Exobiology 5

The detection of exoplanets

Drake's equation

Proposed in 1961 by **Frank Drake**, to estimate the number of civilizations, N , broadcasting their existence in our Galaxy

$$N = R_b t$$

Where R_b is the rate at which broadcasting civilizations appear in our Galaxy

And t is the time over which they broadcast

R_b could be broken into many specific factors:

$R_b = R p_p n_E p_l p_i p_b$, where

$R =$ Rate at which suitable stars are formed

$p_p =$ Probability of planets forming around suitable stars

$n_E =$ Average number of suitable planets in HZ per planetary systems

$p_l =$ Probability of life

$p_i =$ Probability of intelligent life

$f_b =$ Fraction of intelligent life that are broadcasting

Assumption about R : rough estimate = 300×10^9 stars in the Galaxy and age of about 10×10^9 years $\Rightarrow R = 300\times10^9/10\times10^9 \approx 30$ stars/yr

This is not correct for several reasons:

1) We do not know how our Galaxy formed. Probably formed a bulge first by mergers before accreting a disk $\Rightarrow$ age of stars in our Galaxy $\neq$ age of Galaxy $\Rightarrow$ age is ill defined
2) Processes for forming dust and metal not clear. If galaxies formed by mergers $\Rightarrow$ then increases in metallicity may be a cosmological event $\Rightarrow$ time needed to form planets proportional to age of Universe $\Rightarrow$ 14 – 15 Ga
3) Our Sun formed in the disk. Probability of forming planets with life in bulge may be zero – due to high density of stars and – few dust produced during formation (ratio in gas ~ 4% of stellar mass). Based on bulge/disk luminosity ratio and variation of luminosity in bulge and disk $\Rightarrow$ 30% of the mass may be in bulge $\Rightarrow$ correcting factor 0.7
4) More acceptable value $\Rightarrow R = 210\times10^9/14\times10^9 \approx 15$ stars/yr

Assumptions about p_p probability for suitable stars to form planets

1) We may assume G type stars, like the Sun are the most suitable to form planets $\Rightarrow$ based on luminosity function 14% of all stars
2) Depends also on metallicity: roughly 10% of stars (based on Nordström et al. 2006, A&A,)
3) $p_p = 0.14 \times 0.10 = 0.014$

Assumptions about n_E number of planets in ZH: Based on our solar system, only 1 planet out of 8 seems to be located in the ZH $\Rightarrow$ $n_E = 0.125$

Assumptions about p_l probability of life – evidence for life on Earth are almost as old as Earth itself, so we may put this factor equal to $p_l = 1$

Assumption for p_i the probability of intelligent life – here we mean like our own $\Rightarrow$ Homo Sapiens, Sapiens appeared only 130 000 years ago
$\Rightarrow p_i \approx 1.30 \times 10^5 / 4.5 \times 10^9 \approx 3.0 \times 10^{-5}$ - note that this could also be zero

Assumptions about f_b, once again we may assume this factor to be 1, as based on our own experience

Our estimate of R_b would thus be equal to:
$R_b = 15 \times 0.014 \times 0.125 \times 1 \times 3 \times 10^{-5} \times 1 = 8.0 \times 10^{-7}$

Assuming we are broadcasting for the last 50yrs, it means that the probability for **SETI** (**Intelligence Search for Extra-Terrestrial**) to detect something is practically zero

Contrast largely with estimate made by Carl Sagan – but in good agreement with results up to now of SETI – **over sufficiently long time search result is negative**

Detecting exoplanets

Five methods:

1) Reflection or emission of radiation
2) Absorption or occultation
3) Refraction = gravitational lens
4) Tidal effects

All methods biased towards high masses (huge size) planets very near their stars

List of symbols:

R	radius of a star or planet
M	mass of a star or planet
L	luminosity of (energy radiated per unit time by) a star or planet
A	albedo
S	surface area
b_{AB}	brightness (or flux) of A at B
a	semimajor axis of the orbit of a star or planet (equal to the radius for a circular orbit)
d_{AB}	distance between A and B
β	angular radius or distance
i_0	inclination of an orbit relative to the line of sight
P	period of an orbit
t	timescale for gravitational lensing
v_r, $(v_r)_{MAX}$	radial velocity and its maximum value.

$\odot$	the Sun	J	Jupiter
α	alpha Centauri system	E	Earth
$*$	a star	V	Venus
		P	a planet

Detection by reflection

This method requires the following conditions:

1) Collect enough light to detect the planet
2) Separate the star from the planet

Requires large aperture telescopes + long exposure time + good seeing conditions (or adaptive optics capability)

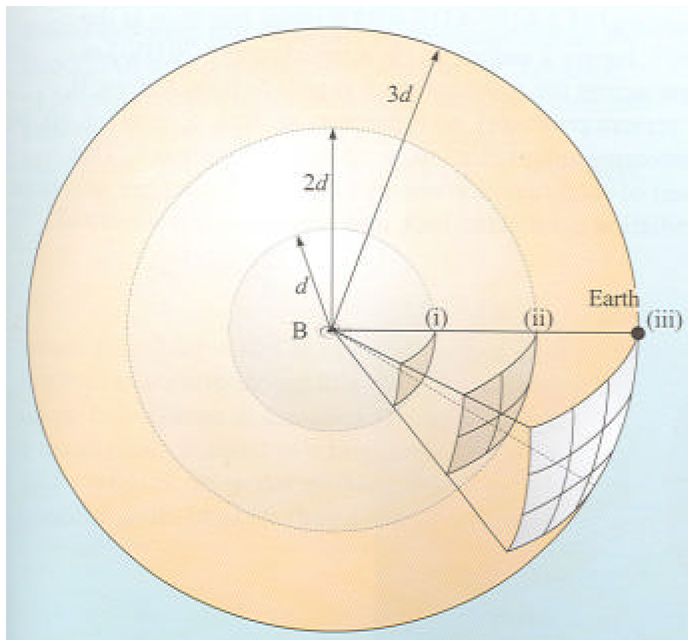
Definition of **brightness**:

$$b = \frac{L}{4p\,d^2}$$

Ex. for the Sun

$$L_\odot = 3.84\times10^{26}\ \text{W}$$
$$a_E = 1.50\times10^{11}\,\text{m} = 1\text{AU}$$

$$\Rightarrow b_\odot = 1.36\times10^{3}\,\frac{\text{W}}{\text{m}^2}$$



At the distance of Jupiter $a_J = 5.2\text{AU} \Rightarrow \text{b}_{\odot\text{J}} = 50.3\text{W/m}^2$
The light emitted by Jupiter is the light of the Sun reflected by its surface
Jupiter radius is $R_J = 70000\text{km} \Rightarrow$ surface $S_J = p\,R_J^2 = 1.54\times10^{16}\,\text{m}^2$
The Albedo of Jupiter is $A_J = 0.70$ so the luminosity of Jupiter is

$$L_J = A_J \cdot S_J \cdot b_{\odot J} = 0.70\cdot 50.4\cdot 1.54\times10^{16}\,\text{W}=5.43\times10^{17}\,\text{W}$$

Considering that only one face of the surface is seen all the time, the brightness of Jupiter is $\Rightarrow b_J = \frac{L_J}{2p\,d_J^2} = 1.42\times10^{-7}\,\frac{\text{W}}{\text{m}^2}$

Transforming brightness into **magnitude**: $m_J = -2.5\log\frac{b_J}{b_0} = -2.0$

where $b_0 = 2.29\times10^{-8}\,\frac{\text{W}}{\text{m}^2}$

For example at the distance of Alpha Centaury (nearest star at 4.3 lyr) a Jupiter like planet: $\Rightarrow b_p = \dfrac{L_J}{2p\,(4.3)^2\,(9.5\times10^{15})^2} = 5.18\times10^{-17}\,\dfrac{\text{W}}{\text{m}^2}$

In magnitude this correspond to $m_p = 21.6$

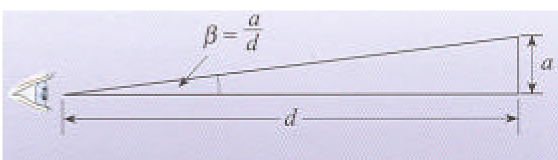
For comparison, the brightness and magnitude of the Sun at the distance of Alpha Centaury would be $b_{\odot a} = 1.84\times10^{-8}\,\dfrac{\text{W}}{\text{m}^2}$ and $m_{\odot a} = 0.24$

This is a huge difference

The **diffraction limit** of a telescope: $a = \dfrac{l}{D}$ where l = wavelength of observation and D = diameter of the telescope

For a 8m telescope in the visible $a = \dfrac{5\times10^{-7}}{8} = 6.25\times10^{-8}$ radian

Since 1 **radian** = 206265 arcseconds $\Rightarrow a = 0.013$ arcseconds



For a Jupiter like planet at the distance of alpha centaury:

$$b_p = \frac{a_J}{d_a} = \frac{5.2\cdot1.05\times10^{11}}{4.3\cdot9.5\times10^{15}} = 1.34\times10^{-5}\text{rad} \Rightarrow b_p = 2.8 \text{ arcseconds}$$

The separation is ~ 300 times larger $\Rightarrow$ can be resolved by large telescope

Principal problem = difference in brightness

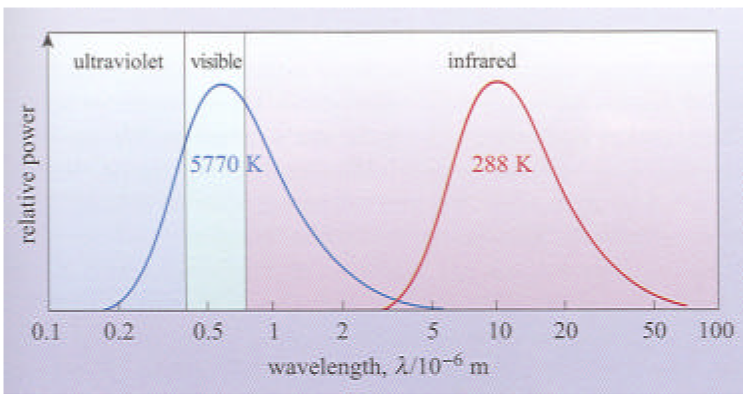
Dim planets are lost in outskirts of their stars ⇒ must find a way to reduce differences

Possibilities:

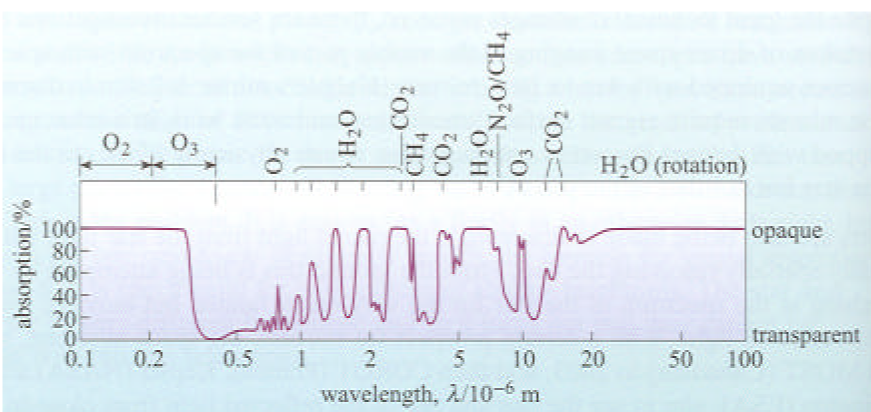
1. Using a **coronograph**
2. Searching for moving spectrum of reflected light

Ex. **MOST** (Canadian 2003), **COROT** (French), **KEPLER** (NASA) and **Eddington** (ESA)

The billion to one ratio in brightness between star and planet can be downgraded to million in the IR



Principal problem = atmosphere absorption in IR



Precludes detection of these lines in atmosphere of planets

Darwin Mission (ESA)

Several separated spacecraft > 1m + several ones to relay information

Distance between mirrors 100m – 1000m maintained with accuracy less than 1cm

INTERFEROMETER: allows to null star radiation – delaying signals between 2 telescopes such that crests coincide with troughs canceling each other

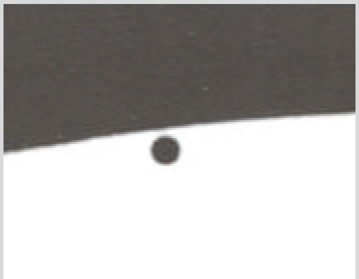
In theory would be possible to study the spectra of the atmosphere of planets and thus to determine if there is evidence for life

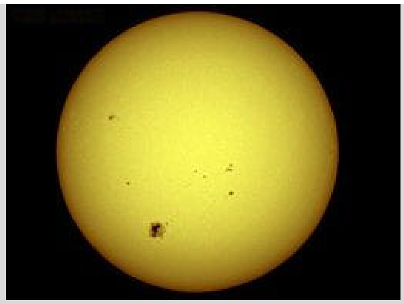
Other similar projects: NASA – **Terrestrial Planet Finder** (**TFP**)

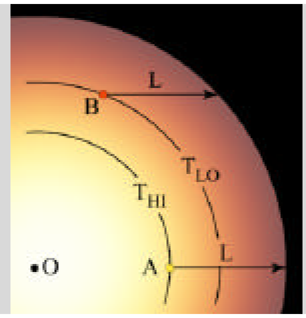
On Earth – **TMT** = 30m telescope – **OWL** = Overwhelmingly large telescope (100m)

Absorbed or occulted radiation

Transit of Venus in front of the Sun







Assume the brightness of the Sun is constant on whole surface (we do not consider **limb darkening**)

