo radio telescope on Puerto Rico was used on 16 November 1974 to send a message to the globular cluster M13, some 25,000 lightyears away.

The message consisted of 1679 binary digits at 2380 MHz and modulated by shifting the frequency by 10 Hz, with a power of 1000 kW.

The total broadcast was less than three minutes.

The Arecibo Message

The message sent in 1974 from the Arecibo radio telescope toward the globular cluster M13 consisted of 1679 "bits" of information. A "0" is represented by an "off" radio pulse, while a "1" is represented by an "on" radio pulse.

00000010101010000000000000000101000001010000000100100010001000100
10110010101010101010101001001000000000000000000000000000000000000
00000110000000000000000000011010000000000000000000001101000000000
00000000001010100000000000000000000011111000000000000000000000000
0000000001100001110001100001100010000000000000001100100001101000
011000110000110101111101111110111111011111100000000000000000000000
00000100000000000000000001000000000000000000000000000000010000000
00000000011111100000000000000011111000000000000000000000000011000
011000011100011000100000001000000000100001101000011000111001
01011111011111101111110111110000000000000000000000000001000000011
000000000100000000000000110000000000000000001000001100000000000011111
100000110000000111111000000000000110000000000000001000000000100000000
010000001000000110000000010000000011000011000000010000000000011000
10000110000000000000000001100110000000000000011000100001100000000
0110000110000000100000000100000001000000000100000010000000011000000
001000100000000011000000000100010000000000100000000100000010000000
100000001000000010000000000000011000000000011000000000110000000000
100011101011000000000000001000000010000000000000000010000001111110000
000000001000010111010010110110000000100111001001111111101110000
11100000110111000000000010100000111011001000000010100000111110
01000000010100000110000000100000110110000000000000000000000000000
00000000011100000100000000000000001110101000101010101010011100
000000101010100000000000000000010100000000000000000111110000000000
00000011111111100000000000000011100000000111000000000110000000000
0110000000110100000000000101100000110011000000000110011000010001
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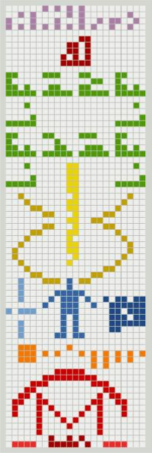
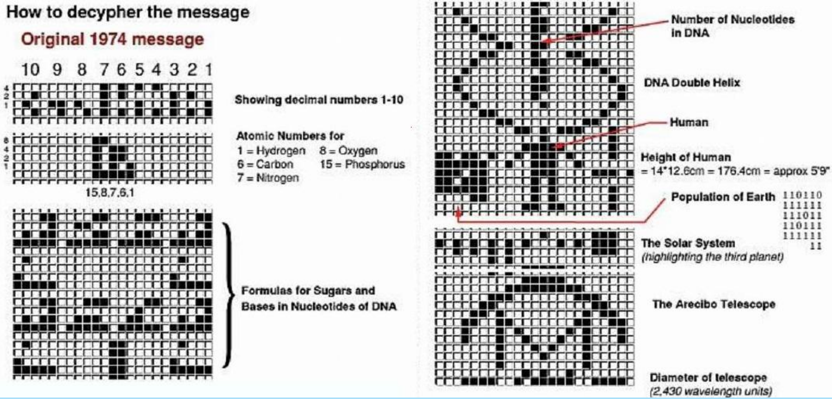


The number 1679 was chosen because it is a semiprime (the product of two prime numbers) and it can be arranged in a rectangle of 73 rows and 23 columns.

It then produces a 'meaningful' image. The alternative arrangement (23 rows by 73 columns) produces nonsense.

This is called Active SETI of METI (Messaging ETIs).


How to decypher the message
Original 1974 message
10 9 8 7 6 5 4 3 2 1
Showing decimal numbers 1-10
15,8,7,6,1
Atomic Numbers for
1 = Hydrogen 8 = Oxygen
6 = Carbon 15 = Phosphorus
7 = Nitrogen
Formulas for Sugars and
Bases in Nucleotides of DNA
Number of Nucleotides
in DNA
DNA Double Helix
Human
Height of Human
= 14*12.6cm = 176.4cm = approx 5'9"
Population of Earth
The Solar System
(highlighting the third planet)
The Arecibo Telescope
Diameter of telescope
(2,430 wavelength units)

- During the seventies and eighties NASA funded a few more dedicated workshops and some 'piggy-back' research on radio telescopes.
- The first workshop in 1977 was called The Search for Extraterrestrial Intelligence[8] and this was the origin of the acronym SETI.
- NASA support of SETI met increasingly strong opposition in Congress.
- E.g. the research program HRMS (=High Resolution Microwave Survey) (at ~12M$ per year less than 0.1% of NASA's budget) was ridiculed (led by Senator Richard Bryan from Nevada) and canceled in 1993.[9]

[8] history.nasa.gov/SP-419/sp419.htm
[9] history.nasa.gov/garber.pdf

Current situation

SETI INSTITUTE

- Currently the efforts are concentrated in the privately funded SETI Institute[10] 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.

[10] www.seti.org

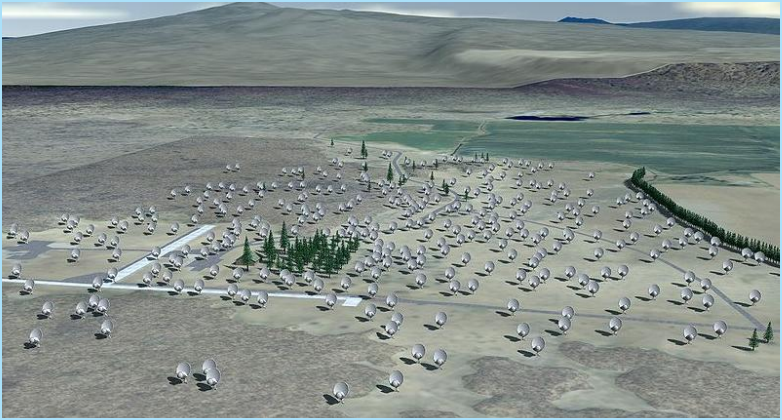
- Seth worked for a number of years in Groningen as a radio astronomer at the Kapteyn Institute.
- He started a computer animation company DIGIMA.
- In 1988 he won the Wubbo Ockels Prize of the city of Groningen.
- He was particularly known for his original use of language and puns[a].

[a] See e.g. Boldly going nowhere, April 2009 in 'The New York Times', www.nytimes.com/2009/04/14/opinion/14shostak.html?_r=1&scp=1&sq=Boldly Going Nowhere&st=cse

- The SETI Institute operates with the University of California at Berkeley, the Allen Array[11] at Hat Creek Observatory in Northern California.
- Currently it has 42 6-meter elements (was closed for a few months earlier this year because of funding problems).

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

- Eventually it should grow to 350 elements.



Data taken with radiotelescopes in SETI programs are being reduced and analyzed by private individuals on their home computers.[12]

Anyone can join. But it takes time and dedication.

For a recent summary of state of affairs see: Korpela *et al.*: *Status of the UC-Berkeley SETI efforts*[13].

