Recently: Life, its origin, early Earth, habitability.
Today: Exoplanets

Reading: As posted.
Homework #4 posted, due Thursday 3rd May.
Final paper: draft or outline+refs, due Thursday 26th April.
EXTRASOLAR PLANETS: DETECTION METHODS
Detecting Extrasolar Planets

Basic tools for detecting exoplanets:

• Image them directly (seeing is believing).
• Other direct radiation (natural IR, radio emission).
• Measure gravitational perturbations:
  - Doppler shift of spectral lines from the host star.
    The planet orbits the center of mass of its star + planetary system.
    So does the star, but with smaller and slower orbit.
  - Wobble of star on the plane of the sky (astrometry).
  - Time of arrival of pulses from a pulsar with orbiting planet.
  - Gravitational microlensing of background stars by foreground stars
    and planets (bending of light).
• Photometry of host star with orbiting planets: measure change
  in light when planet transits the star or star eclipses the planet.
• Perhaps: measure signals from exo-civilizations.
Exoplanets: Where do we stand?

• Till 1990: 9 planets, one solar system.
• 1992: First confirmed extra-solar planets. PSR B1257+12, with 2.8 $M_\text{\textsc{e}}$ and 3.4 $M_\text{\textsc{e}}$ planets.
• Since then …
Exoplanets: Where do we stand?

3710 total confirmed planets! + 2620 as-yet unconfirmed candidates.
Discovering Extrasolar Planets I

• **Pulsar timing:**
  – Measuring the change in path length from pulsar to Earth caused by recoil of the neutron star from planetary motion.
  • Can measure position of neutron star to ~ one light microsecond or better.

• **Radial velocity measurements of starlight:**
  – Doppler recoil of star from planetary orbits.
  – “Radial” means motion along the line of sight.
  • Measurement accuracy ~10 m/s (not as good as pulsar timing).

• **Transits:** passing of planet across stellar disk.
  – < 1% dips in the star’s brightness.
  – Orbit needs to be nearly “edge on” unless planet is large and close to the star.
  – Secondary transit as planet passes behind star.
Discovering Extrasolar Planets II

- **Gravitational microlensing:**
  - Gravitational bending of light (focusing).
  - Predicted by Einstein in 1912.
  - Background star is lensed by foreground star + planet.

- **Direct detection:** imaging a planet’s light directly.
  - Difficult because of host star’s brightness (10^5 to 10^6 times brighter).
  - Planet’s light is reflected starlight.
Discovering Extrasolar Planets III

- **Astrometry**: measuring the wobble of a star’s position on the sky from recoil motion.

- **Planetary radiation**:  
  - Analogous to the Jupiter-Lo effect (non-thermal radiation from particles from Io in Jupiter’s magnetic field).

- **SETI**: search for transmissions from technological civilizations.  
  - Low likelihood, tremendous payoff.  
  - The ETs can tell us all about their planet (and presumably many others).
GRAVITATIONAL LENSING
Gravitational Lensing

- Bending of light by masses (General Relativity).
- 2\textsuperscript{nd} test of GR: Eddington’s eclipse measurements of 1919: stellar offsets from Sun’s gravity (about 1 arcsec).

\[
\theta = \frac{4GM}{rc^2}
\]

(Bending from a neutron star is \(~50\) deg.)
Fig. 1. Notes about gravitational lensing dated to 1912 on two pages of Einstein’s scratch notebook (12). [Reproduced with permission of the Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem].

J Renn et al. Science 1997;275:184-186
LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

Some time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

The light coming from a star A traverses the gravitational field of another star B, whose radius is $R_0$. Let there be an observer at a distance $D$ from B and at a distance $x$, small compared with $D$, from the extended central line $AB$. According to the general theory of relativity, let $\alpha$ be the deviation of the light ray passing the star B at a distance $R_0$ from its center.