Angular radius of Venus: $b_V = \dfrac{R_V}{d_{EV}}$

For the Sun: $b_\odot = \dfrac{R_\odot}{a_E}$

The fraction of the sun surface which is obscured: $f_V = \left(\dfrac{b_V}{b_\odot}\right)^2 = \left(\dfrac{R_V}{R_\odot}\right)^2 \cdot \left(\dfrac{d_{EV}}{a_E}\right)^2$

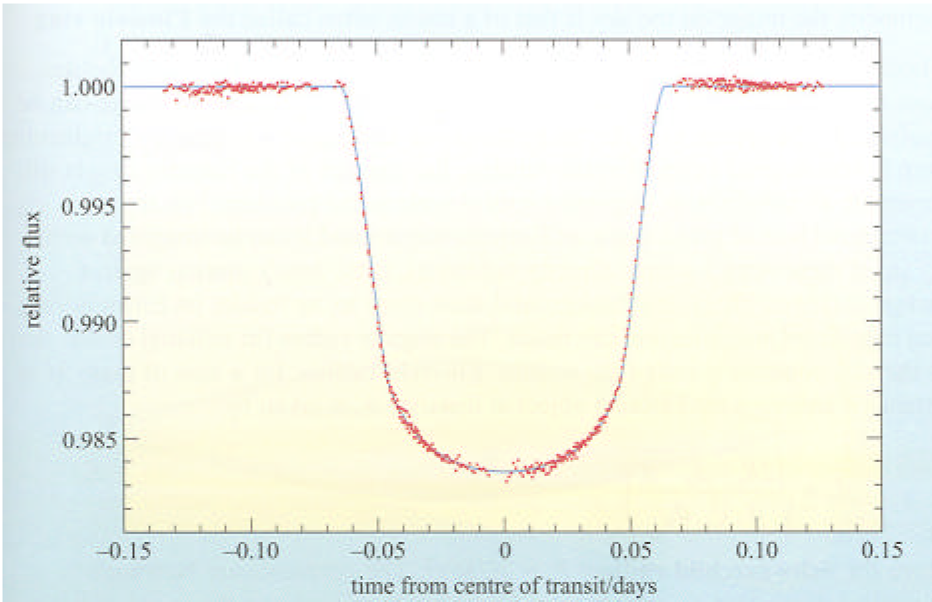
$R_V = 6200\text{km}$, $a_V = 0.72\text{AU}$, $d_{EV} = 0.28\text{AU}$, $R_\odot = 6.96\times10^5\,\text{km}$

$\Rightarrow f_V \simeq 1.01\times10^{-3}$, this is 0.1% drop in apparent brightness

For an exoplanet: $d_{Ep} = d_{E*} \Rightarrow f_p = \left(\dfrac{R_p}{R_*}\right)^2$

For a Jupiter like planet: $f_p = \left(\dfrac{7\times10^7\,\text{m}}{6.96\times10^8\,\text{m}}\right)^2 = 0.01$ that is 1% lost in brightness

Up to 2003, only one planet was discovered using this technique (**OGLE-TR-56**) and one confirmed **HD209458**



The graphic is consistent with $f_p = 0.016 \Rightarrow \frac{R_p}{R_*} = \sqrt{f_p} = 0.13$

HST occultation of HD209458 shows absorption lines of sulfur

Occultation method – only work for special orientation of planet orbits around its star – assuming random orientation $\Rightarrow$ 1/10 of stars with short periods and less for longer period planets

Future space missions (MOST, COROT, Kepler and Eddington) will be able to detect dips due to occultation of stars by planets

Refracted radiation

Gravitational lensing – micro lensing (brightness amplification)

For source + lens + observer all in perfect alignment $\Rightarrow$ **Einstein ring**

Einstein radius:

$$b_e = \sqrt{\frac{2R_S}{d}\left[\frac{d_b - d}{d_b}\right]}$$

Where $R_S = \dfrac{2GM}{c^2}$ is the **Schwarzchild radius** of mass M

$G = 6.672\times10^{-11}\,\text{N m}^2\ \text{kg}^{-2}$

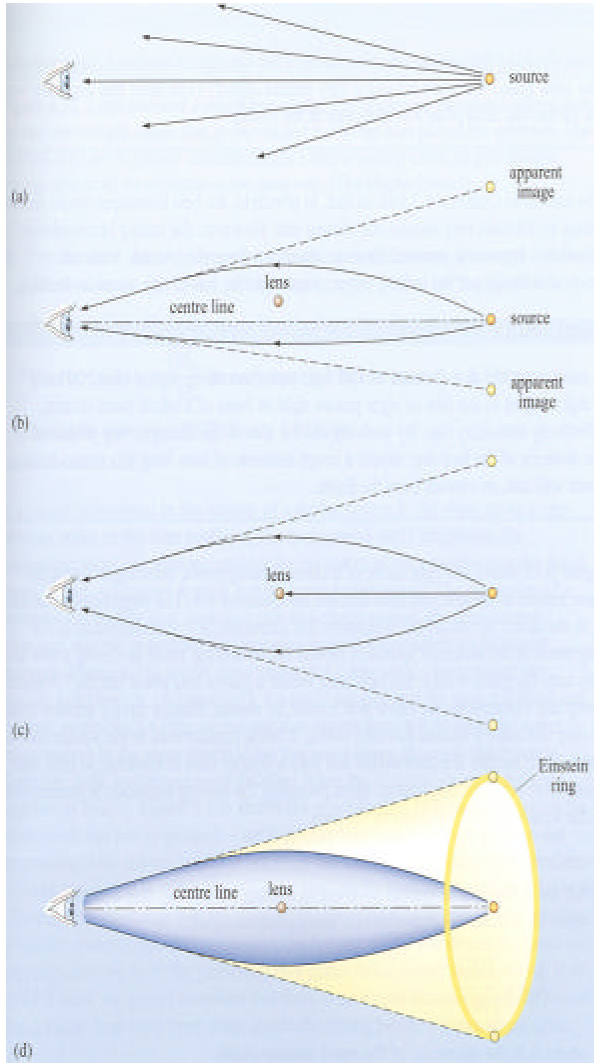
For the sun: $M_\odot = 1.99\times10^{30}\,\text{kg}$

$\Rightarrow R_S = 2950\,\text{m}$

Very small compared to radius $R_\odot = 6.96\times10^{8}\,\text{m}$

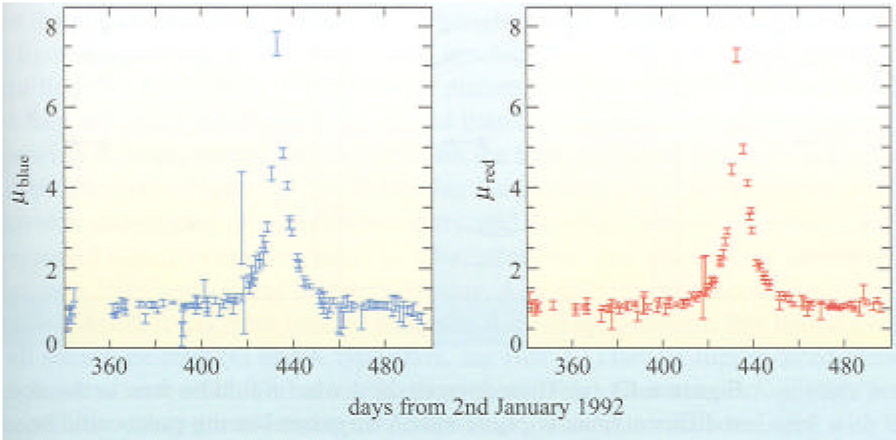
For very distant object in background:

$$d_b \gg d \Rightarrow b_e = \sqrt{\frac{2R_S}{d}}$$



For alpha Centaury (solar like star): $b_e = 3.8\times10^{-7}\,\text{radian} \approx 0.078''$

In principle resolvable by large telescope $\Rightarrow$ **problem = seeing**



The figures (**MACHO** project) show the light curve of microlensing effect in two colors (confirming the effect since gravitational lens independent of wavelength); the amplification factor m is the factor by which the brightness has increased

For a 1 solar mass star at 100 lyr: $b_e = \sqrt{\frac{2R_S}{d_*}} = \sqrt{\frac{2 \cdot 2950\text{m}}{100 \cdot 9.47 \times 10^{15}\text{m}}} = 7.89 \times 10^{-8}$ radian

Physical size of the ring: $R_e = b_e d_* \simeq 7.47 \times 10^{10}\,\text{m} \sim 0.5\text{AU}$

If perpendicular to line of sight velocity of star ~ 20km/s
$\Rightarrow t = R_e / v \simeq 3.74 \times 10^6\,\text{s} \approx 43.2$ days is the duration of lensing effect

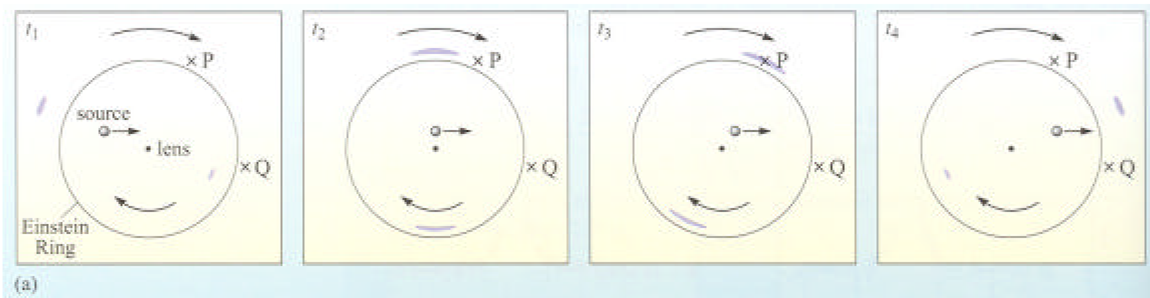
For planets, microlensing effect is shorter due to smaller R_S

Characteristic lensing time-scale: $t_p = t_* \sqrt{\frac{M_p}{M_*}}$

For a Jupiter like planet: $M_J = 1.90 \times 10^{27}\,\text{kg} \;\Rightarrow t_p = 1.33$ days

For Earth like planet: $M_E = 5.98 \times 10^{24}\,\text{kg} \;\Rightarrow t_p = 1.8$ hours

Planet involved in lensing of stellar system, in principle detectable as very obvious spikes in time profile of background stars brightness

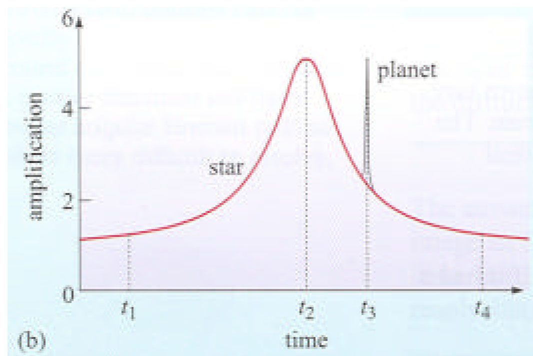


The images show what would be seen in the sky at different times if a microlensing event could be observed by a telescope with spatial resolution well beyond today telescope

The light curve of the event shows a spike

Depends on geometry of lens = position of planet

$\Rightarrow$ microlensing by planet not easy to detect and no detection does not mean there is no planet



If a lens is an angular distance b from the source (a background star) on the sky

Amplification factor: $m = \dfrac{(b/b_e)^2 + 2}{(b/b_e)/\sqrt{(b/b_e)^4 + 4}}$

This break down for perfect alignment $b = 0$

For amplified cases: $b < b_e \Rightarrow m = \dfrac{b_e}{b} \Rightarrow m \propto b_e \propto M^{1/2}$

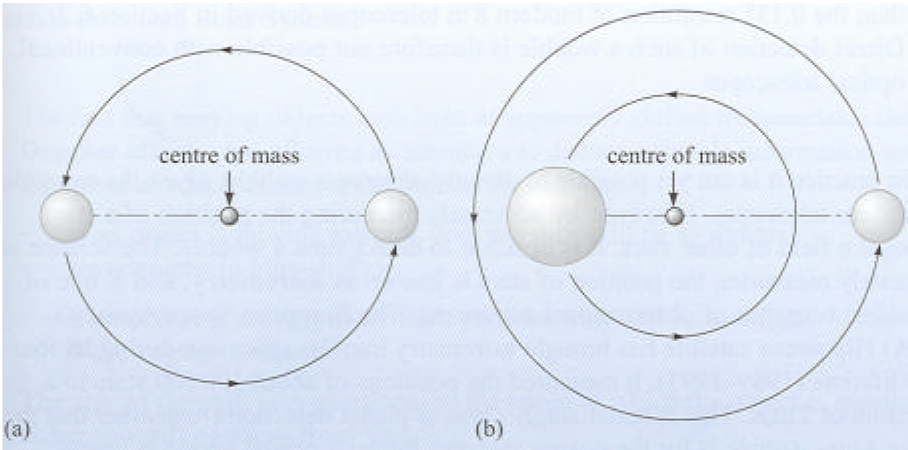
Application of method imply long term monitoring – discovery needs to be confirmed by other method

After less than a decade no planets has been found this way $\Rightarrow$ less than 1/3 of G and K stars have Jupiter-sized planets

Method tested on binary stars – detection by microlensing match other observations $\Rightarrow$ ½ of stars in our galaxy are binaries

(BBC news 7/4/2008 - **OGLE-2006-BLG-109L**: Jupiter + Saturn like planets)