[12] setiathome.berkeley.edu
[13] adsabs.harvard.edu/abs/2011SPIE.8152E..27K

SETI Protocols

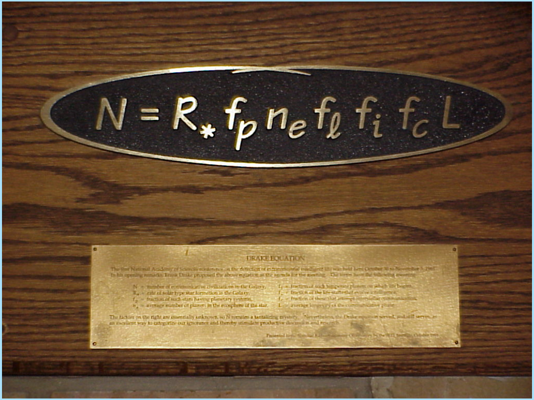
- There has been much discussion of how to respond to the discovery of an ETI.
- How and by whom will it be announced to the general public?
- How will we respond? And who decides on that?
- Will the aliens be benevolent and can they be trusted?
- The SETI Permanent Committee of the International Academy of Astronautics[14] has drawn up a Post-Detection Protocol discussed this.
- It produced a Declaration of Principles, the Proposed SETI Reply Protocols and a Position paper: Sending Communications to Extraterrestrial Civilizations.

[14] www.setileague.org/iaaseti/index.html

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 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.
- The crucial point is this lifetime.
- 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 technological civilizations.[15]
- And even if it does, it may not survive for many millennia.[16]

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[15] See e.g. Jared Diamond: *Guns, Germs, and Steel: The fates of human societies* (1997).

[16] See e.g. Bonnet & Woltjer: *Surviving 1000 Centuries: Can we do it?* (2008).

Drake equation: conclusions

Intelligent life, that SETI searches for[17] is abundant in the universe:

- if most stars have planets suitable for life to occur;
- if life will then 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.

[17] 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[18] (after his fellowship ended).
- Later he became interested in history and an ultra-conservative Republican, and he even proposed racial segregation.

[18] 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."[19]

Although ways out have been suggested (e.g. zoo hypothesis[20]), the implication of the paradox would be that intelligent extraterrestrial life is extremely rare.

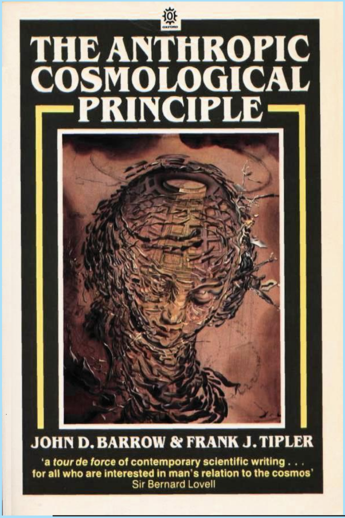
[19] From Wikipedia

[20] 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' ($3\,^4\text{He} \rightarrow {}^{12}\text{C}$) 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[21] 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."*

[21] 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[22]:

$$T_\star \sim \frac{\alpha\hbar}{\alpha_G \beta^2 m_p c^2} \sim 10^{10} \text{ years.}$$

- 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.

[22] Here α is the fine-structure constant, α_G the gravitational coupling constant (defined as $Gm_p^2/\hbar c$), 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.
- Leonard Susskind has written a popular book about this.[23]
- Tipler has gone further and deduced from the anthropic principle that 'extraterrestrial beings do not exist'[24].

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

[24] 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.

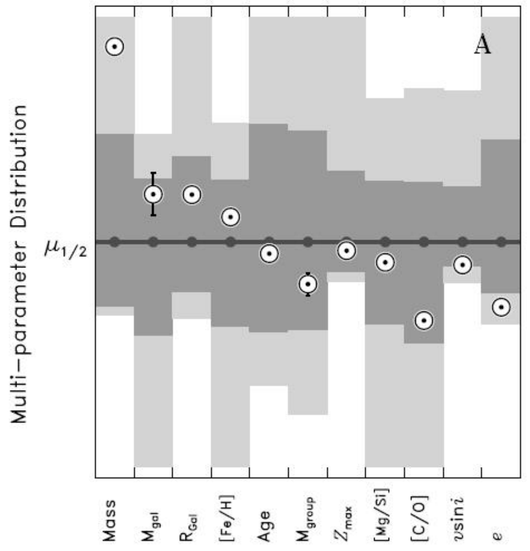
Anthropic principle: implications

- 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.

Is the Sun a typical star?

- One may compare various properties of the Sun (mass, age, chemical composition, galactic orbit) with the common stars in the solar neighborhood.
- There is a study[25] that does this for 11 properties that may in one way or the other be related to the possibility of harboring habitable planets.
- The result is that if we select a star at random only 1 out of 4 will be less typical (in a χ^2-sense) than the Sun.
- There is every reason to regard the Sun as a typical star.

[25] Robles, Lineweaver *et al.*, adsabs.harvard.edu/abs/2008ApJ...684..691R



The figure shows medians, 68 and 95 percentiles (‘1σ’, ‘2σ’).

The Sun is exceptional in two respects:

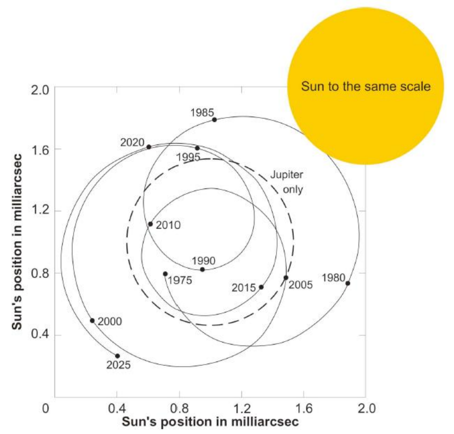
- 95% of the stars are less massive.
- 93% of stars have more excentric orbits in the Galaxy.

Exoplanets: Search methods[26]

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.[27]

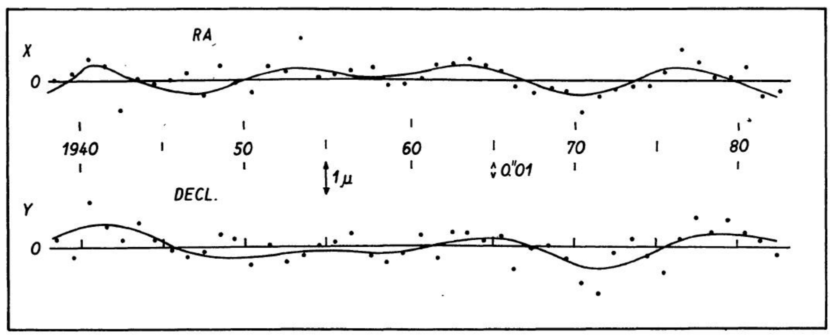
[26] See e.g. Jones, adsabs.harvard.edu/abs/2008IJAsB...7..279J
[27] See www.eso.org/sci/facilities/eelt/science/index.html



- 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.

Of course people were expecting planetary systems like our own.

Peter van de Kamp claimed two planets around Barnard's Star[28].



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

[28]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[29] and masses are 0.5 and 0.7 $M_{\rm Jup}$.
- Barnard's star has metallicity[30] 0.1 times that of the Sun.
- 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.

