GCE A level

1325/01-B

PHYSICS

ASSESSMENT UNIT PH5

A.M. MONDAY, 18 June 2012

CASE STUDY FOR USE WITH SECTION B

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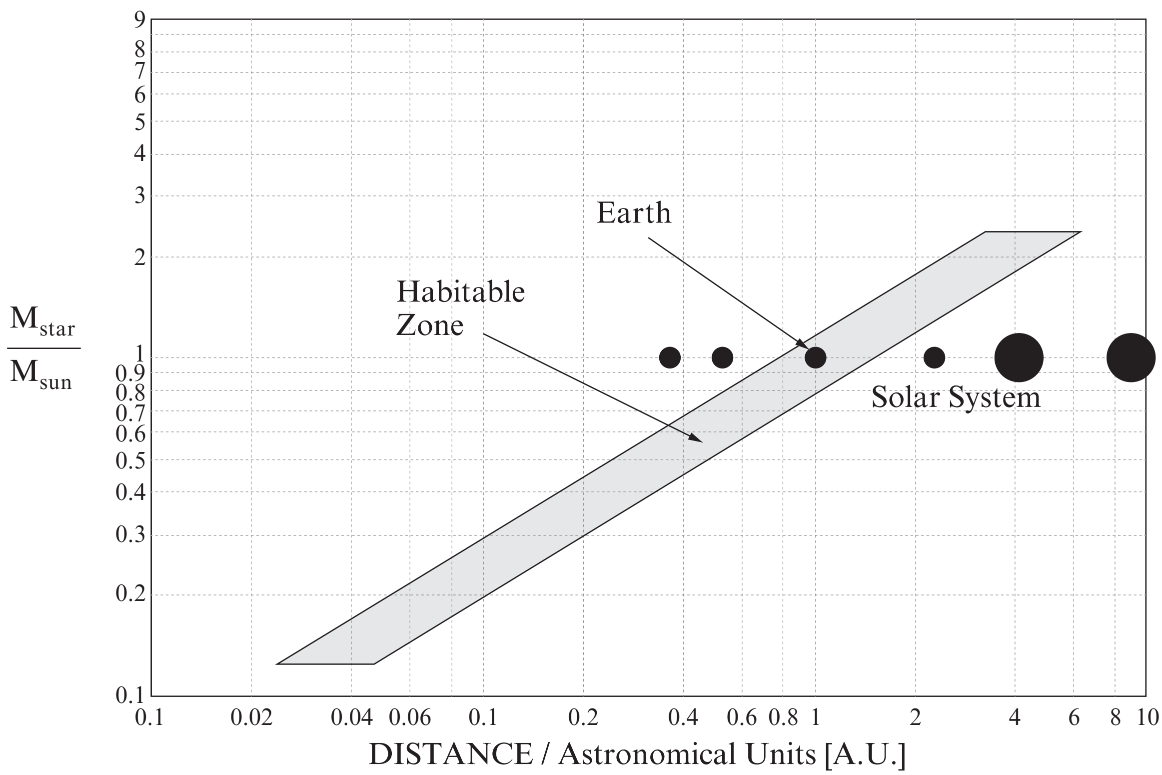
Paragraph

Extrasolar planets

An **extrasolar planet**, or **exoplanet**, is a planet outside the Solar System. Astronomers have announced the confirmed detection of more than 500 such planets. Most exoplanets have been detected through radial velocity observations and other indirect methods rather than actual imaging and most of these are giant planets thought to resemble Jupiter. It is now known that a substantial fraction of stars 1
have planetary systems, including at least around 10% of sun-like stars (the true proportion may be much higher). It follows that billions of exoplanets must exist in our own galaxy alone. There are over a thousand planet candidates awaiting confirmation by more detailed investigations, including nearly a hundred that may be in the "Habitable Zone" (see below).

Graph of Star Mass (relative to our Sun) v Planet Distance from the Star



This planetary habitability chart shows where life might exist on extrasolar planets based on our own solar system and life on Earth. The habitable zone represents the distance from the star 2
where the temperature is not so hot that all the water evaporates and not so cold that all the water freezes.

History of detection

Unconfirmed until 1992, extrasolar planets had long been a subject of discussion and speculation. In the sixteenth century the Italian philosopher Giordano Bruno, an early supporter of the Copernican theory that the Earth and other planets orbit the Sun, put forward the view that the fixed stars are similar to the Sun and are likewise accompanied by their own planets. In 3
the eighteenth century the same possibility was mentioned by Isaac Newton in the "General Scholium" that concludes his *Principia*. Making a comparison with the Sun's planets, he wrote "And if the fixed stars are the centres of similar systems, they will all be constructed according to a similar design and subject to the dominion of *One*."