Astrometry



Two stars orbiting each other rotate around **center of mass**

Consider 2 masses M_A and M_B at distances a_A and a_B to the center of mass
$\Rightarrow M_A a_A = M_B a_B$, since orbital periods are the same

Ex. for Jupiter like planet around the Sun - $a_\odot = \frac{M_J}{M_\odot} a_J = 7.45\times10^8 \mathrm{m}$, this is near the surface of the Sun

This produce **weak wobble** of position of star – if star at the distance of alpha Centaury
$b_* = \frac{a_\odot}{d_{aE}} = \frac{7.45\times10^8}{4.07\times10^{16}} = 1.83\times10^{-8} \approx 3.77\mathrm{mas} \Rightarrow$ not directly detectable

However, through precise astrometry = accurate measuring of positional stars among field of view

Ex. **Hipparchos** precision = 2mas $\Rightarrow$ confirmed planet around HD209458
NASA projects = SIM should launch in 2009 – will measure position of stars with precision 4mas
ESA project = **GAIA** to be launch ~ 2012 – precision of 10µas for 10^9 stars
Earth like planet: $a_* = \frac{M_E}{M_\odot} a_E = 4.51\times10^5 \mathrm{m} \Rightarrow b_* = \frac{a_*}{d_a} = 1.11\times10^{-11} \approx 2.29 \mathit{m}\mathrm{as}$ not even detectable by GAIA

Doppler Spectroscopy

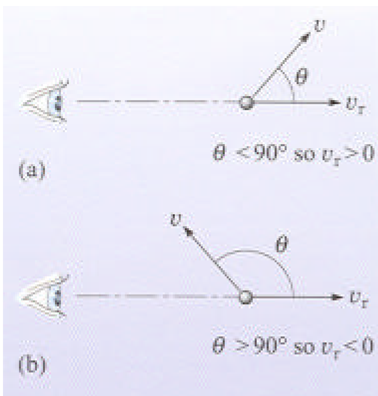
Radial velocity method = most successful method so far – almost all exoplanets detected by this method

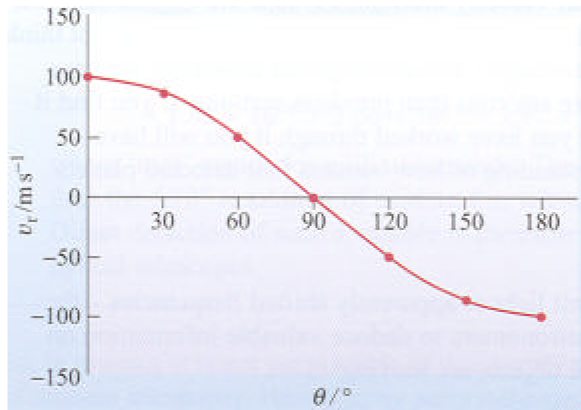
Doppler effect: $\frac{\Delta l}{l} = \frac{v_r}{c}$ < 0 blue shifted, > 0 red shifted

Relation between radial and true velocity in space:

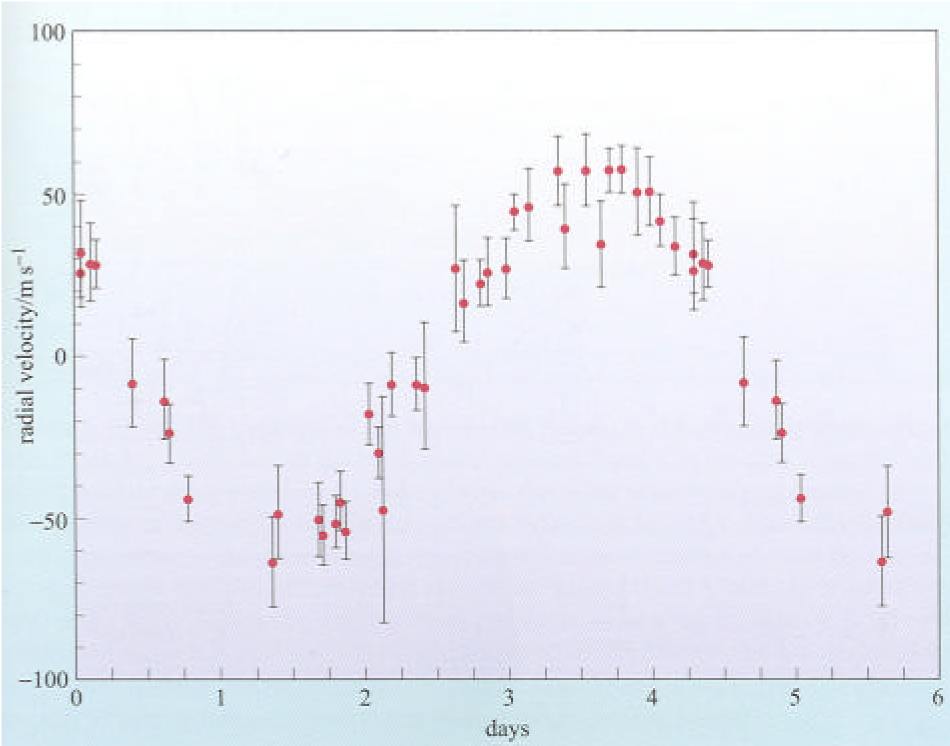
$$v_r = v \cos q$$

Where q is the angle between object's velocity in space and line of sight





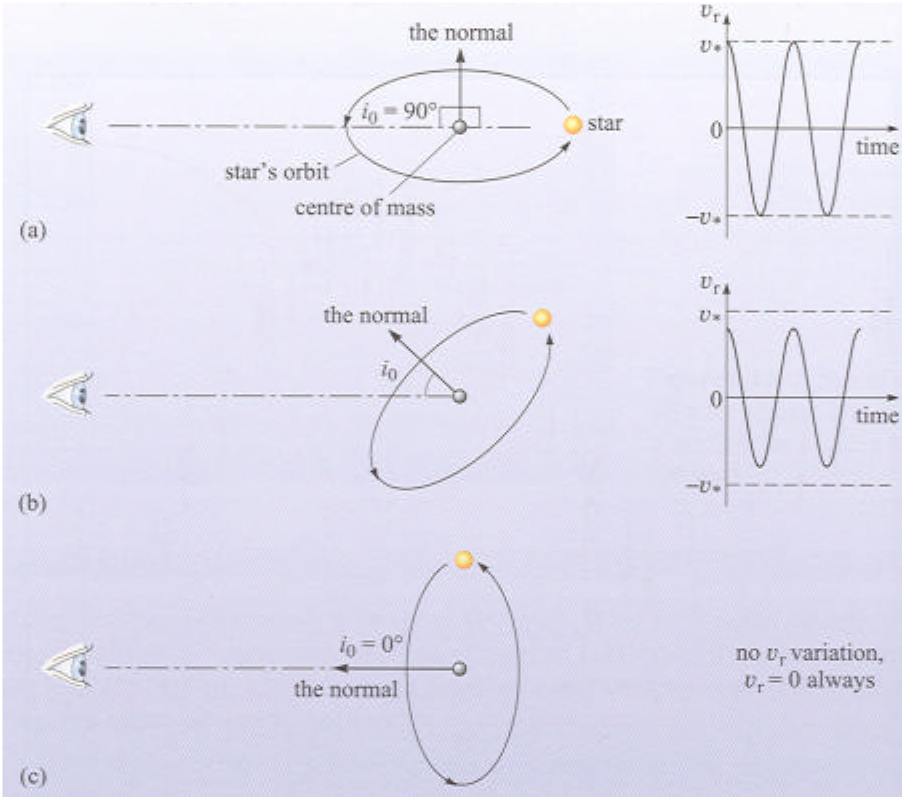
Wobble of star around center of mass produce a Doppler shift which is periodic in time



The figure shows the Doppler shifts measured for **51 Pegasi** (first exoplanet detected by this method)

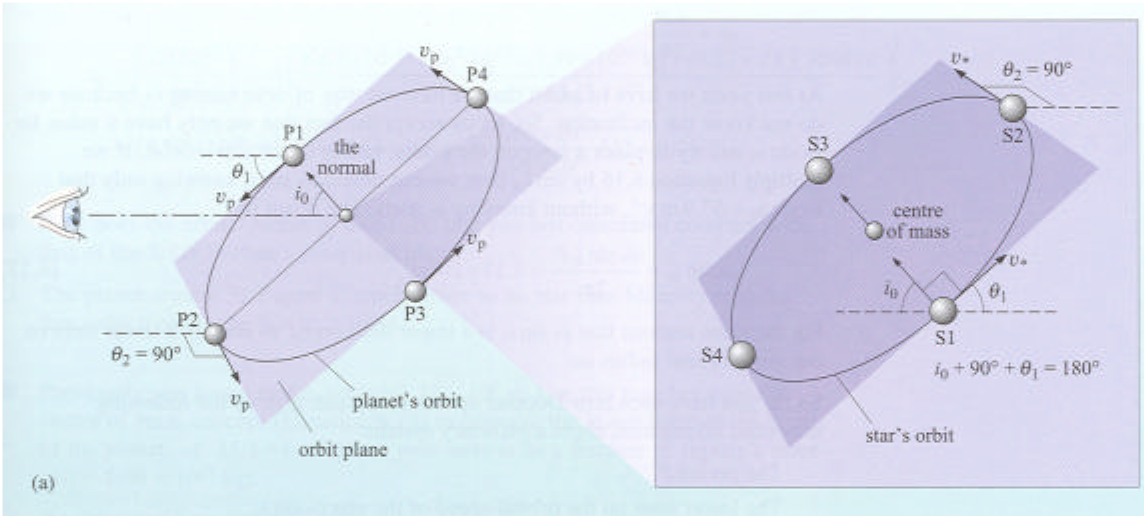
From the figure we deduce $(v_r)_{max} \approx 50-60$ m/s with period of 4 days

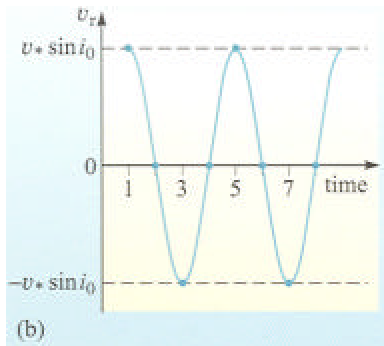
Taking into account the tilt (inclination i_0) of stellar system:



$$(v_r)_{max} = v_* \cos\theta_{t_1} = v_* \cos\left(90^\circ - i_0\right) = v_* \sin i_0$$

Star maximum radial velocity occurs at position P1 $\Rightarrow v_* \sin i_0 =$ lower limit





If we assume a circular orbit $\Rightarrow v =$ constant

Then we have that $v_* P = 2p\, a_* \Rightarrow a_* = \dfrac{v_* P}{2p}$

For 51 Pegasi $\Rightarrow P = 4.23$ days and $(v_r)_{\max} = 57.9$ m/s

Multiplying by $\sin i_0 \Rightarrow a_* \sin i_0 = \dfrac{v_* P \sin i_0}{2p} = 3.37 \times 10^6$ m

For the mass of the star we use the relation: $\dfrac{L_*}{L_\odot} = \left(\dfrac{M_*}{M_\odot}\right)^3$ where $L_* = b_* 4p\, d_*^2$

Applying **Kepler law**: $P^2 = 4p^2 \left(\dfrac{a_p^3}{GM_*}\right) \Rightarrow a_p = \left(\dfrac{GM_* P^2}{4p^2}\right)^{1/3}$

For 51 Pegasi, $M_* \approx M_\odot$ such that $a_p = 0.051$AU

Compared with Mercury $a = 0.39$AU this planet is extremely near its star

Using the center of mass relation: $M_p \sin i_0 = \dfrac{a_* \sin i_0}{a_p} M_* \approx 0.46\ \mathrm{M}_J$

This is a very massive planet located very near its star = **hot Jupiter**

Bias due to method

Since $v = \dfrac{2\pi a}{P}$

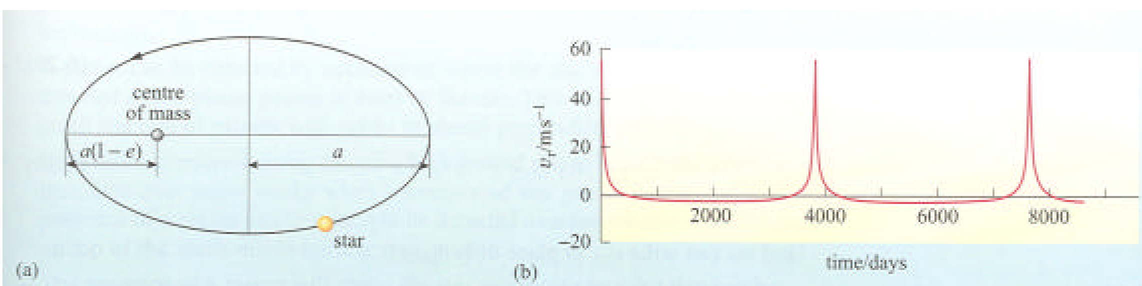
Replacing in Kepler law: $v = \dfrac{2\pi a_p M_p}{M_*} \cdot \left(\dfrac{G M_*}{4\pi^2 a_p^3} \right)^{1/2} = \left(\dfrac{G}{M_*} \right)^{1/2} \dfrac{M_p}{a_p^{1/2}}$

Clearly massive planets with short semi-major axis orbits are favored by method

This translate also in short period, compared to Jupiter 12yrs period

Shape of the curve gives information on star orbit

Elliptical orbits $\Rightarrow$ complicated time profiles $\Rightarrow$ **ellipticity** can be deduced



Difference between $(v_r)_{max}$ and $(v_r)_{min} = 2 v_{rA}$ is the **observable radial velocity amplitude**

Nature of exoplanetary systems

Planets discovered so far

First to search (and claim discovery) for exoplanet: **Peter van de Kamp** (Sproul Observatory)

- 1937 – using astrometry
- Thought he detected one around Barnar's star (5.9 lyr)
- Not confirmed – variations observed related to changes on telescope used between 1949 and 1957

First discovery: **Alex Wolszcan & Dale Frail**

- 2 planets around a pulsar?
- Few times mass of Earth
- How could they have survived SN explosion?
- Could have formed from residue?