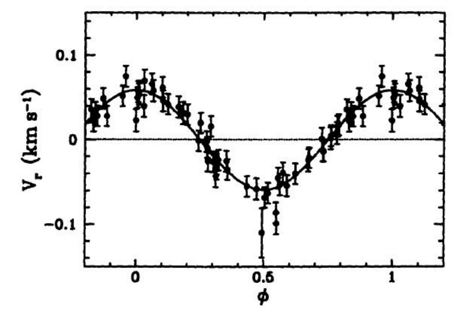
[29] Astronomical Unit = mean distance Earth – Sun
[30] In astronomy 'metals' means all elements heavier than helium

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)[31] instrument of Geneva Observatory on the ESO 3.6-meter La Silla telescope is very prominent.

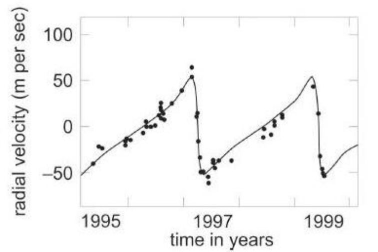
[31] obswww.unige.ch/Instruments/harps

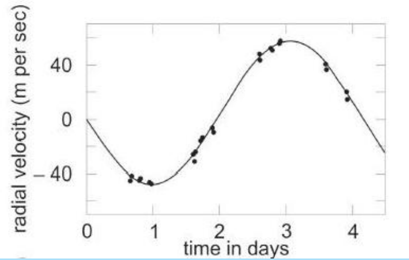
First detection of an exoplanet in 1995.[32]

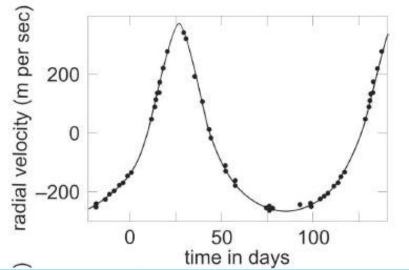


- 51 Pegasi is a solar-type star ($M = 1.06 M_\odot$) at about 50 lightyears.
- It somewhat more metal-rich than the Sun.
- Planet mass is $0.47/\sin i \; M_{\rm Jup}$.
- Roughly circular orbit of 4.23 days and radius about 0.05 AU.
- First example of a 'hot Jupiter'.

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



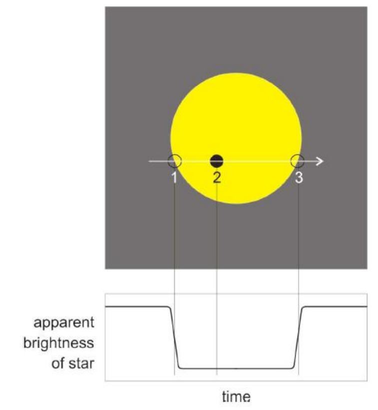




The form can be used to determine the excentricity[a] of the orbit.

[a] Often spelled eccentricity

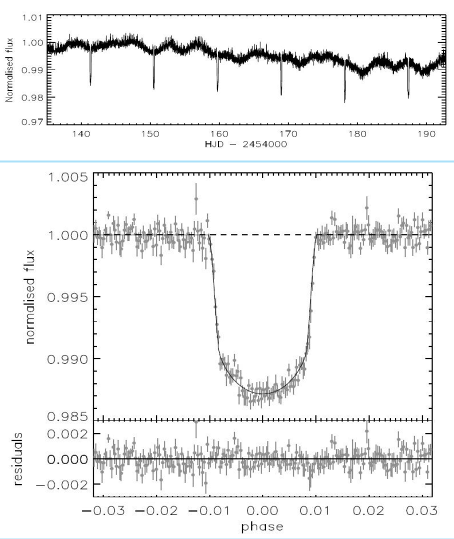
Transits



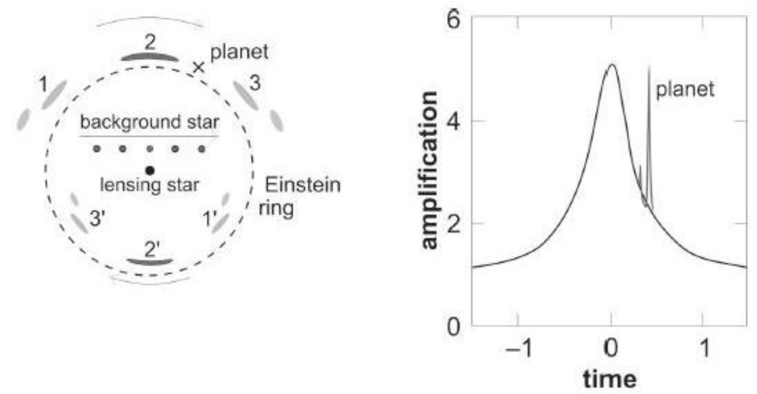
- Transit of Jupiter: Dip of 1.1% for maximum 36.6 hours and repeating every 11.9 years. No more than 0°.05 from plane of orbit.
- Transit of Earth: Dip of 0.0083% for maximum 13.1 hours and repeating every 1.0 years. No more than 0°.25 from plane of orbit.

- 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 $R_{\rm Jup}$, 9.2 days).
- Follow-up is needed to determine excentricity.

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



Gravitational microlensing

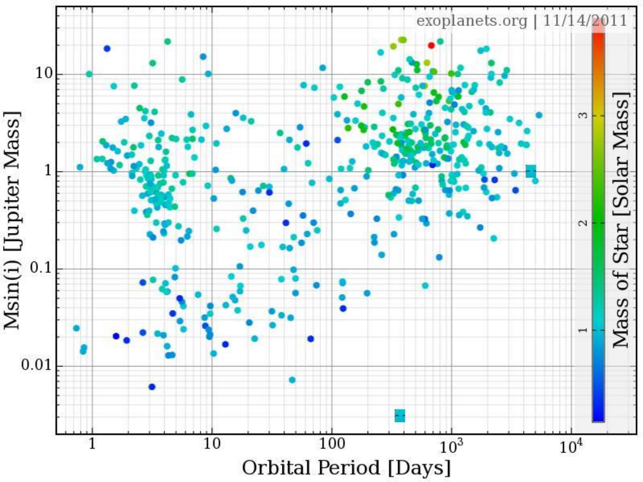


Gravitational lensing amplifies the light when a star+planet move in front of a background star.

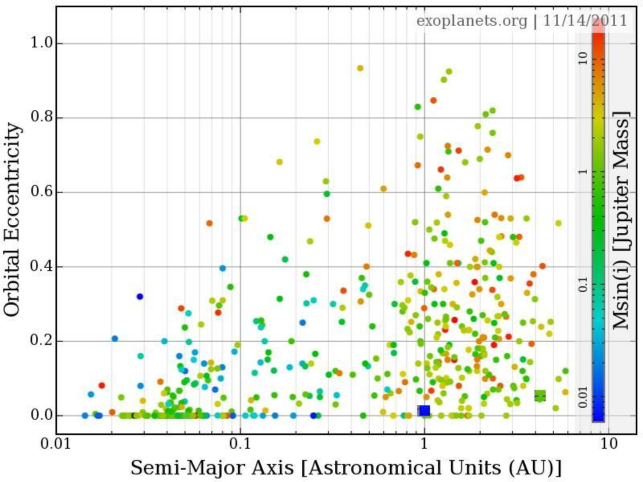
Exoplanets: Results of searches

The following applies to November 14, 2011.