For the sake of simplicity, let us assume that $AB$ is large, compared with the distance $D$ of the observer from the deviating star $B$. We also neglect the eclipse (geometrical obscuration) by the star $B$, which indeed is negligible in all practically important cases. To permit this, $D$ has to be very large compared to the radius $R_0$ of the deviating star.

It follows from the law of deviation that an observer situated exactly on the extension of the central line $AB$ will perceive, instead of a point-like star $A$, a luminous circle of the angular radius $\beta$ around the center of $B$, where

$$\beta = \sqrt{\frac{R_0}{\alpha D}}.$$

It should be noted that this angular diameter $\beta$ does not decrease like $1/D$, but like $1/\sqrt{D}$, as the distance $D$ increases.

Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever approach closely enough to such a central line. Second, the angle $\beta$ will defy the resolving power of our instruments. For, $\alpha$, being of the order of magnitude of one second of ares, the angle $R_0/D$, under which the deviating star $B$ is seen, is much smaller. Therefore, the light coming from the luminous circle can not be distinguished by an observer as geometrically different from that coming from the star $B$, but simply will manifest itself as increased apparent brightness of $B$.

The same will happen, if the observer is situated at a small distance $x$ from the extended central line $AB$. But then the observer will see $A$ as two point-like light-sources, which are deviated from the true geometrical position of $A$ by the angle $\beta$, approximately.

The apparent brightness of $A$ will be increased by the lens-like action of the gravitational field of $B$ in the ratio $q$. This $q$ will be considerably larger than unity only if $x$ is so small that the observed positions of $A$ and $B$ coincide, within the resolving power of our instruments. Simple geometric considerations lead to the expression

$$q = \frac{1}{x} \cdot \frac{1 + \frac{x^2}{4R_0^2}}{\sqrt{1 + \frac{x^2}{4R_0^2}}}.$$

where

$$l = \sqrt{\alpha D R_0}.$$

If we are interested mainly in the case $q > 1$, the formula

$$q = \frac{l}{x}$$

is a sufficient approximation, since $\frac{x^2}{4R_0^2}$ may be neglected. Even in the most favorable cases the length $l$ is only a few light-seconds, and $x$ must be small compared with this, if an appreciable increase of the apparent brightness of $A$ is to be produced by the lens-like action of $B$.

Therefore, there is no great chance of observing this phenomenon, even if dazzling by the light of the much nearer star $B$ is disregarded. This apparent amplification of $q$ by the lens-like action of the star $B$ is a most curious effect, not so much for its becoming infinite, with $x$ vanishing, but since with increasing distance $D$ of the observer not only does it not decrease, but even increases proportionally to $\sqrt{D}$.

Albert Einstein

Institute for Advanced Study,
Princeton, N. J.

Bright ring is called a caustic

Einstein ring: image when observer, lensing object, and source are along a line
Einstein letter to Editor of Science:

“Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy.”
The results obtained by the British expeditions to observe the total eclipse of the sun last May verified Professor Einstein's theory that light is subject to gravitation. Writing in our issue of November 15 [1919], Dr. A.C. Crommelin, one of the British observers, said: "The eclipse was specially favourable for the purpose, there being no fewer than twelve fairly bright stars near the limb of the sun. The process of observation consisted in taking photographs of these stars during totality, and comparing them with other plates of the same region taken when the sun was not in the neighbourhood. Then if the starlight is bent by the sun's attraction, the stars on the eclipse plates would seem to be pushed outward compared with those on the other plates. The second Sobral camera and the one used at Principe agree in supporting Einstein's theory. It is of profound philosophical interest. Straight lines in Einstein's space cannot exist; they are parts of gigantic curves." From the *Illustrated London News* of November 22, 1919.
Gravitational Lensing

Lensing of a background galaxy by a foreground galaxy.
Gravitational lensing in galaxy cluster Abell 2218. NASA, A Fruchter and the ERO Team (STScI).
Gravitational Lensing as a tool for cosmology, astrophysics, and exoplanets