First discovery around Sun like stars: **Michel Mayor** & **Didier Queloz** (Geneva Observatory)

- 51 Pegasi b

Up to 2003:

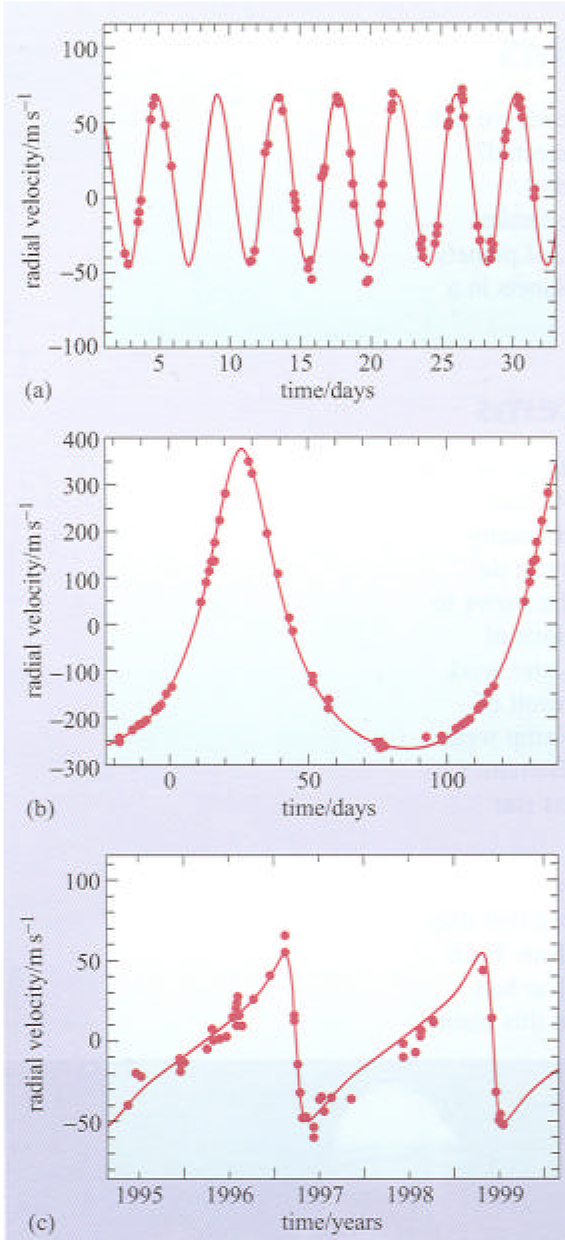
- 105 planets around 91 stars
- 12 are multiple planet systems

Up to (October) 2007 - 212

Exoplanet classification: first = b, second = c, etc. starting from inner ones

Almost all detected by Doppler shift technique

a) 51 Pegasi
b) 70 Virginis
c) 16 Cygni B



90 stars are nearby – most distant HD47536b (100pc)

The closer and the easier they are to detect

HD209458 also detected by occultation
⇒ very edge-on orbit (1 out of 100)

Gliese 876b – detected astrometrically

OGLE-TR-56 only one detected by microlensing method (5000 lyrs) – verified by Doppler method – P ~1.2 days

Base on microlensing experiment, less than 1/3 of stars have Jupiter like planets around them - effect of metallicity?

Of 91 stars, 5 are multiple systems – planet only orbit one of the stars

Known properties

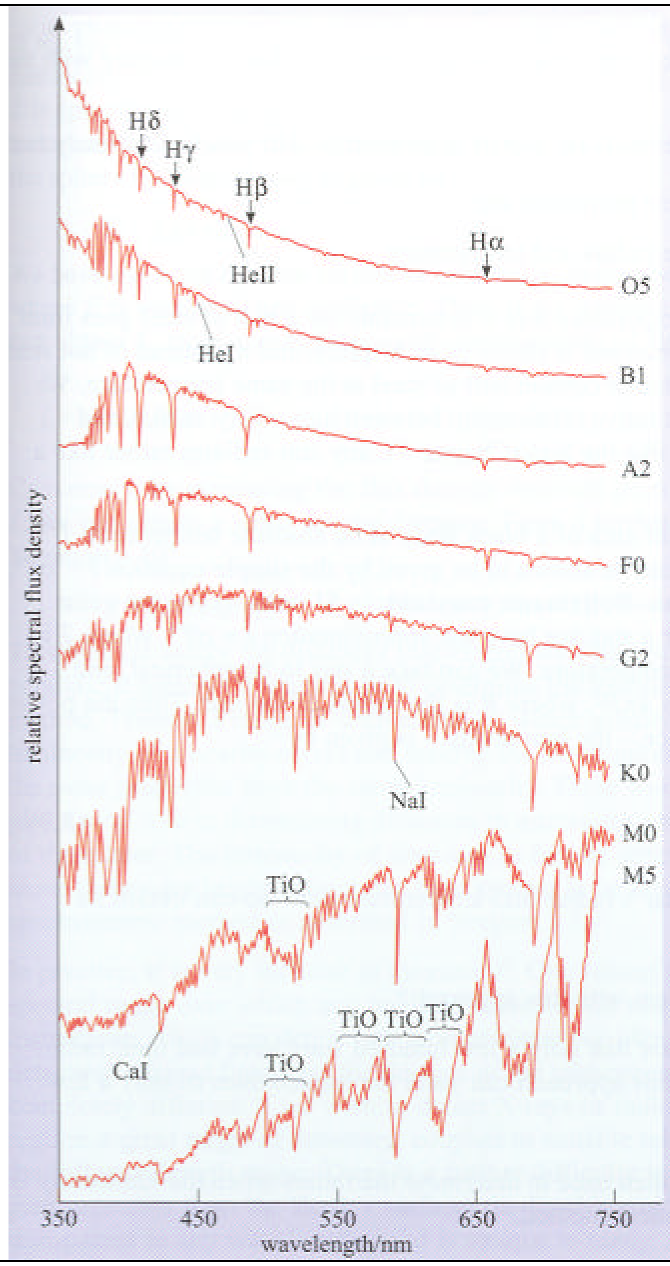
Sun like (G2) stars – spectral types F, G, K

- Sharp spectral lines + good surface stability Plenty of bright examples
- Sufficiently long MS life time $\Rightarrow$ existence of biosphere longer than 2000 Ma

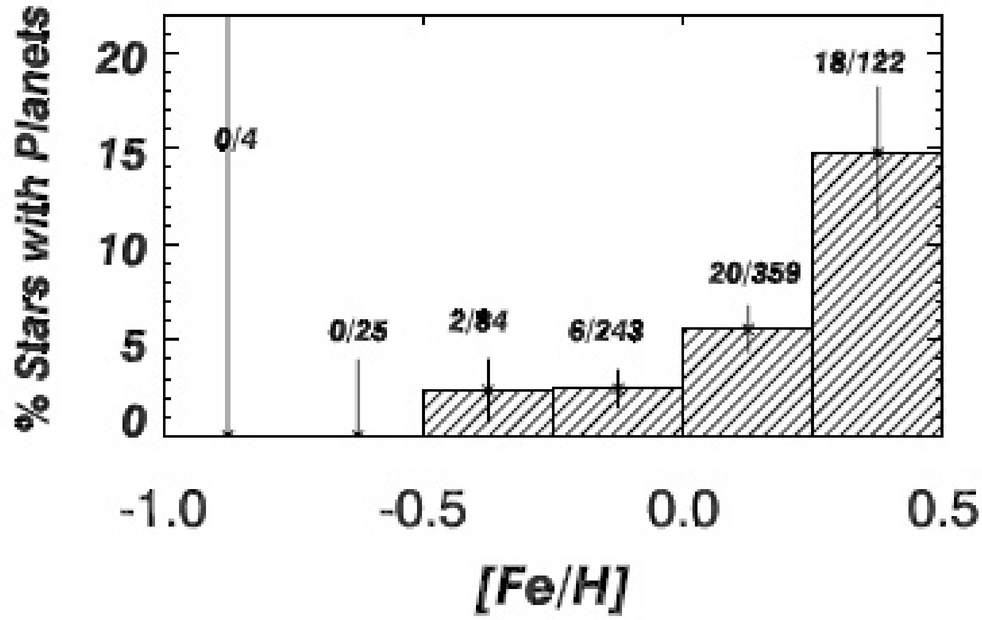
M dwarfs more complex and lower luminosities

- Planets in HZ very near their sun $\Rightarrow$ Synchronous rotation = one side kept in the dark

Only 8% of the stars surveyed showed planets

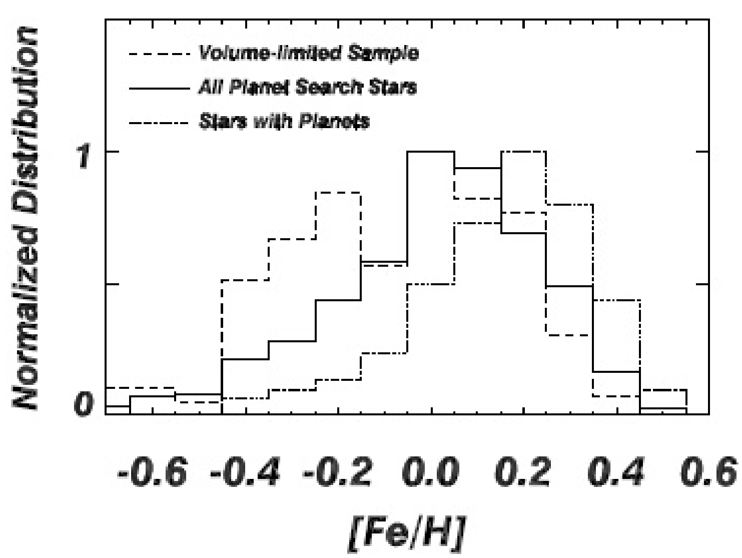


High metallicity favors formation of planets?



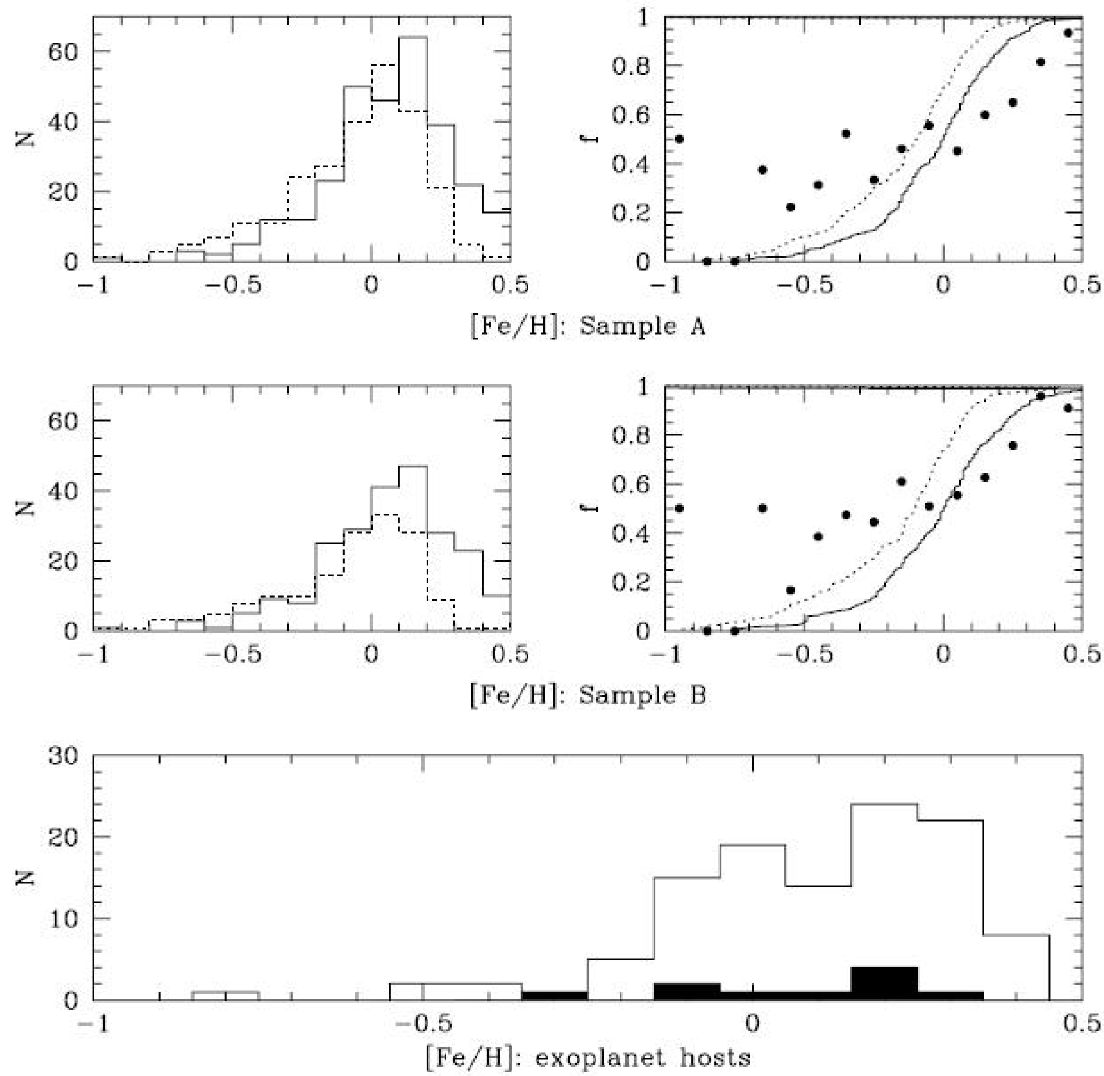
Fischer & **Valenti** 2005, ApJ, 622, 1102 – percentage of stars with detected planets rises with iron abundance – the sample is still small however