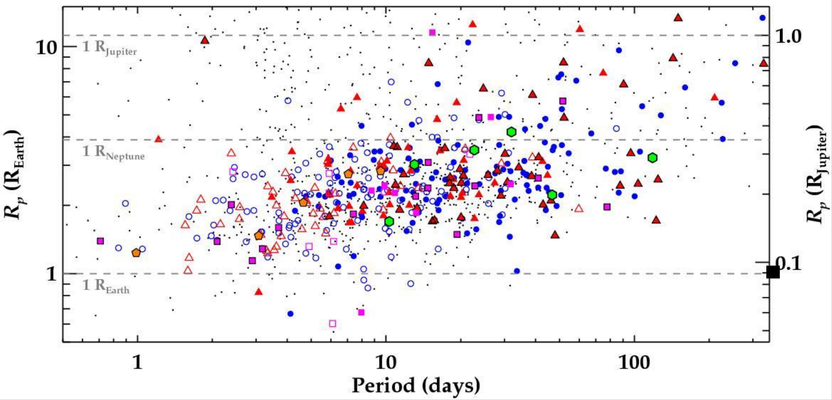
- In exoplanet.eu and exoplanet.org there are 698 exoplanets around 573 stars.
- Of this 614 have measured excentricities.
- There are 82 multiple planet systems.
- There is a long list of candidates by Kepler that need confirmation.



The points for Jupiter and Earth have been added.

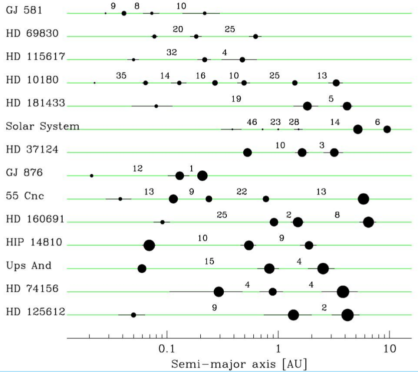


Especially for major axes larger than ∼0.5 AU the distribution of the excentricities is broad.

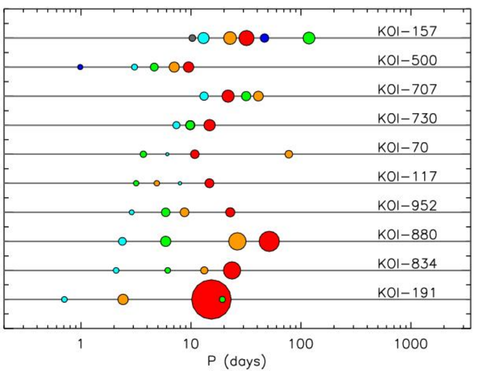


The Kepler mission (launched March 2009) has now 1235 candidate planets (black square is Earth).

Many multiple systems are found.

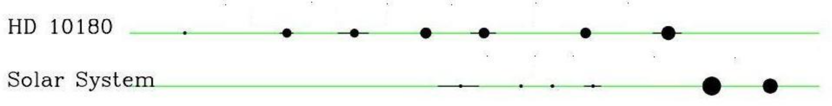


Systems with more than 3 planets from radial velocities.



Systems with 4 to 6 planets from transits.

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



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

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

These systems are still very different from the Solar System.

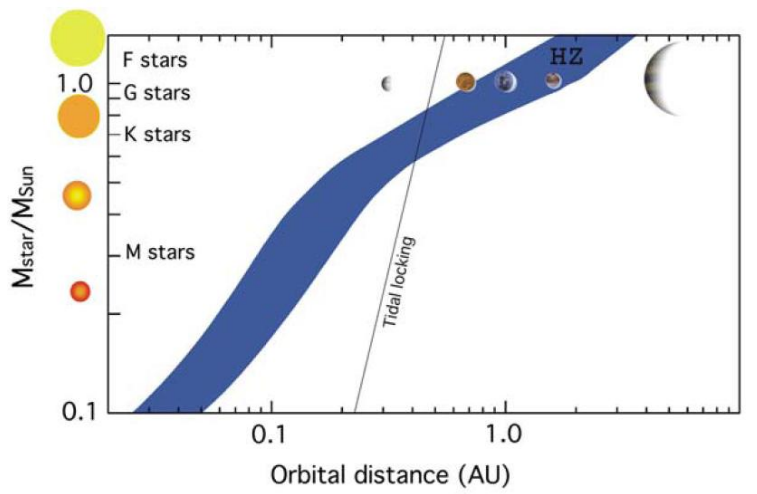
Exoplanets: conclusions

- The Sun is a very typical star, except for its mass.
- Many stars have exoplanets, but we ones we have seen have large planets close to the star and orbits are generally very excentric.

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
HZ
Tidal locking
1.0
0.1
Mstar/MSun
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.
- Latest estimates from HARPS[33] and Kepler[34] 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.

[33] Pepe *et al.*, adsabs.harvard.edu/abs/2011A%26A...534A..58P
[34] Traub, adsabs.harvard.edu/abs/2011arXiv1109.4682T

- For the range (0.5–1.5) $M_\odot$ (FGK-stars) we have the following statistics.
- According to RECONS[35] 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.

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

Timescales[36]

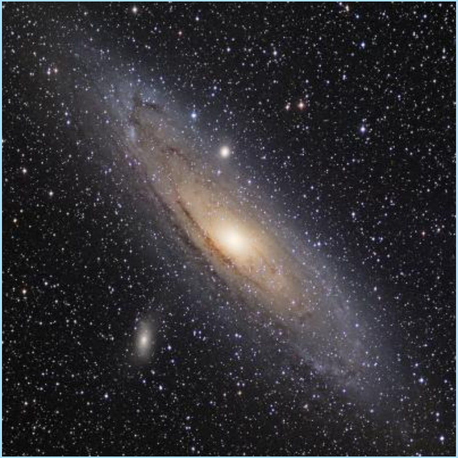
- The Earth is 4.566 ± 0.002 Gyr old.
- For the first 0.5 ± 0.4 Gyr life was impossible.
- Life exists now for $4.0^{+0.4}_{-0.2}$ Gyr.
- Therefore the genesis of life took place $0.1^{+0.5}_{-0.1}$ Gyr after it was possible.
- This extremely rapid appearance of life indicates that it may appear almost 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.

[36] 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 primitive life that there are many stars that are old enough to harbor intelligent life if conditions are suitable.

There are further conditions for the development of life that relate to the properties of the star.

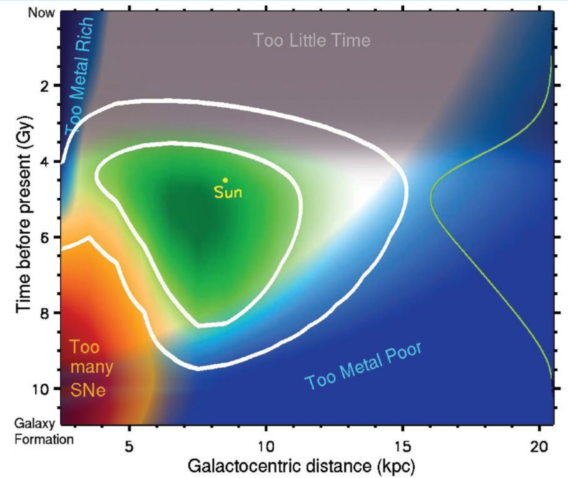
- The star needs to have sufficient chemical elements heavier than helium (metals).
- But also not too metal-rich, otherwise there will be too many 'hot Jupiters', destroying the terrestrial planets.
- This eliminates all stars outside the disk and in the outer region.