- Lensing action is from baryonic matter and dark matter.
- Any mass can lens but the effect is much greater with larger masses.
- Lensing from galaxy clusters is used to map out the distribution of dark matter surrounding visible galaxies. → i.e., map out the cosmic web.
- Gravitational lensing useful in trying to obtain a radio image of the Milky Way’s black hole.
- Planet detection.
Milky Way Black Hole

- $\text{Sgr A}^* = 4.6 \times 10^6 \, M_\odot$ black hole
Gravitational lensing of the accretion disk around Sgr A* (the $4 \times 10^6 \, M_\odot$ black hole in the center of the Galaxy).

Potentially can be imaged using radio telescopes and very long baseline interferometry.

Movie credit: Dolence
Gravitational Microlensing

The Earth, a close star, and a brighter, more distant star, happen to come into alignment for a few weeks or months. Gravity from the closer star acts as a lens and magnifies the distant star over the course of the transit.

Before | During | After
--- | --- | ---

The change in brightness can be plotted on a graph:

The Einstein ring has a radius of about 2 AU and is the width of the angular width of the distant star.

If there is a planet orbiting the closer star, and it happens to align with the Einstein ring, its mass will enhance the lens effect and increase the magnification for a short time.

The planet causes a small blip on the graph.
The MACHO and OGLE Projects

• MACHO = Massive Compact Halo Objects as dark matter candidates.

• (Alternative: WIMPS = Weakly Interacting Massive Particles.)

• OGLE = Optical Gravitational Lensing Experiment.

• Goal: search for dark objects in the halo of the Milky Way that gravitationally lens background stars in the Large and Small Magellanic Clouds.

• Results: no exotic dark objects were found this way but gravitational lensing was seen, including from foreground stars with planetary companions.
DETECTING EXOPLANETS WITH DIRECT IMAGING
Direct imaging

- Trying to detect reflected starlight…
- … next to a star. This is hard.
- Block light of star with coronographs.
Direct imaging

- Trying to detect reflected starlight…
- … next to a star. This is hard.

- Block light of star with coronographs.
- Example: 2008 discovery of Fomalhaut b.
  - Measured light is scattered light from surrounding dust, not reflected light from the planet itself or planetary emission.
Measured motion of Fomalhaut b

Dust ring is eccentric and is sculpted by Fomalhaut b.

→ Fomalhaut b orbit is eccentric too.

Current position? Planet was probably deflected by a larger planet closer in to the star, not yet seen.
Direct imaging

• Use coronograph to directly image planets – dream for Terrestrial Planet Finder, JWST.

• Can be done from the ground too. Difficult…

Kuchner & Traub (2002):

Planets around HR8799 with coronograph at Palomar Hale telescope.
DETECTING EXOPLANETS WITH RADIAL VELOCITY MEASUREMENTS
Doppler Shift due to Stellar Wobble
Circular Orbits: Planet & Star

Let \( m_1 = \) planet mass \( \ll m_2 = \) stellar mass

Rename as \( m_p \) and \( M_* \)

Also \( r_1 \) and \( r_2 \) become \( r_p \) and \( r_* \)

The center of mass is given by \( r_p m_p = r_* M_* \), so

\[
\frac{r_*}{r_p} = \frac{m_p}{M_*} \ll 1
\]

Velocities are given by the usual balance between centripetal force and gravity for each of the objects:

\[
\frac{m_p v_p^2}{r_p} = \frac{M_* v_*^2}{r_*} = \frac{G(m_p + M_*)}{(r_p + r_*)^2}
\]

This implies a ratio of velocities:

\[
\frac{v_*}{v_p} = \left( \frac{m_p}{M_*} \frac{r_*}{r_p} \right)^{1/2} = \frac{m_p}{M_*}
\]
Circular Orbits: Planet & Star

\[ \frac{v_*}{v_p} = \left( \frac{m_p r_*}{M_* r_p} \right)^{1/2} = \frac{m_p}{M_*} \]