Bias towards metal rich stars in searching sample – do not reflect distribution of metallicity of solar environment

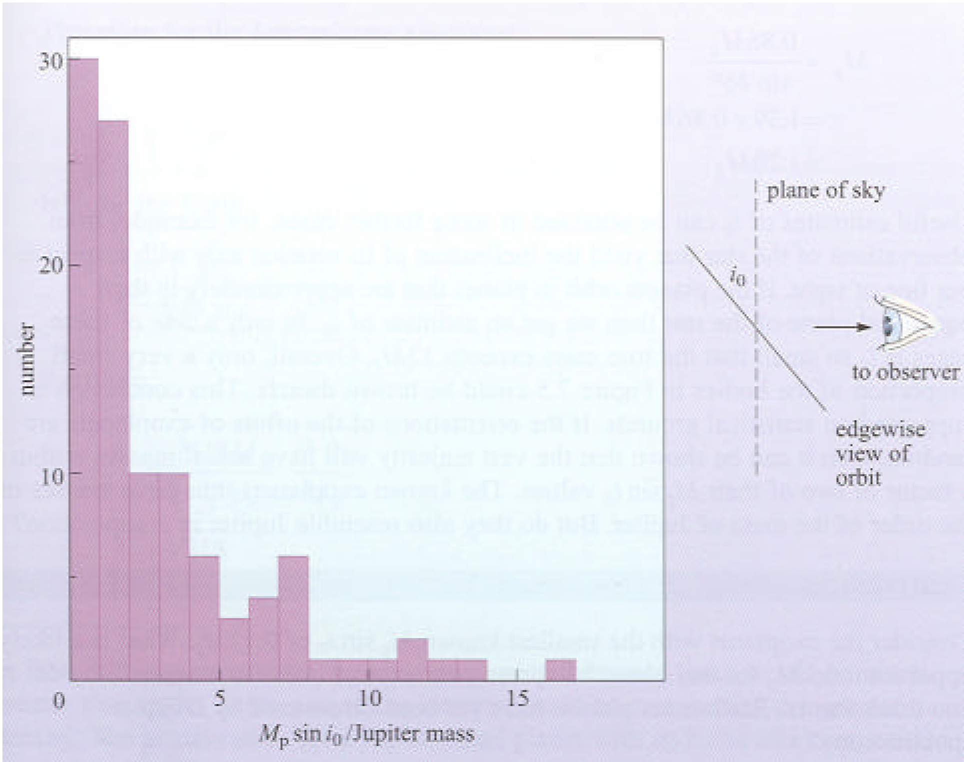


The whole sample of stars surveyed so far is strongly biased towards metal rich stars

This + small statistics ⇒ relation with metallicity only reflects the bias ⇒ relation not well established



Reid et al. 2007, ApJ, 665, 767



Least massive $0.12M_J \sim 38M_E$ (Saturn 95 M_E)

- Bodies with $M > 13M_J$ = brown dwarfs – large number discovered
- This is threshold for D fusion (last 1000Ma), greater than $80M_J \Rightarrow$ fusion of H

Possible brown dwarfs masquerading as planets $\Rightarrow \sin i_0$ is small

- Ex. for $M_p \sin i_0 = 4.5M_J \Rightarrow i_0 = 5.7^\circ \Rightarrow M_p = 45M_J$
- HD209458b – transit $\Rightarrow i_0 \geq 87^\circ$, not a brown dwarf
- Epsilon Eridani – dust ring visible
  - Assuming circularity $\Rightarrow i_0 = 46^\circ$ and $M_p = 1.20M_J$
- Using statistical argument real mass may be bigger by factor 2 $\Rightarrow M_p \sin i_0 < 5$ to be sure $\Rightarrow$ **only 70% may be real planets**

So Far the planets discovered have masses typical of Jupiter- in large part due to bias in method of detection (Doppler shift).

Composition? Unknown – assumed to be similar to Jupiter $\Rightarrow$ 73% H + 25% He + 2% metal (or 5% - 10% if metal rich)

Density? Unknown!

- Taking $M_p = M_J = 318 M_E$
- And assuming $r_p = r_E$
- For Jupiter mass exoplanet: $\frac{R}{R_E} = \frac{\left(318 M_E \Big/ \frac{4p}{3} r_E\right)^{1/3}}{\left(M_E \Big/ \frac{4p}{3} r_E\right)^{1/3}} = \sqrt[3]{318} = 6.8$
- In fact pressure would be greater so more realistic radii would be 5 - 6 R_E, this is compared to Jupiter $\sim 11 R_E$, because H and He less dense

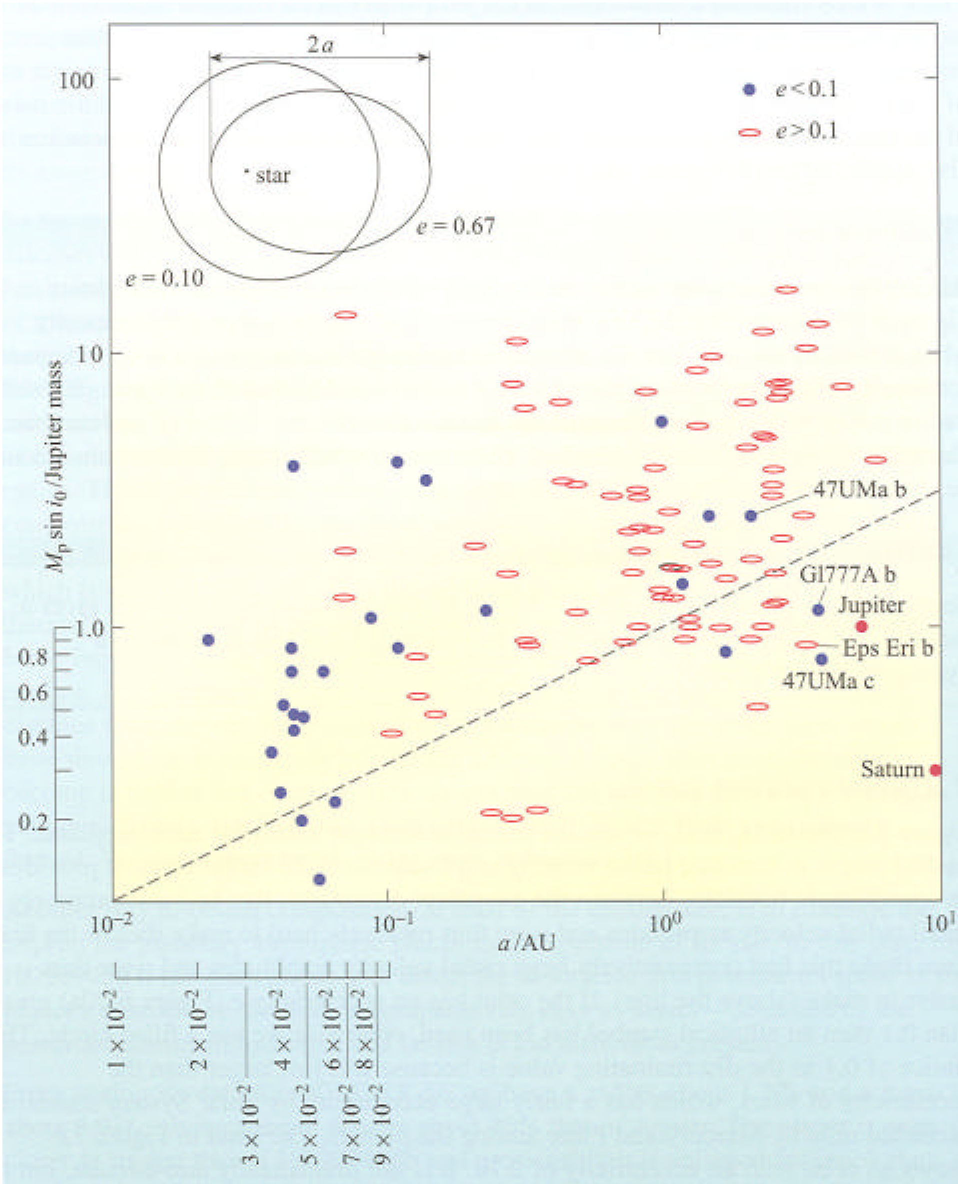
Diameter? Unknown! – In fact, only in 2 cases it is possible to deduce it $\Rightarrow$ **Hot Jupiter**

- HD209458b - decreases in luminosity with P ~3.52 days
  - Due to occultation dimming $\Rightarrow 1.35 R_J$
  - With mass, $M_p = 0.69 M_J$ this rules out silicate-iron like planet
  - Short distance 0.045AU $\Rightarrow$ star heat planet slowing down cooling explaining large envelop – but does not explain how you form such planet at the first place
- OGLE-TR-56
  - Mass of 0.9M_J and diameter D ~ 1.3 R_J $\Rightarrow r = 40\% r_J$
  - Still nearer to its sun – atmosphere may have been heated up by proximity of the star

For other exoplanets – only conjectures

- If silicate-iron then must be richer in metal to form such massive planet
- Increase in metallicity required – too high considering ISM
- Stars should also be metal rich (which is partly the case)
- Standard model of formation of giant gas planets do not predict formation of such system so near their stars
- Alternative = migration of planets?

Orbits



- Dashed line = limit in detection – high radial velocity amplitude = easier to detect
- $e = 0.1$ for Mars $\Rightarrow$ most have very eccentric orbits
- High eccentricity $\Rightarrow$ large variation of radiation on planets
- Extremely small semi-major axis
- Does not fit standard model based on solar system

Migration model

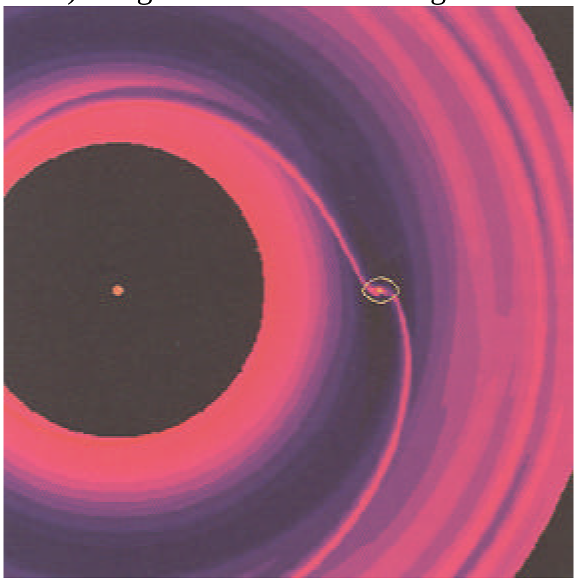
Within month of discovery of hot Jupiter planets one model was suggested = **migration of planets**

In fact some solar models were predicting this possibility 10 years before but were not taken seriously

Key: gravitational effects of giant planet on circumstellar disk of gas and dust

1) Disk is symmetrical
2) As mass of giant planet grows gravitational field produces spiral structures in the disk destroying symmetry
3) Spiral structures tends to push kernel of planet inward
4) **TYPE 1 MIGRATION**: Rate of migration is proportional to mass of disk + Mass of kernel $\Rightarrow$ increases as kernel grows

5) Migration continues until grow of kernel open up a gap in the disk



6) **TYPE II MIGRATION**: gap slow migration by factor 10-100, but do not stop it
7) Kernel mass depends on: density + thickness of disk + viscosity + temperature + .etc. – typical kernel masses from between 10 to 100 M_E are possible
8) Since gap does not stop growing $\Rightarrow$ Jupiter like planets are possible
9) PROBLEM = how do you stop migration?
   a. Removal of the disk by infall + solar wind – but typical life time 1-10Ma too long for giant planets to survive
   b. Counter effect is needed = magnetic breaking + evaporation of inner part

Model is very contrive

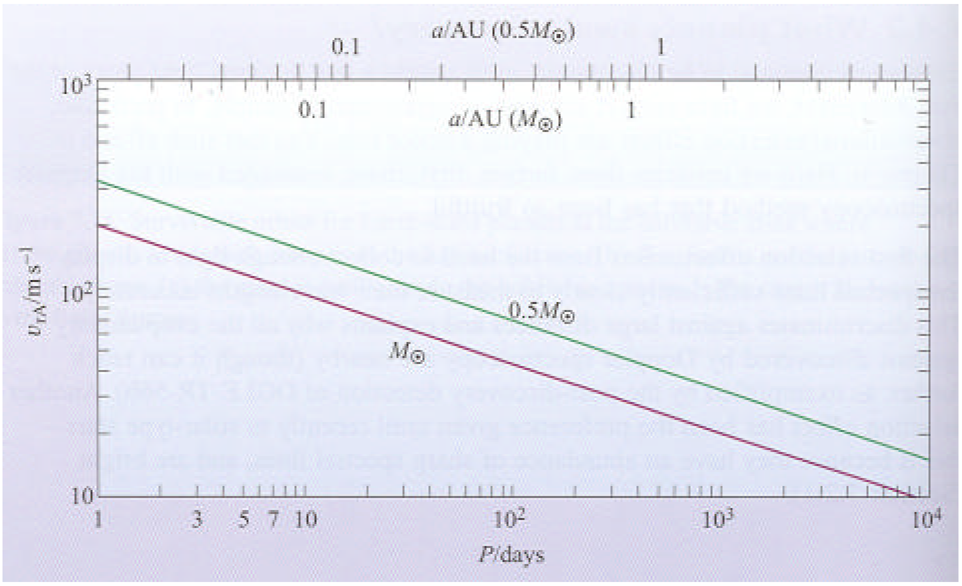
- Too many free parameters
- Need other mechanisms to explain high eccentricity
  - Multiple giant planet interactions
- Do not allow Earth like planets to form $\Rightarrow$ not a standard model
  - Earth mass planet rapidly migrated into their stars
  - Not impossible but implies very fine tuning of the models