The Galactic Habitable Zone

- The Galactic Habitable Zone[37] is derived using a model for the history of star formation and chemical enrichment in the Galaxy.
- Limitations are
  - If too metal-poor then no material available for planet formation.
  - If too metal-rich then too many heavy Jupiters form that may migrate inward.
  - If too many supernovae (SNe) than too close to the Galactic Center, where SNE may destroy life.
  - If too recently formed then no time (4 ± 1 Gyr) for biological evolution.
- Then GHZ between 5 and 10 kpc and 75% of the stars in it are older than the Sun!

[37] Lineweaver, Fenner & Gibson, adsabs.harvard.edu/abs/2004Sci...303...59L

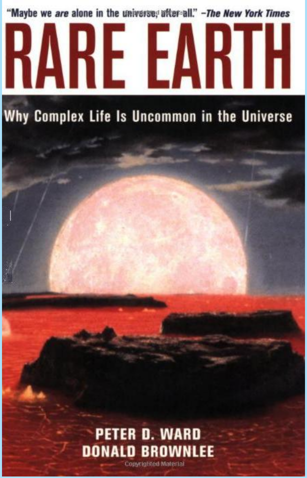


Lines show 68- and 95-percentiles; on the right the age distribution of 'life'.

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.*

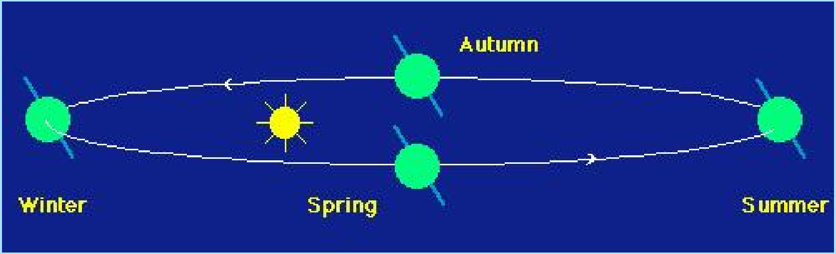
Tides, magnetic field, plate tectonics



- 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.

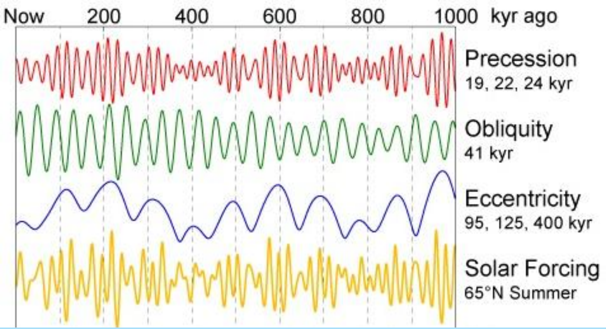
Earth's obliquity, Moon and Milankovitch Cycles

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



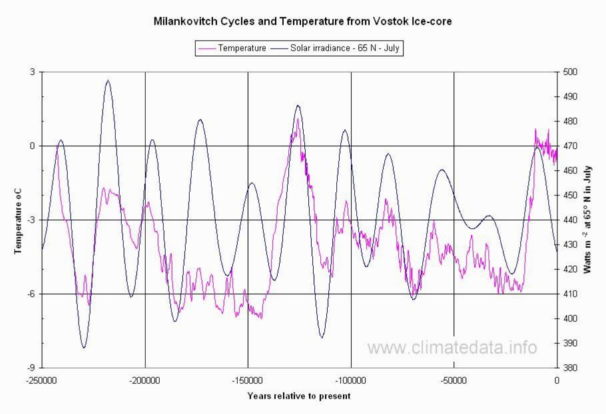
- The Earth moves around the Sun in an elliptical orbit with excentricity $e = 0.017$ and with the aphelion occurring around January 3.
- The Earth's rotation axis makes an angle with the plane of the orbit (the obliquity) of $\epsilon = 23\overset{\circ}{.}44$.
- In the northern hemisphere the seasons 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 excentricity e vary.

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



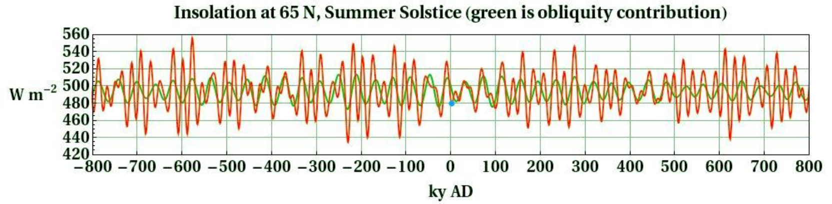
- The 'Milankovitch cycles'[38] force the temperature fluctuations and may be *'pacemakers of the Ice Ages'*.

[38] 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).



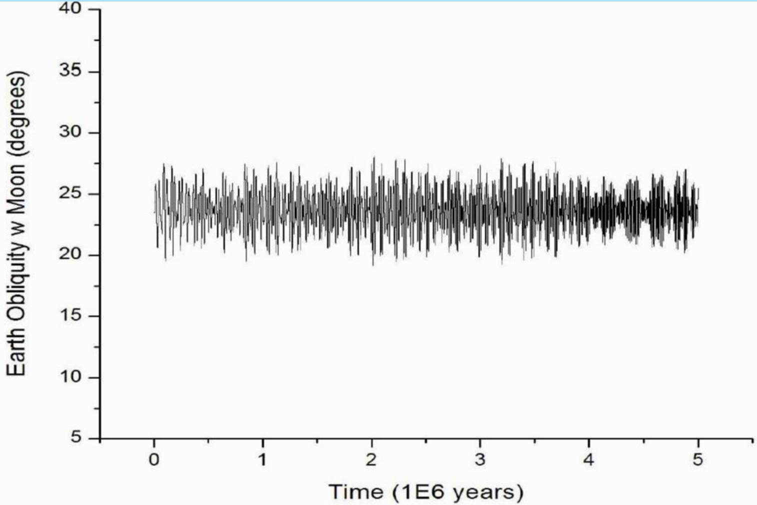
The obliquity of the Earth (green) is an important factor.

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

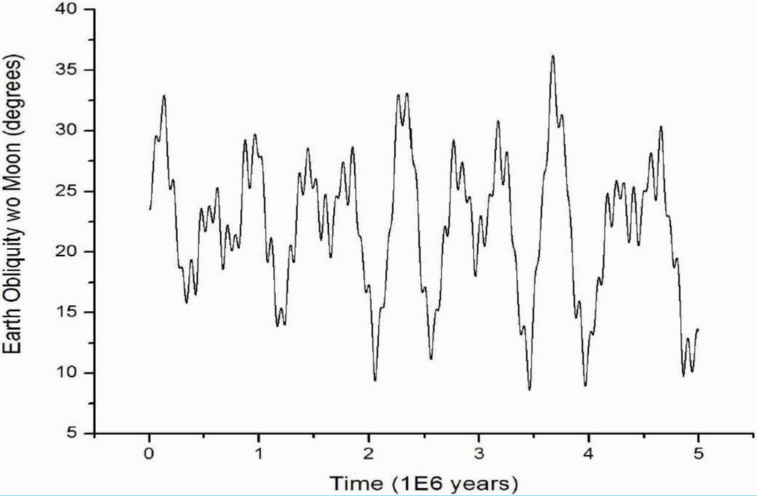
- It has been realized for some time that the presence of a large Moon stabilizes the Earth's rotation axis.
- If there were no Moon the dynamics of the obliquity would be chaotic and it would vary between 0° and 85°[39].
- This can be understood as the result of the larger angular momentum (factor about 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[40].