E.g. Earth and Sun:

\[ v_\oplus = 30 \text{ km s}^{-1} \]
\[ m_\oplus = 6 \times 10^{27} \text{ g} \]
\[ M_\odot = 2 \times 10^{33} \text{ g} \]

\[ \Rightarrow v_\odot = 30 \text{ km s}^{-1} \times \frac{6 \times 10^{27} \text{ g}}{2 \times 10^{33} \text{ g}} = 0.09 \text{ m s}^{-1} \]

Jupiter - about 316 x Earth’s mass:

\[ \Rightarrow v_\odot = 316 \times 0.09 \text{ m s}^{-1} \times \left( \frac{13}{30} \right) = 12 \text{ m s}^{-1} \]

The largest effect is from massive planets close to the star.
If ETs were measuring the radial velocity of the Sun ...
Power spectrum = decomposition into sinusoids

Power Spectrum of the Sun's Radial Velocity

- Jupiter 1st and 2nd harmonics
- Detection of Jupiter + Saturn easiest
- Uranus, Neptune harder
- Uranus + Neptune
- Earth et al. very difficult
Astrometric displacement of the Sun due to Jupiter as at it would be observed from 10 parsecs, or about 33 light-years.
Astrometric displacement of the Sun due to motions of the planets.

Astrometric Displacement: all planets
Chronology

• Several groups attempting to measure radial velocities of stars in the 1990s.
• Expectation was that Jupiter-like planets would be seen in Jupiter-type orbits.
  - Long orbital periods $\rightarrow$ long data sets.
  - (> 10 yr) needed to see in time series.
• A European group (Mayor & Queloz) discovered a planet in radial velocity data of 51 Pegasi.
  • Sun-like star (G5V), 37-day period, 6 Gyr old.
  • 51 Pegasi b = planet with 4.2 day period.
    • Mass > 0.47 x Jupiter’s mass.
    • 0.053 AU semi-major axis.
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

For more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m s⁻¹. As the reflex motion of the Sun due to Jupiter is 13 m s⁻¹, all current searches are limited to the detection of objects with at least the mass of Jupiter (M_J). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s⁻¹. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 M_J, orbiting at 0.05 au around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 M_J for
51 Pegasi observations

AFOE observations of 51Peg

$K: 57.496 \pm 0.053$
$e: 0.075 \pm 0.001$
$P: 4.231 \pm 0.001 \text{ d}$
$\alpha: 132.54 \pm 7.98$
$T_0: -1.936 \pm 0.070 \ (\text{HJD} - 2450000.0)$

RMS[residuals]: 8.15 m/s 38 pts fitted
reduced x^2: 0.85
Triple system in Gliese 581.

Fig. 4. Temporal display of the 3-planet Keplerian model of Gl581, on time intervals with dense observational sampling.
Planets detected by radial velocity

• 450+ confirmed extrasolar planets found with the RV method only.
• 134 confirmed in multiple planet systems.
• Most massive planet
  = HD 180314 b (22.6 Jupiter masses).
• Least massive planet
  = Gliese 581 e (0.00613 M_{Jupiter} or 2.5 M_{Earth}).
  = Alpha Cen B b (0.0035 M_{Jupiter}).

... Changes by the day! Explore at http://exoplanets.org
PLANETS AROUND NORMAL STARS

INNER SOLAR SYSTEM

47 UMa
2.4 M_Jup

51 Peg
0.47 M_Jup

55 Cancri
0.84 M_Jup

Tau Bootis
3.8 M_Jup

Upsilon Andromedae
0.68 M_Jup

70 Vir
6.6 M_Jup

HD 114762
10 M_Jup

16 Cyg B
1.7 M_Jup

Rho Cr B
1.1 M_Jup

ORBITAL SEMI-MAJOR AXIS (AU)