CONCLUSIONS:

- Detection technique strongly bias the sample = massive + eccentric + very close to star
- Statistic is small – effect of metallicity bias of surveyed sample is not clearly identified
- Planets found do not fit standard model
- It may be that what is discovered as much more to say about formation of special kind of brown dwarfs than of planets
- **MAY NOT BE REPRESENTATIVE OF PLANETARY SYSTEMS IN GENERAL**
- Do not say ANYTHING about the origin of solar system

Undiscovered exoplanets

Selection effects are extremely important



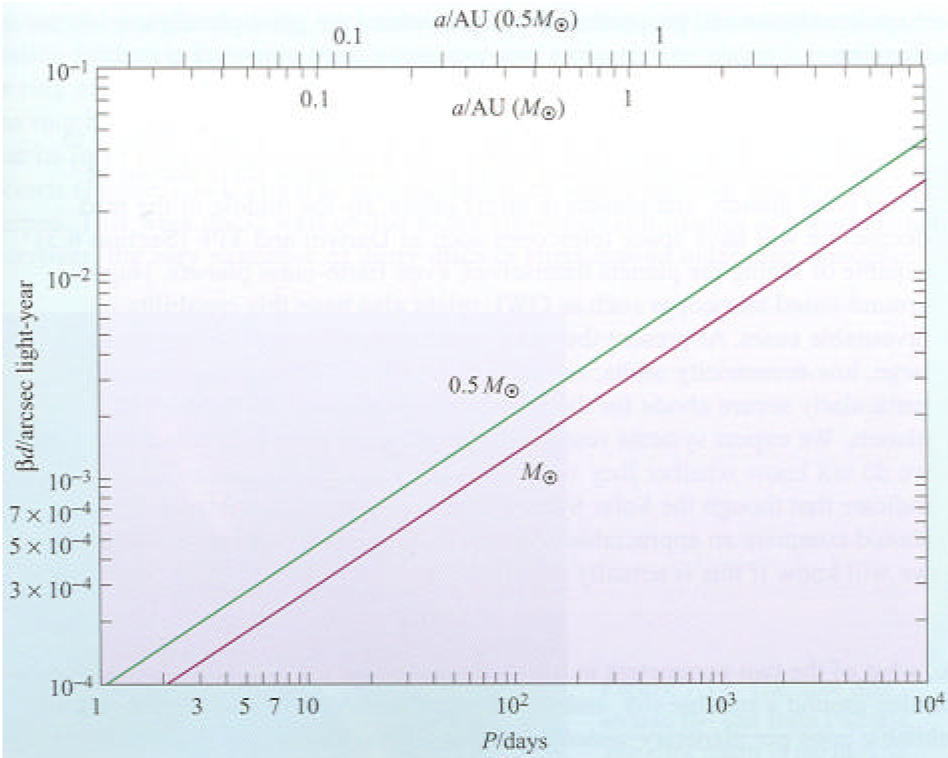
Graphics shows observed velocity amplitude against period or semi-axis orbit

- The smaller $M_p \sin i_0$ the smaller v_{rA} $\Rightarrow$ the harder is to detect a planet
- The smaller P and the higher v_{rA} $\Rightarrow$ massive planets in short period favored
- For Jupiter like planets $\Rightarrow$ 12 yrs of observation is required
- This explain why no Earth like planet detected so far

Doppler technique

- Only 8% of stars surveyed have massive planets within 4AU
- Missing = face-on orbits
- Method is searching over periods long enough to have detected Jupiter like planet
- Radial velocity is precise enough (1m/s) for detection of Earth Like planet
- **SOMETHING IS WRONG IN SELECTION OF SAMPLE?**

Astrometry = periodic shift



- Larger Period favor larger semi-major axis
- However, needs long series of observations
- Projects like SIM and GAIA (2010) will be required

Microlensing

- Highest potential to detect Earth like planet
- However **NEEDS TO KNOW WHERE TO LOOK FOR – OTHERWISE NOT PRACTICAL**

How to detect the presence of life

Once planets around other stars are discovered it is important to try to determine if they also show the presence of life – (this is the main goal of exobiology)

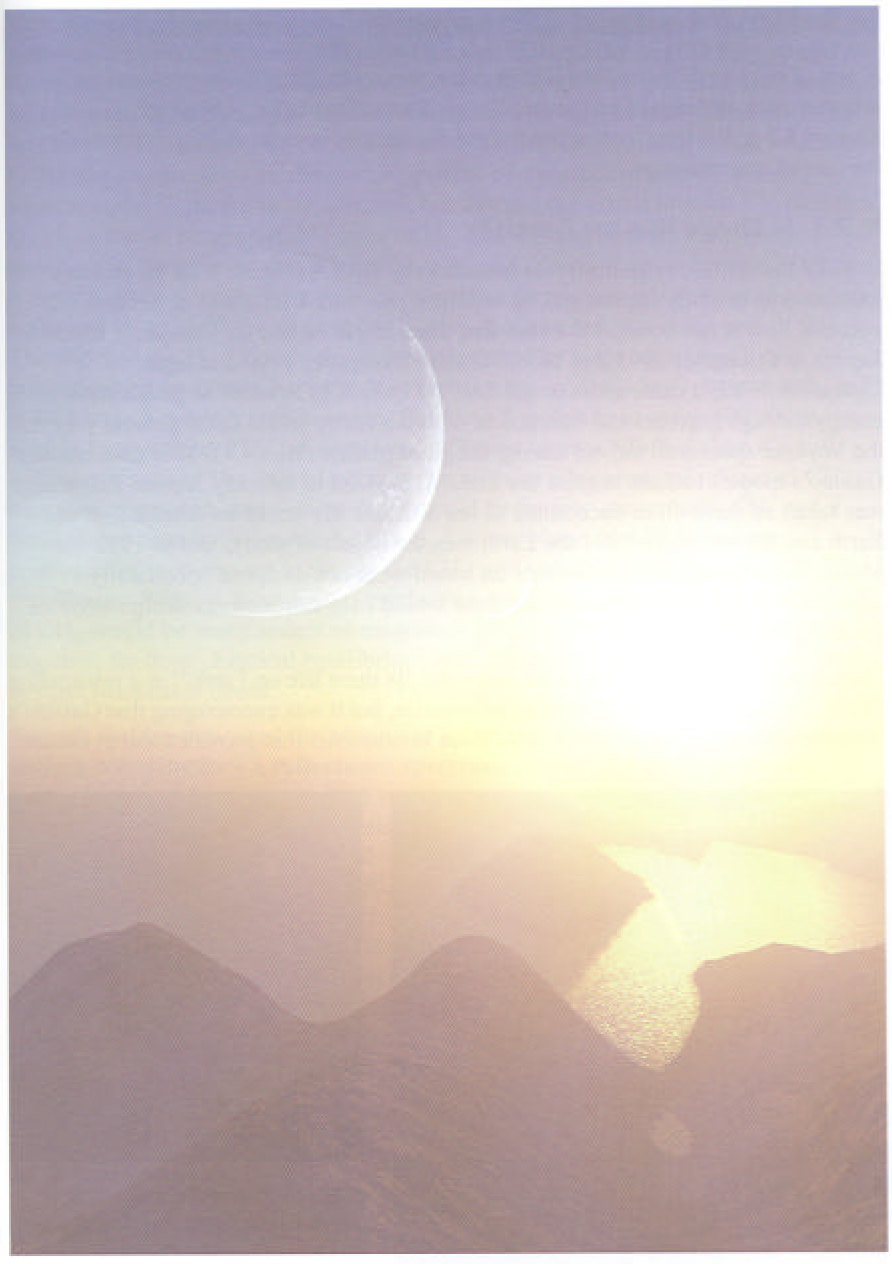


Figure 8.1 An impression by the artist Julian Baum of a large satellite around a giant planet in a habitable zone. (Copyright © Take 27 Ltd)

In 1989, NASA sent an exploration spacecraft to study Jupiter and its moons

- **GALILEO** – reached Jupiter in 1995

To gain energy, came back twice near Earth and Moon and took some observations to see if its instruments can detect evidence of life – the answer was YES!

Figure 2.1 From 4 million miles away on 16 December 1992, NASA's Galileo spacecraft, on its way to Jupiter, took this picture of the Earth–Moon system. The bright, sunlit half of the Earth contrasts strongly with the darker subdued colours of the Moon. (NASA)

NIMS – Near Infrared Spectrometer

- Atmospheric substances detected – O_3(Ozone) and CH_4 (Methane)
- O_3 strong spectral signature in IR, its presence $\Rightarrow$ large amount of O_2
- CH_4 - small infrared signature
  - Like O_2 generated by large living organisms + bacteria
  - Readily oxidized by O_2 to give CO_2+ H_2O (1 mol/600000)
  - Without large rate of CH_4 released, would be impossible to detect
- Observation of O_2 + CH_4 $\Rightarrow$ irrefutable signature of life

Reflectance spectrum – amount of light reflected at different wavelengths

- Beyond 0.8μm sharp rise in reflectance $\Rightarrow$ green vegetation
  - Chlorophyll + structures that reject radiation not used by Chlorophyll
  - Less certain indicator of life

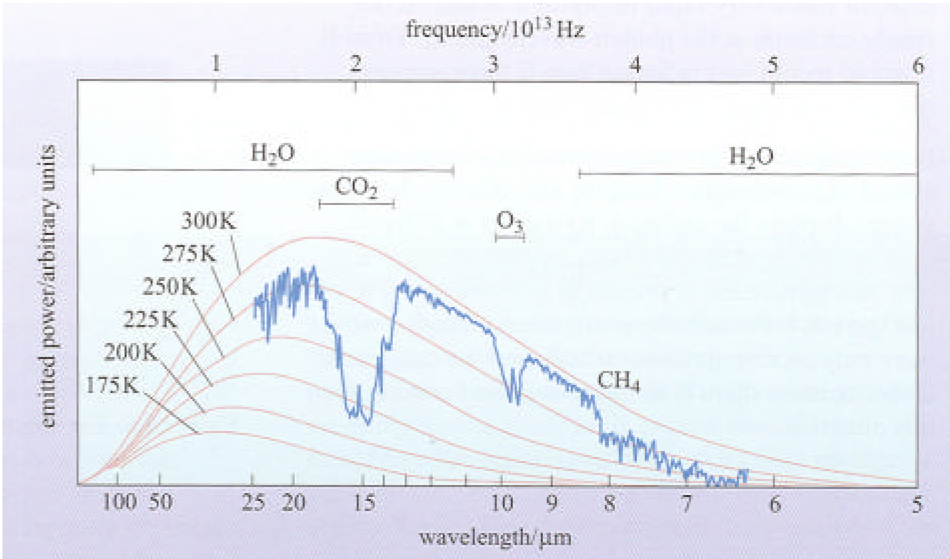
Radio receiver – strong radiation confined to narrow wavelengths

- Intensity not constant in time = modulated
  - Modulated signal $\Rightarrow$ information carried by radio + television programs

Camera images – no detection of city lights (during night) or any other artifacts
Similar observation pointed to the Moon revealed no signals what so ever

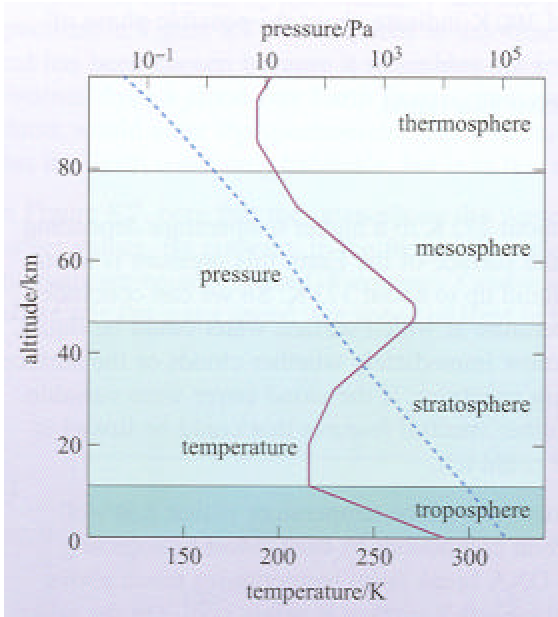
In 1970, **NIMBUS-4** satellite took IR spectrum of Earth during day time over Pacific Ocean

- Equivalent to cloud free Earth seen from great distance when light of whole planet enter the spectrograph