[39] Laskar *et al.*, adsabs.harvard.edu/abs/1993Natur.361..615L
[40] 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:

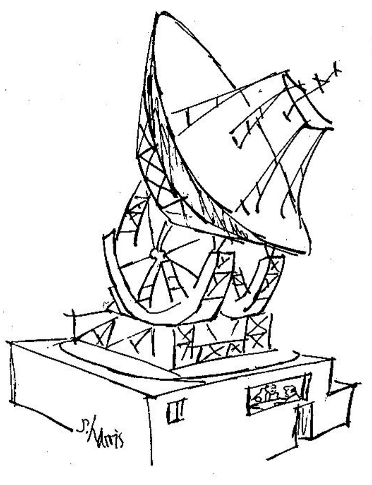
- Planets are common, but the systems that have been discovered are almost all very different from the Solar System.
- Complex life requires a terrestrial planet in the habitable zone of an FGK-star in the GHZ that is, moderately metal-rich and at least 4 Gyr or so old, and a relatively massive Moon 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?

INTERMISSION

This presentation is available on

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



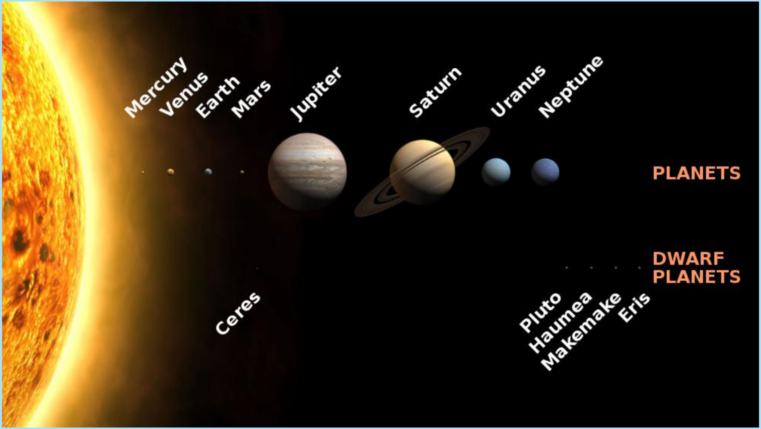
"As I understand it, they want an immediate answer. Only trouble is, the message was sent out 3 million years ago."

Is the Solar System unique?

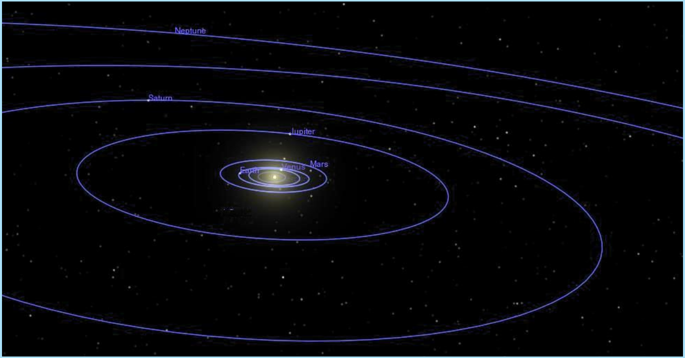
Characteristics of the Solar System

- 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.

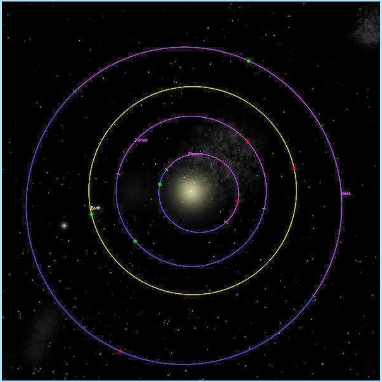


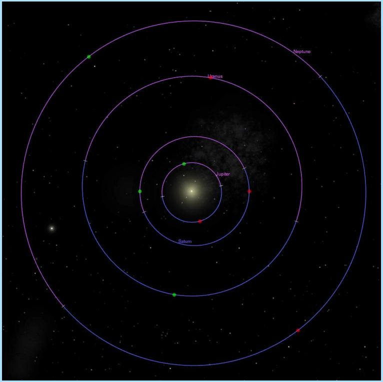
Here we see the orbits on relative scales.



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

Left the inner and right the outer planets.



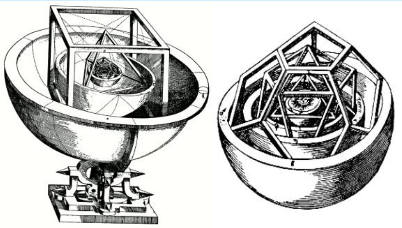


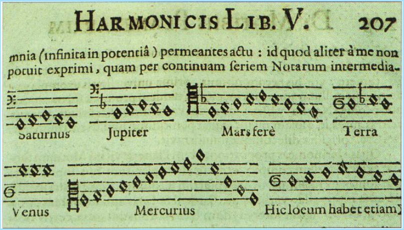
Except maybe Mercury and Mars the orbits are not very excentric.

- 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?

Titius-Bode law, resonances, stability and chaos

- People have for a long time looked for regularity in the distribution of distances of the planets from the Sun.
- Actually Johannes Kepler thought it had to do with the five Platonic solids or Pythagoras' Harmony of the Spheres[41].





[41] In: *Mysterium cosmographicum* (1596), and *Harmonices Mundi* (1619).

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.
- And (by the way) also in mean orbital velocities:

$$V = (2\pi GM_\odot)^{1/3} T^{-1/3}.$$

and this is the basis for Kepler's Harmony of the Spheres in terms of harmonious musical intervals.

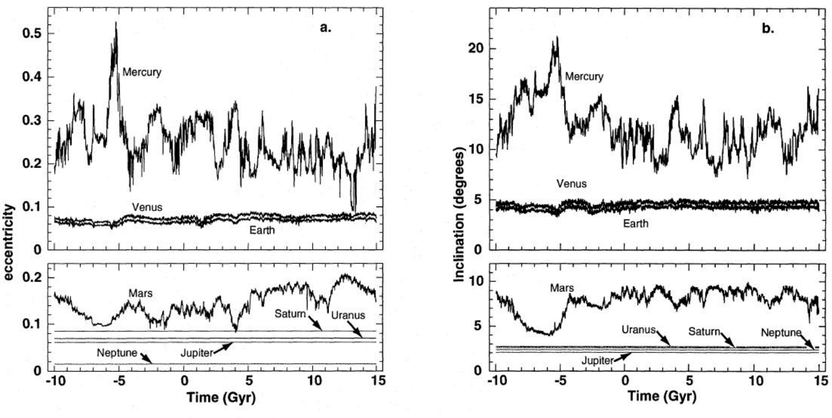
We have almost precise 'Mean Motion Resonances' (MMR):

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[42].

