The reader may seek to consign these speculations wholly to the domain of science-fiction. We submit, rather, that the foregoing line of argument demonstrates that the presence of interstellar signals is entirely consistent with all we now know, and that if signals represent the means of detecting them is now at hand. . . The probability of success is difficult to estimate; but if we never search, the chance of success is zero.

### Sun-like Stars

**R_s** – how many “useful” stars of 200,000,000,000 in our galaxy form each year?

- long lasting - to allow complex life to develop
  - 3.5 - 4.0 billion years for the Earth

- quiet and steady energy production
  - few big flares or other ‘stellar flares’
  - no binary companion

- about 1/3 of all stars are “useful”

**R_s** ~ 8 stars / year

### The Drake Equation

Parameterizing our ignorance

\[
N = R_s \times f_p \times n_p \times f_L \times f_i \times f_c \times L
\]

- **N** is the number of communicating civilizations in the Galaxy today

<table>
<thead>
<tr>
<th>Astronomical factors</th>
<th>(= R \times f \times n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological factors</td>
<td>(x \times f \times x )</td>
</tr>
<tr>
<td>Sociological factors</td>
<td>(x \times f \times L ) (# of years communication continues)</td>
</tr>
</tbody>
</table>

#### Searching for planets around other stars

- **Jupiter and the Sun**
  - the Sun has a luminosity of \(4 \times 10^{33} \) erg/s
  - Jupiter emits at most \(8 \times 10^{24} \) erg/s
  - the Sun emits 500,000,000 times more light than Jupiter
  - viewed from 10 pc, they are separated by 5 arc sec

- **equivalent to**
  - 1 candle,
  - 10 feet away from a stadium light bank,
  - viewed from 80 miles away!
Searching for planets around other stars

There are other ways to find them....

- Kepler’s 3rd Law
- The "See-Saw" Law
- \( M_{\text{planet}} \ll M_{\text{star}} \)
  - star moves in a small orbit
  - measure \( d_{\text{star}} \) and you know \( M_{\text{planet}} \)

**Wobbles of stars from reflex motion:**

\[
\frac{d_{\text{planet}}}{d_{\text{star}}} \approx \frac{M_{\text{star}} - M_{\text{planet}}}{M_{\text{star}}}
\]

Credit: R. Pogge, OSU
Reflex Orbital Motion

- Jupiter is $1/1000 \, M_{\text{sun}}$
- Sun orbits $5\,\text{au}/1000 = 1/200 \, \text{a.u.}$ around CM
- A ‘Jupiter’ around Barnard’s star would cause a wobble $1/200$ the size of the wobble below

Spectroscopy - look for the velocity wobble

**Orbital motion:**

- **Improved chances for detection ($V_{\text{star}}$ bigger):**
  - if planet is massive
  - if planet is close to star
  - also - shorter period = faster detection

- Biggest effect if orbit viewed EDGE ON
- Tilt of orbit to line-of-sight reduces observed velocity

Jupiter as an example:

- $V_{\text{Sun}}$ around CM of Solar System = 13 m/s (= 30 mph)
- Doppler effect of 13 m/s is 1 part in 23,000,000 (!)
- varies cyclically over a 12 year cycle
- very difficult (but not impossible) to measure
- need stable spectroscope over long time
- Earth? 9 cm/s!

**Improved chances for detection ($V_{\text{star}}$ bigger):**

\[
V_{\text{star}} = \frac{30 \text{ m/s}}{\sqrt{M_{\text{star}}}} \times 2\pi \times \frac{1}{\sqrt{d}} \times \frac{M_{\text{planet}}}{M_{\text{Jupiter}}}
\]

if planet is massive

1990-1995 Searches

- precision needed finally achieved
- first searches looked for orbit periods of months
- first discovery: 1995: Mayor & Queloz:

- $P_{\text{orb}} = 4.233$ days
- $M_{\text{planet}} = 0.45 \, M_{\text{Jupiter}}$
They are Planets: proof from HD 209458 (1999)

Radial Velocity variable:
M = 0.69 ± 0.05 M_J
P = 3.524738 ± 0.000015 d.

and orbits along our line-of-sight so --> planet transits across the star!

1995 - 2014 Huge strides

• now over 419 known extrasolar planetary systems found by RV
• many found by Geoff Marcy, Paul Butler, & Friends
• Most are massive planets
• Most have small orbits
• Many are multiple-planet systems
• one system looks like our own solar system in 5 billion years

Two interesting systems:
55 Cancri and V391 Pegasi

• a 5(?) planet system
• planet distribution similar to our own solar system
• room in between for stable earthlike planets
Two interesting systems: 55 Cancri and V391 Pegasi

- a 5(±?) planet system
- planet distribution similar to our own solar system
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A Giant Planet Orbiting a Hot, Evolved Star

Silvotti et al.

submitted to Nature on 6 April 2007
accepted 26 July 2007
published September 13, 2007

2001-2002

2007 - 6 more years

- f1 and f2 remained stable
- (O-C) analysis yields
  - secular change in frequencies (parabola)
  - reflex orbital effects (sinusoid)
Two interesting systems: 
55 Cancri and V391 Pegasi

- planetary system that has survived first death of the parent star
- discovered by pulsation phase drift in the remnant stellar core
- work done (in part) with the Whole Earth Telescope
- Roberto Silvotti (Naples) and a bunch of us!
The Habitable Zone

• water essential to life (as we know it)
• liquid water has to exist on (or in) the planet
• must be right distance from star
  • heat from star ~ maintain $32^\circ F < T < 212^\circ$
  • too close - runaway greenhouse (Venus)
  • too far - CO$_2$ ice - no greenhouse (Mars)
• BUT
  • life exists in extreme environments on Earth
  • liquid water a constraint for “normal” life only

Planet Size and Habitability

• Planets form by accretion from a disk of gas and dust

• Too small (about <0.5 M$_{\oplus}$):
  • Can’t hold onto a life sustaining atmosphere (Mercury, Mars)
  • no tectonics - no carbon regulation
  • surface gravity g < 0.8 G

• Too big (about >10 M$_{\oplus}$):
  • Can hold onto the very abundant light gases (H$_2$ and He)
  • turns into a giant (Jupiter, Saturn) or ice giant (Uranus, Neptune)
  • surface gravity g > 2.2 G