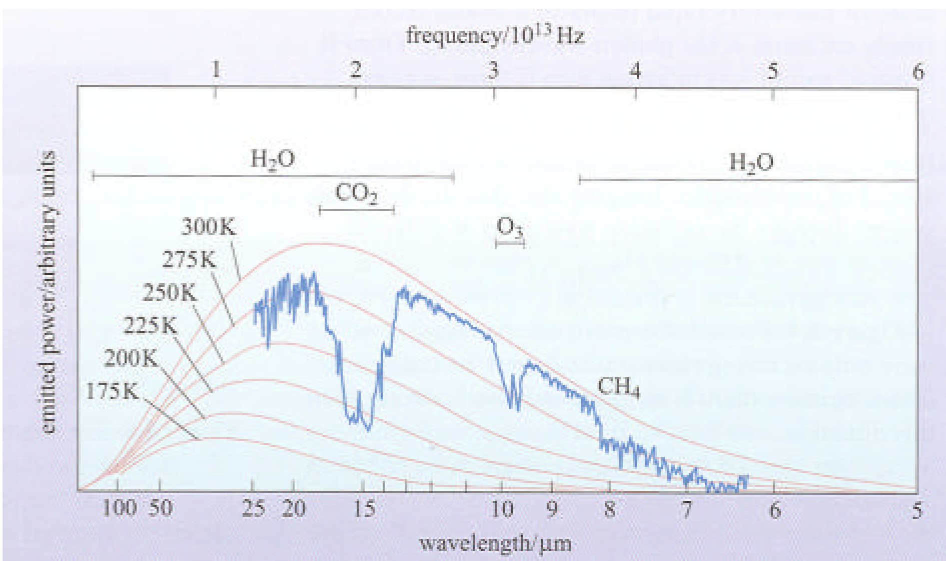


- Between 12µm and 8 µm continuum curve consistent with T ~ 300K $\Rightarrow$ water could exist under liquid form
- Temperature well within range for complex life compounds
- Presence of water vapor in atmosphere produces many absorption bands longwards of 12µm – intense between 20 µm and 25 µm – continuum in this part suggests temperature of 275K
    - Water vapor stop emission from surface to reach space, reemitting at lower temperature

- Graph of variation of temperature (solid line) with altitude suggests a few km above surface ⇒ water vapor concentrated in lowest part of atmosphere



- Around 15μ very strong CO_2 absorption bands
  - Dip of absorption line consistent with temperature 220K ⇒ 10km = upper atmosphere
  - Actual amount of CO_2 = 0.035% of all molecules

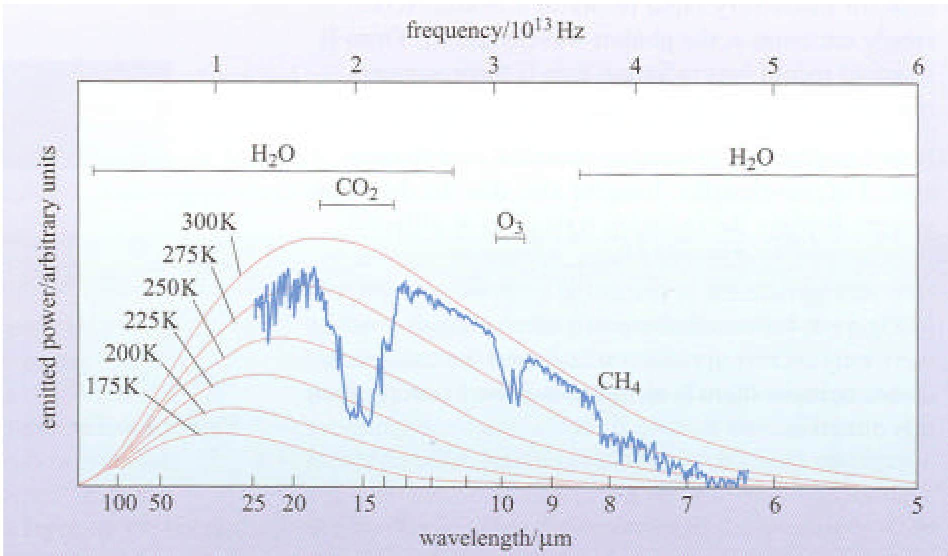


- Dips around 9μm and 6 μm ⇒ O_3
  - Produced by O_2 photolysis ⇒ depth of band implies large amount of O_2

Large amount of O_2 cannot be produced by H_2O photolysis $\Rightarrow$ must be the product of biogenic process

When Sun luminosity will increase in 1000Ma photolysis contribution will be more important but this will not last very long before Earth dry completely $\Rightarrow$ probability that an exoplanet without life shows such structures is very small

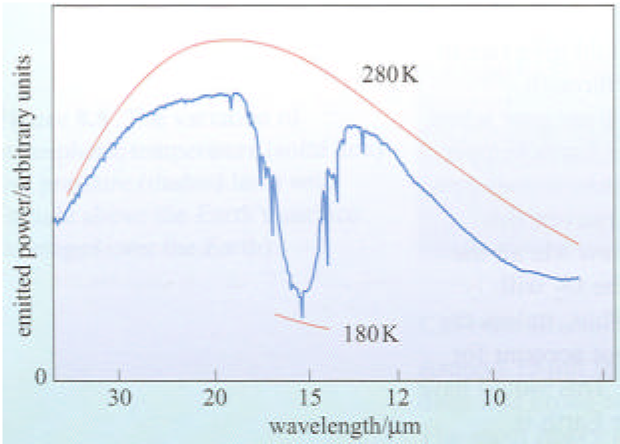
Small planets very near their suns may also have high O_2 in its atmosphere



Central region of the dips consistent with 270K $\Rightarrow$ lower or upper altitude
High altitude favored considering UV more abundant

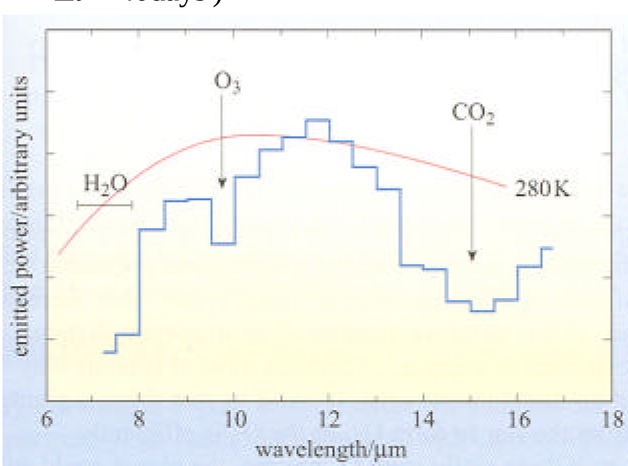
The presence of CH_4 + O_2 = definite signature of life

MARINER 9: IR spectrum of Mars - mid latitude + daytime + clear conditions



- No evidence of O_3 $\Rightarrow$ no O_2
- No biosphere $\neq$ absence of life, could be more primitive or burry underground?
- However, no evidence from Landers also
- Strong absorption in CO_2 consistent with temperature of 270K – below freezing points of water
- No water absorption bands $\Rightarrow$ whole planet looks dry
- Global surveyor + Odyssey $\Rightarrow$ possibly buried water 1-11 km below surface

Possible IR spectrum of an exoplanet – prediction for an Earth like planet in HZ at 30lyrs, as observed with Darwin size IR spaceships ($\Delta l \approx 0.5 mm$ and $\Delta t = 40\text{days}$)



- Low resolution $\Rightarrow$ must increase $\dfrac{l}{\Delta l}$

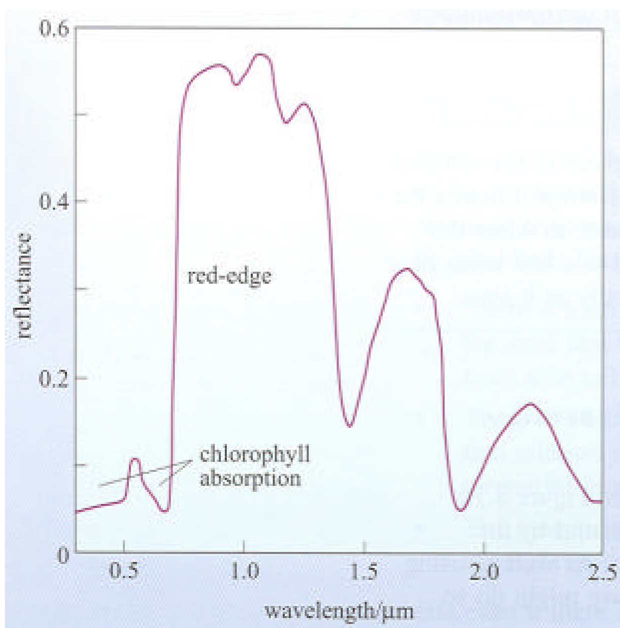
Absence of O_2 may not imply absence of life

- Little UV to form O_3
- O_3 efficiently removed from atmosphere
- Biosphere on Earth formed only 2000Ma ago, compared to apparition of life 4Ga ago
- Organisms may use anaerobic photosynthesis = Photosynthetic Eubacteria
- Presence of other gas may also suggest life activity
    - Any redox pairs (CH_4 and O_2 is one example) far from equilibrium could be evidence of alien biochemistry – but this unlikely since C-based life is more probable

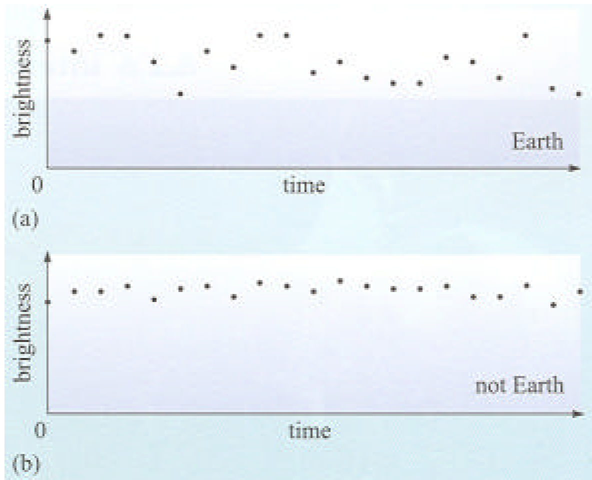
Exoplanets in the visible

The red edge of green vegetation (0.38 µm – 0.78µm) could be detected ⇒ Sun like stars

- Chlorophyll absorbs photons in the red + blue (explain green appearance)



Very large aperture telescopes could detect variation of reflectance produced by variation of surface Albedo (10% for Ocean, 60% for ice and snow and in between for desert)



The graphic show the variation of brightness due to rotation

- Greater for isolated *l* but need very large aperture and long exposure
- Problem also is variation in cloud cover ~ 20% contribution?

Visible spectrum

- Very strong signatures for H_2O, + CO_2 + O_2
    - Because involve 1 e^- instead of whole molecule ⇒ less symmetric = more intense effect
- Need space telescope + special design to reduce factor billion to one difference in luminosity

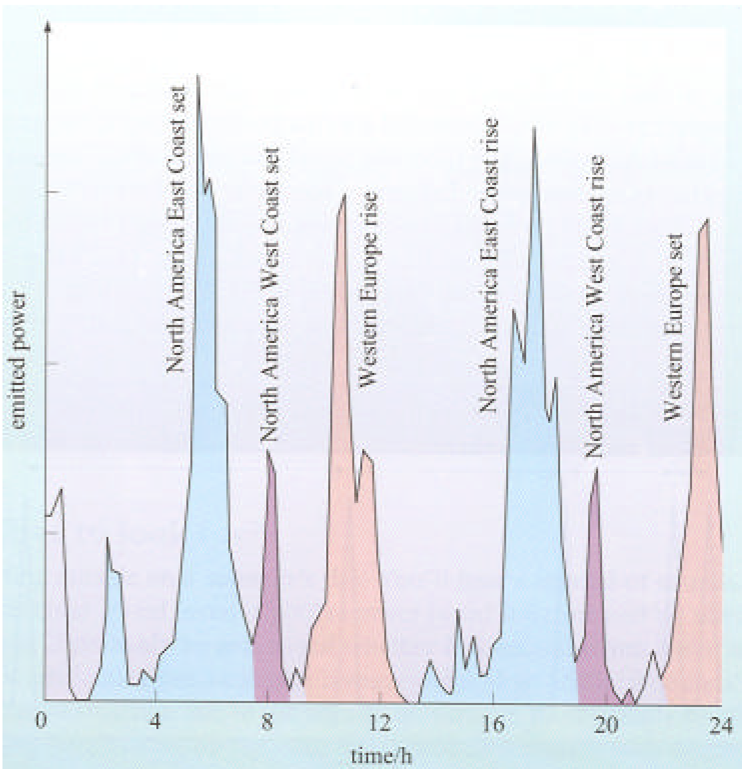
Direct probe (spaceship) – not quite possible

- 10% of velocity of light ⇒ 44yrs to reach Alpha Centaury
- Energy to accelerate at 0.1c is enormous
- Voyager 1 (launched in 1977) – will take 10000yrs before reaching nearest stars
- Possible = ion motors ⇒ small quantity of gas + long cumulative acceleration time

Radio detection

Unintentional signal sent to space is practically undetectable

- Problem = weak transmission at any frequencies
- Very rapidly, signal is lost in radio noise of space
- Limit of detection is only a few 10s of lyrs
- Regular variations would be expected related to rotation of planet



SETI project

SETI = **Search for Extraterrestrial Intelligence**

Carl Sagan (1960s) – Based on Drake's equation there must be 10^6 living intelligent civilizations in our Galaxy – very much exaggerated (see beginning of notes)

Definition of intelligent = capable of communicating message through space = working hypothesis $\Rightarrow$ SETI looking for intentional extra terrestrial communication – We are not doing it so why other civilization would do this?