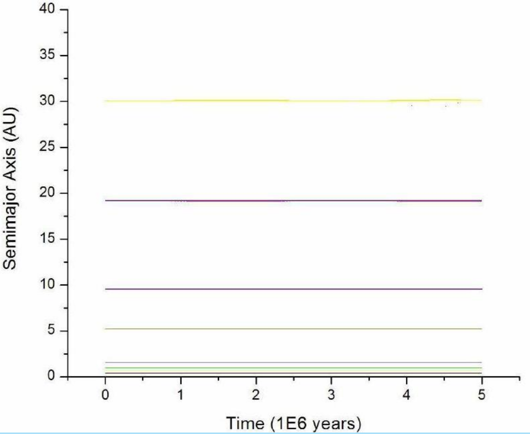
[42] adsabs.harvard.edu/abs/1994A%26A...287L...9L

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.



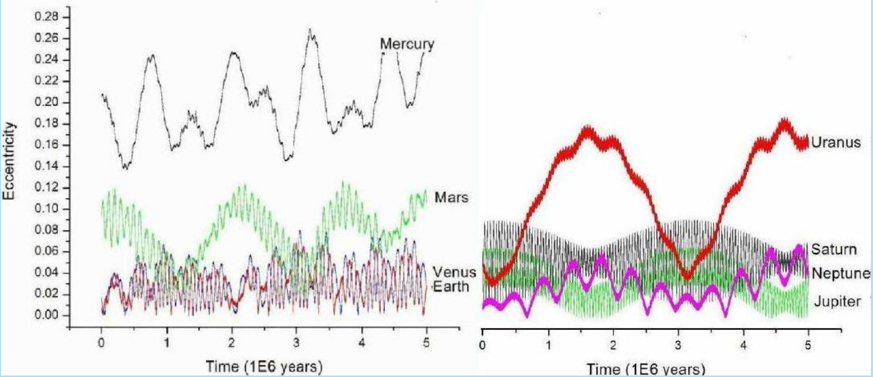
Here is a recent simulation (over 5 Myr) of the time evolution of the orbits of the planets[43].

The semi-major axes do not shown any significant change with time.

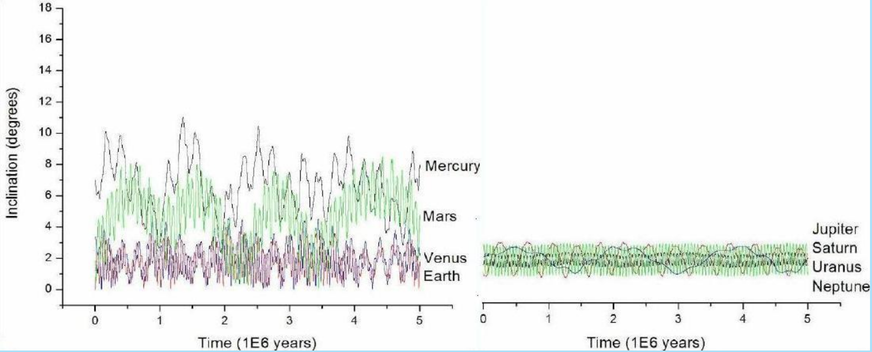


[43]Girkin: etd.ohiolink.edu/view.cgi?acc_num=miami1133292203

Excentricity



Inclination



- 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.[44]
- 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.

[44] *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.*

- Resonances can stabilize orbits, but not necessarily.
- In the Solar System they seem to provide a long-term stability over Gyrs and lock the planets in their orbits.
- The resonances have some width and overlapping resonances[45] make the planetary positions in their orbits chaotic.
- Other resonances, such as between the rotation rates of the perihelia may play a role also.[46]

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[45] E.g., the Venus-Earth resonance (0.62) is between 3:5 (0.60) and 5:8 (0.625).

[46] The perihelia of Mercury and Jupiter both rotate at about 1.5 degrees every 1000 years.

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.*

Planet formation

- Planetary systems like the Solar System form from a proto-planetary disk of gas and dust around the proto-star.
- It contains most of the angular momentum of the system.
- Such disks have been observed around other young stars and are very common.
- Planets form through accretion (giant planets maybe through gravitational instability).
- The inner part of the Solar System was swept of light gases (H_2, He, H_2O, CH_4, etc.) out to the frost line (4–5 AU). What remained was dust grains with metals and silicates.

- When the disk is still massive, a planet will experience unequal torques from the inner and outer parts and will loose angular momentum.
- The planet will then migrate inwards on timescales of order 10^5 years (Type I migration)
- When the planet is massive (compared to the disk density) it will open up a gap in the disk. The disk rotates more slowly because of its pressure.
- Due to the disk's viscosity the gap and planet then drift inwards on timescale of order 10^6 years. (Type II migration)
- Hot Jupiters are believed to be the result of Type II migration.

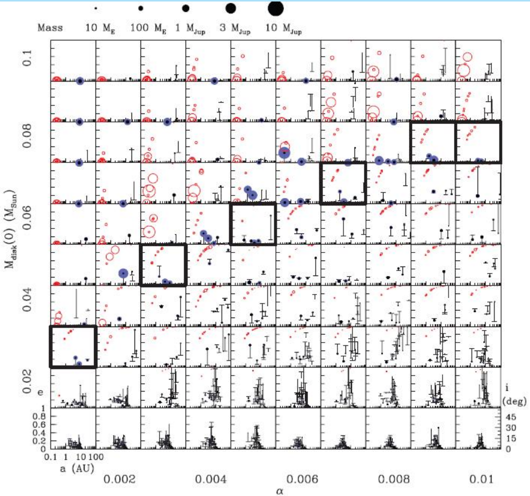
- In the Nice Model the Jovian planets form and leave a dense, massive disk of rocks and icy planetesimals.
- In the late stages Saturn, Uranus and Neptune are moving outward under the influence of Jupiter.
- In this process they scatter this primordial population of icy planetesimals and send some of them inward.
- This explains the Late Heavy Bombardment, as suggested by Lunar craters and the Apollo samples, when the Solar System was 600 – 700 Myrs old.
- It also explains the occurrence of water, carbon and maybe the whole atmosphere on Earth.[47]

[47] Delsemme, adsabs.harvard.edu/abs/2000Icar..146..313D

Uniqueness of the Solar System

- When the disk is more massive, many giant planets form (and migrate).
- When the disk is more viscous it will live longer before the gas is removed (by accretion and/or evaporation).
- So, there is a balance between mass of disk and its viscosity.
- Detailed models of the resulting planetary systems have been performed.[48]
- Planetary systems like our own form only under very special circumstances, when only a few giant planets can form before the disk is removed.

[48] Thommes *et al.*, adsabs.harvard.edu/abs/2008Sci...321..814T

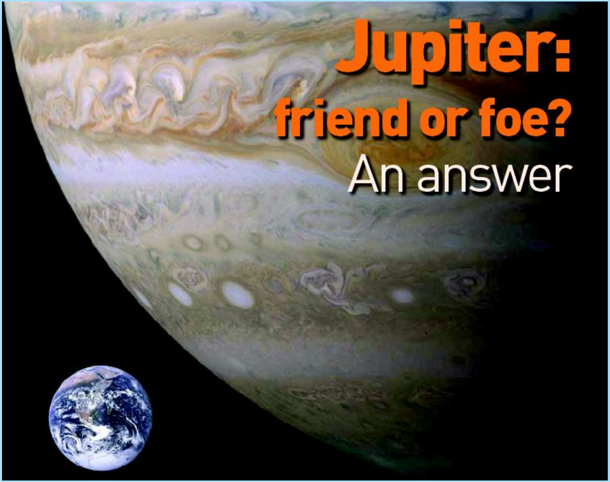


- Viscosity of the disk on the horizontal axis and its mass on the vertical one.
- Top-left: giant planets form early, migrate (red circles) and orbits become very excentric. Lower-right: No gas giants form.
- Only 6 out of 100 simulations produce systems like ours.

Jupiter

- It has long been thought that Jupiter acts as a shield against impacts of minor bodies.[49]
- This can be either comets or asteroids.
- Such impacts would result in overly frequent mass extinctions or even global sterilization.
- The presence of Jupiter would be one of the unusual circumstances in the Rare Earth hypothesis.
- Recent calculations[50] indicate that Jupiter only shields us from long-period comets, but not from asteroids and short-period comets.

[49] Wetherill, adsabs.harvard.edu/abs/1994Ap%26SS.212...23W
[50] Jones & Horner, adsabs.harvard.edu/abs/2010A%26G....51f..16H



So it is likely that Jupiter is not a protecting friend.

Occurrence of Earth-Moon systems

- If the Moon stabilizes the Earth rotation axis, the question arises how common Earth-Moon systems are.
- The Moon was probably formed by a collision of the young Earth with another Mars-size proto-planet.
- This process has been simulated as a function of possible collision parameters.[51]
- This results in roughly one in ten terrestrial planets having a massive moon like Earth.
- So: not common, probably rare, maybe extremely rare.

[51] Elser *et al.*, adsabs.harvard.edu/abs/2011arXiv1105.4616E

Stability and Milankovitch cycles.

- Milankovitch cycles probably should be very minor for complex and intelligent life to develop.
- There is a study[52] that uses simulations to study the probability of slow cycles.
- An important ‘clock’ in the cycles is the precession rate which governs the frequency of the obliquity variations.
- This is calculated using simulations of Earth-Moon systems with different combinations of Moon mass and total angular momentum.
- Out of 20,900 combinations 99.2% have faster precession rates than the Earth’s axis.

[52] Waltham, adsabs.harvard.edu/abs/2011AsBio..11..105W

- Next the architecture of the Solar System is altered by moving the orbit of one planet.
- Then the excentricity changes of the other planetary orbits are calculated.
- For Jupiter and Mars have positions such that the rate of change of excentricities is almost always increasing.
- The probability that this arises by chance is of order 3%.
- Commensurability is studied by putting planets in precise adjacent resonances n/m with n=1–6 and m=2–7.
- Then the mean frequency of excentricity variations of the orbits is calculated using 10,000 simulations.

- The system closest to the actual Solar System is:

TABLE 3. NEAREST APPROXIMATION TO THE SOLAR SYSTEM ASSUMING THAT ORBITAL PERIODS OF ADJACENT PLANETS ARE IN THE EXACT RATIO *N:M* AND THAT NEPTUNE'S LOCATION IS FIXED TO SET THE OVERALL SCALE

Inner planet	*Outer planet*	n	m	a *true* (AU)	a *predicted* (AU)
Mercury	Venus	2	5	0.39	0.36
Venus	Earth	3	5	0.72	0.67
Earth	Mars	1	2	1.00	0.94
Mars	Jupiter	1	6	1.52	1.50
Jupiter	Saturn	2	5	5.20	4.94
Saturn	Uranus	1	3	9.54	9.11
Uranus	Neptune	1	2	19.19	18.94
Neptune				30.07	30.07

- Of the 10,000 cases, only 3.9% have slower mean frequencies than this one.

Waltham concludes that the chance that these three coincidences occur by chance is less than 10^{-5}.

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 excentric 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

This presentation is available on

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

Zie ook mijn boek bespreking in de ‘Academische Boekengids’:

‘Dan zouden we het toch gehoord hebben’[53]

Of de uitgebreidere XL-versie op

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

[53] www.academischeboekengids.nl/do.php?a=show_visitor_artikel&id=1219

Suggestions for further reading

- The six books that I review in my article in the Academische Boekengids.
- References given in that article and in footnotes in this presentation.
- Some more selected articles are listed in the next frames.

Note: I refer often to papers in the astronomical literature. The NASA Astrophysics Data System (ADS) lists the full astronomical literature and provides electronic (e.g. pdf) scans of all astronomical papers from the nineteenth century up to the introduction of electronic journal subscriptions. I have given the URL of the papers in ADS, and when only available for subscribers to journals ADS gives (when available) the URL to the papers on astro-ph, the astrophysics preprint server on arXiv.org.

Selected articles:[54]

A set of 'education' papers from ESA's Terrestrial Planet Science Advisory Team in *Astrobiology, volume 10, (2010)*:

- Fridlund & Lammer: The astrobiology habitability primer, adsabs.harvard.edu/abs/2010AsBio..10....1F
- Fridlund *et al.*: The search for worlds like our own, adsabs.harvard.edu/abs/2010AsBio..10....5F
- Alibert et al.: Origin and formation of planetary systems, adsabs.harvard.edu/abs/2010AsBio..10...19A
- Dvorak *et a;.*: Dynamical habitability of planetary systems, adsabs.harvard.edu/abs/2010AsBio..10...33D
- Lammer *et al.*: Geophysical and atmospheric evolution of habitable planets, adsabs.harvard.edu/abs/2010AsBio..10...45L

[54] Some of the below are only available with electronic journal subscriptions.

- Brack *et al.*: Origin and evolution of life on terrestrial planets, adsabs.harvard.edu/abs/2010AsBio..10...69B
- Grenfell *et al.*: Co-evolution of atmospheres, life, and climate, adsabs.harvard.edu/abs/2010AsBio..10...77G
- Kaltenegger *et al.*: Deciphering spectral fingerprints of habitable exoplanets, adsabs.harvard.edu/abs/2010AsBio..10...89K
- Kaltenegger *et al.*: Stellar aspects of habitability - Characterizing target stars for terrestrial planet-finding missions, adsabs.harvard.edu/abs/2010AsBio..10..103K
- Fridlund *et al.*: A Roadmap for the detection and characterization of other Earths, adsabs.harvard.edu/abs/2010AsBio..10..113F
- Schneider *et al.*: The far future of exoplanet direct characterization, adsabs.harvard.edu/abs/2010AsBio..10..121S

Some more selected articles:

- Tarter: The evolution of life in the Universe: are we alone?, adsabs.harvard.edu/abs/2007HiA....14...14T
- Cirkovic: Fermi's Paradox - The last challenge for Copernicanism?, adsabs.harvard.edu/abs/2009SerAJ.178....1C
- Lammer *et al.*: What makes a planet habitable?, adsabs.harvard.edu/abs/2009A%26ARv..17..181L
- Ehrenfreund *et al.*: Astrophysical and astrochemical insights into the origin of life, adsabs.harvard.edu/abs/2002RPPh...65.1427E
- Laskar: Large scale chaos and marginal stability in the solar system, adsabs.harvard.edu/abs/1996CeMDA..64..115L