Search restricted to radio + visible part of spectrum

- Advantage of Radio – stars are many orders of magnitude weaker than a intentional radio signal + narrow bandwidth + beamwidth
- Such a transmission from radio telescope on planet orbiting a distant star would cause apparent increase in brightness by factor 10^6 = unmistakable signature

Carl Sagan – search at $1420\boldsymbol{p}$ or $1420/\boldsymbol{p}$ MHz

- because very few natural emission at these frequencies
- Other possibility = 1720MHz – OH molecule
- Narrow bandwidth is best – because of larger flux
- Also more easily detected if receiver observe narrow bandwidth centered on correct frequency
- Large bandwidth = lower amplitude signal but less crucial for frequency emitted
- Ex. 1420MHz with 10Hz band width – best = receiver with 5Hz band width – 1HZ $\Rightarrow$ 1/10 of signal while 100Hz include noise.

Modern Radio Telescopes can monitors 100s of 10^6 narrow band (less than 1HZ) channels at the same time speeding up search

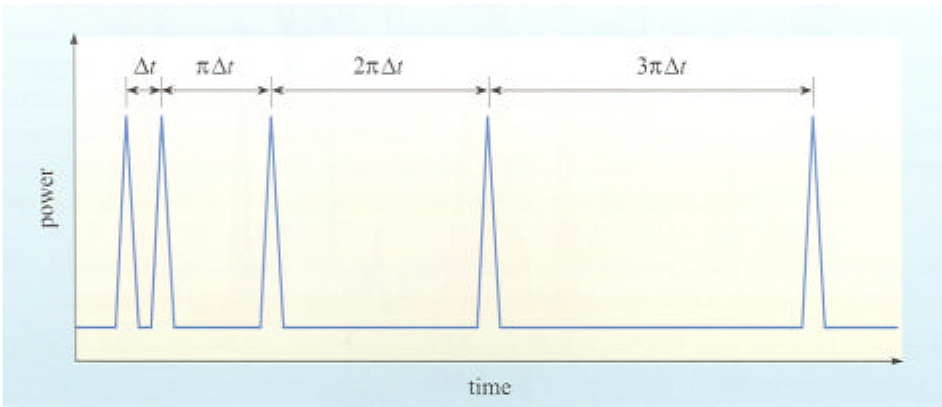
Problem = studying the data $\Rightarrow$ SETI@Home project – use personal computers on the INTERNET, analyzing large chunks of data

Where to look?

- Nearby stars are up to now the best targets – why? Not very clear! – this is going fishing

What to look for?

- Natural signals are aperiodic – exception = pulsars
- Periodic signal of the order of s, d, m, y = human origin
- Search for regular structures in Δt or Δu



CETI – Communicating with extraterrestrial intelligence

In 1974, Drake sent a message towards M13 with Arecibo telescope

The message was sent 2 times for 2 minutes each time at 2380 MHz with bandwidth 10Hz

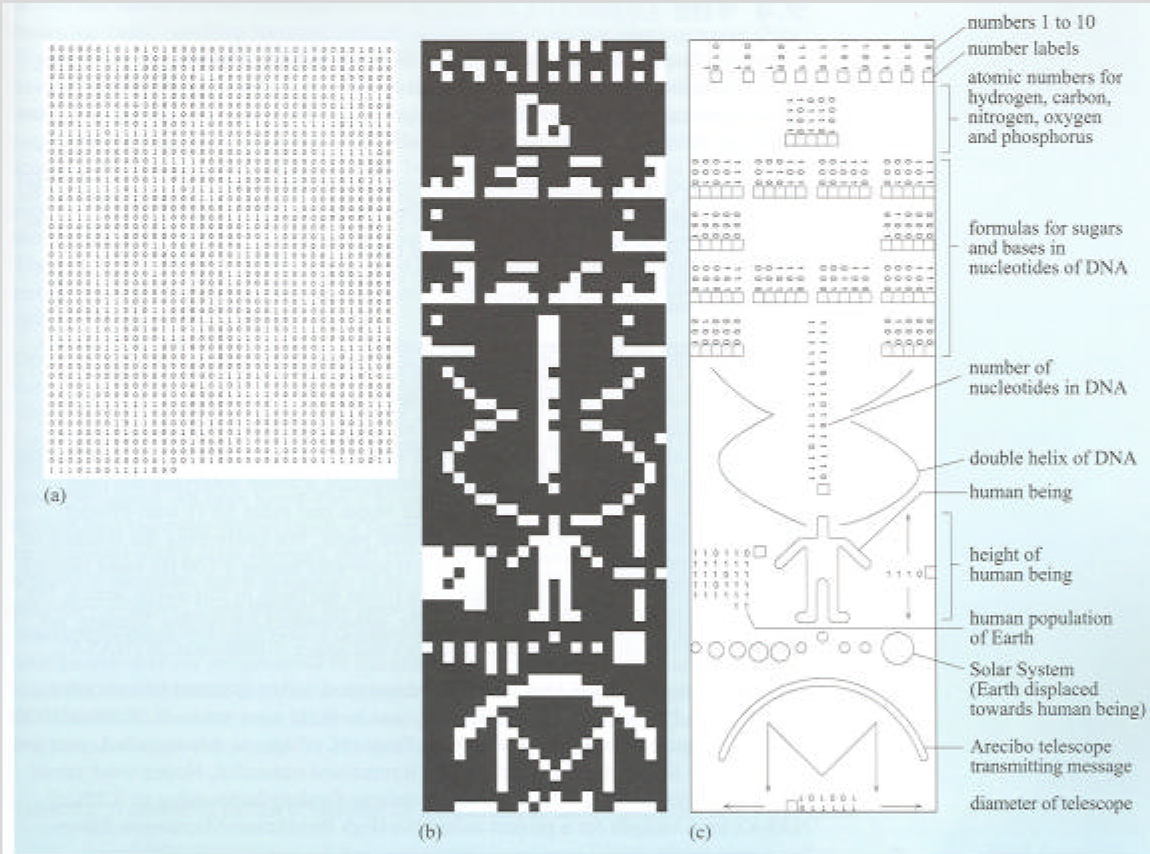
Sir Martin Ryle spoke to Drake asking about wisdom of doing so

The answers:

1- Messages already leak in space for many years – but very weak power – not relevant
2- No immediate treat – response in 50000 yrs

Message sent = 1679 bits of information

- 1679 = 23 x 73 (product of 2 prime numbers)
- Image dimension is 23 x 73



When Drake presented the message to colleagues, only a few could decipher part of it

No one could decode every bits of it

Search to date

First paper on SETI = 1959, Nature – **G. Cocconi** & **P. Morrison** (Cornell University)

- Suggested that radio waves are better to do the work and that 1420MHz is best

The next year Drake started the project **OZNA**

- Drake was not aware of the previous article
- Search at 1420MHz with bandwidth 100Hz
- No result but raised interest of public + NASA

Plan of NASA = **CYCLOPS**

- Directed by **Bernard Oliver** (Hewlett-Packard head of research)
- Consisted in network of 1000 radio telescopes 100m each
- Never funded – judged too costly by Congress

Early 1990s – NASA planned 0.1% of its budget for project **HRMS** – High Resolution Microwave Survey

- Also cut by Congress

SETI institute – **Project Phoenix**

- Private funding
- Using – Arecibo + Jodrell Bank + Parkes + Greenbank + West Virginia
- Plan = Allen array project – one hectare telescope = 500 antenna standard satellite dishes – will also be used for standard astronomy observations

University of California at Berkeley – **SERENDIP project**

- Serendip use of constant observations made by radio astronomers at Arecibo
- Data every second from 168 channels (bandwidth 0.6Hz) around 1420MHz
- Random position of different part of the sky, but since the telescope is fixed only needs a few months to cover the whole sky
- Rate of incoming data exceeds computational capacity
- They run SETI@Home – a program that runs like a screen saver

Table 9.2 A chronological list of searches for extraterrestrial radio signals from alien civilizations.

Year	Investigator(s)	Antenna diameter/metres	Observation frequency/MHz	Frequency resolution/kHz	Total frequency band/MHz
1960	Drake	26	1420	0.1	0.4
1968–82	Troitskii	14	100, 1800, 2500	0.013	2.2
1972–76	Zuckerman & Palmer	91	1413–1425	4	12
1972	Verschuur	43, 91	1420	7	20
1972–76	Bridle & Feldman	46	22, 235	30	–
1973–86	Dixon et al.	53	1420	30	0.4
1975–76	Drake & Sagan	305	1420, 1653, 2380	1.0	3
1976–85	Bowyer et al.	26	variable	2.5	20
1988	Bania & Rood	43	8665	0.3	–
1992–93	NASA	305	1300–2400	1, 7, 28	1100
1992–93	NASA	26, 34	1700, 8300–8700	0.019	400
1992–	Bowyer et al.	305	424–436	0.0006	10
1995–	Horowitz	26	1400–1720	0.0005	320
1995	SETI Institute	64, 22	1200–1750	0.001	550
1996–	Werthimer	305	1370–1470	0.0006	100

Recently – **OSETI** = Search for laser light pulses using optical telescopes

CONCLUSION

After 42 years of search no detection – significant null result $\Rightarrow$ decreases upper limit on N_b

Fermi paradox

If intelligent life is not rare and if it is able to colonize the Galaxy within a few millions years of becoming an intelligent civilization why isn't the galaxy obviously teeming with such life?

Let assume humans embarking on a 90yrs voyage to a 10lyr away star

- Ship depart with 500 couples
- Assumes individual 25 yrs old with life expectancy 75yrs
- Assumes also that each couple have 4 children, that have offspring after 25 yrs
- First generation: 4 x 500 = 2000 children
- After 25 yrs offspring = 4 x 1000 = 4000 grandchildren
- 50 yrs first generation dies
- But 4 x 2000 = 8000 greatchildren
- After 75 yrs 16000 greatgreatchildren + second generation dies
- In total 24000 = 2 generations – 16000 mid 20 and 8000 with 50

    - Now let assumes that upon arrival the crew makes a copy of itself so that after 100 yrs of departure from Earth, 2 ships are going to stars distant by 10 lyrs
    - Repeating this process human could colonize the opposite side of the galaxy in 1Ma
    - The population would have grown by a factor $10^6/25 = 40000$ times $\Rightarrow 2^{40000}$ individuals
    - The number of ships also double every 100 years so after 30000 yrs you would have as many ship as there are stars in the Galaxy

CONCLUSION we could colonize the whole galaxy with sub-light speed technology over a time scale much shorter than 10^9

- **This remains true even if one takes 1000yrs to reach nearby stars**

- **Resources is the main problem not technology**

The above scenario emphasizes Fermi paradox

The answer is that we may be the first civilization in the Galaxy to reach such level

The explanation is given by **J. D. Barrow** (1998 Astro-ph/9811461)

- Strangely enough the answer to Fermi Paradox is the same as for another well known paradox, the **Olbers paradox:** Why is the sky dark at night?
- The most important discovery about the Universe is that it is expanding $\Rightarrow$ the physical state of the universe suffers steady changes – for example the density would change with time as $r \approx \frac{1}{Gt^2}$, where G is the gravitational constant
- Drama in many acts: formation of first atoms + molecules, then formation of galaxies and stars, and more recently the formation of planets and life
- For a universe infinite in time and space (steady state theory) any event that has a finite probability of occurring should occur not just once but infinitely often $\Rightarrow$ the Universe should be teeming with life
- Chemical complexity in an expanding Universe requires heavy atoms (C, N, O etc.) to form
- These are made in stars (only H, He, D and Li made by Big Bang) $\Rightarrow$ on time scale for nuclear reaction 10^9 years
- SN explosion (for O, C) + planetary nebulae (for N) are then necessary to disperse the metals in the ISM
- This metal form grains (dust) that form planets and finally life
- Therefore a Universe that is billions of years + in size + sparse (large distance between stars and galaxies) + cold is natural environment for life
- **The low density + temperature explained Olber paradox: there is not enough energy available in space to provide significant apparent luminosity from all stars in all directions**

- Life evolve on time scale intermediate between typical scale for stars reaching MS and time for exhaust of nuclear fuel: $t_* \simeq \left(\frac{Gm_p^2}{hc}\right)^{-1} \propto \frac{h}{m_p c^2} \approx 10^9\,\text{yrs}$, where m_p is the mass of the proton, h is Planck constant and c the velocity of light

- On the other hand, the expansion rate of the Universe is given by $t_0 \approx \frac{2}{3H_0}$ where $H_0 \approx 75\text{km s}^{-1}\ \text{Mpc}^{-1}$ which is Hubble constant

- The fact that $t_* < t_0$ is a natural consequence of the expanding Universe

- Based on what we know about the emergence of life on Earth we can say that the timescale for biological life is $t_{bio} = t_*$

- Now, if t_{bio} is independent of t_* (as is more naturally assumed) then the time that life takes to rise is random with respect to the stellar time scale

- Then it is most likely that $t_{bio} \gg t_*$ or $t_{bio} \ll t_*$

- However, if $t_{bio} \ll t_*$, then the event that $t_{bio} = t_*$ (our solar system) is therefore a very extraordinarily unlikely event

- On the other hand, if $t_{bio} \gg t_*$ then the first observed system (us) is most likely to have $t_{bio} = t_*$

- Most system with $t_{bio} \gg t_*$ have yet to form

- In an expanding Universe we should thus expect extraterrestrial life to be exceptionally rare

- We are a rarity, one of the first living intelligent system to arrive to the scene

CQFD