In early 1992, radio astronomers Aleksander Wolszczan and Dale Frail announced the discovery of planets around a pulsar, PSR 1257+12. This discovery was quickly confirmed, and is generally considered to be the first definitive detection of exoplanets. These pulsar planets are believed to 4
have formed from the unusual remnants of the supernova that produced the pulsar, in a second round of planet formation, or else to be the remaining rocky cores of gas giants that survived the supernova and then decayed into their current orbits.

On October 6, 1995, Michel Mayor and Didier Queloz of the University of Geneva announced the first definitive detection of an exoplanet orbiting an ordinary main-sequence star (51 Pegasi). This discovery, made at the Observatoire de Haute-Provence, ushered in the modern era of 5
exoplanetary discovery. Technological advances, most notably in high-resolution spectroscopy, led to the detection of many new exoplanets at a rapid rate.

Detection methods

Planets are extremely faint compared with their parent stars. At visible wavelengths, they usually have less than a millionth of their parent star's brightness. It is extremely difficult to detect such a faint light source, and furthermore the parent star causes a glare that tends to wash it out.

For the above reasons, telescopes have directly imaged no more than about ten exoplanets. This has only been possible for planets that are especially large (usually much larger than Jupiter) and widely separated from their parent star. Most of the directly imaged planets have also been 6
very hot, so that they emit intense infrared radiation; the images have then been made at infrared rather than visible wavelengths, in order to reduce the problem of glare from the parent star.

At the moment, however, the vast majority of known extrasolar planets have only been detected through indirect methods. The following are the indirect methods that have proven useful:

- **Radial velocity or Doppler method**

  As a planet orbits a star, the star also moves in its own small orbit around the system's centre of mass. Variations in the star's radial velocity – that is, the speed with which it moves towards or away from Earth – can be detected from displacements in the star's spectral lines due to the 7
  Doppler effect. Extremely small radial-velocity variations can be observed, down to roughly $1\,m\,s^{-1}$. This has been by far the most productive method of discovering exoplanets. It has the advantage of being applicable to stars with a wide range of characteristics.

  The Doppler shift of a spectral line is proportional to the orbital velocity of the star and we can use the following equation to approximate the orbital velocity of a star (v_s).

$$v_s = M_p\sqrt{\frac{G}{M_s d}}$$

from, $\frac{M_s v_s^2}{r_s} = \frac{G M_s M_p}{d^2}$ ← centripetal F = gravitational F

and $M_s r_s = M_p d$ ← approximation of centre of mass equation

where M_p is the mass of the exoplanet, M_s is the mass of the star and d is the distance between 8
them (the approximation is that the mass of the star is far greater than the mass of the planet). This equation explains why the Doppler method is most sensitive to large planets which are close to small stars.

Transit method
If a planet crosses (or transits) in front of its parent star's disk, then the observed brightness of the star drops by a small amount. The amount by which the star dims depends on its cross-sectional area and on the cross-sectional area of the planet. For instance, the Earth has a radius 9
approximately 100 times less than the Sun, so as it passes in front of the Sun an observer would notice a 0.01% drop in the Sun's apparent intensity. This has been the second most productive method of detection, though it suffers from a substantial rate of false positives (due to the small drop in intensities) and confirmation from another method is usually considered necessary.

- **Transit Timing Variation (TTV)**
  TTV is an extension of the transit method where the variations in transit of one planet can be used to detect another. The first planetary candidate found this way was exoplanet WASP-3c, using WASP-3b in the WASP-3 system by Rozhen Observatory, Jena Observatory, and 10
  Toruń Centre for Astronomy. The new method can potentially detect Earth sized planets or exomoons.

- **Gravitational microlensing**
  Microlensing occurs when the gravitational field of a star acts like a lens, magnifying the light of a distant background star. Planets orbiting the lensing star can cause detectable anomalies in the magnification as it varies over time. This method has resulted in only a few planetary 11
  detections, but it has the advantage of being especially sensitive to planets at large separations from their parent stars.

- **Astrometry**
  Astrometry consists of precisely measuring a star's position in the sky and observing the changes in that position over time. The motion of a star due to the gravitational influence of 12
  a planet may be observable. Because that motion is so small, however, this method has not yet been very productive at detecting exoplanets.

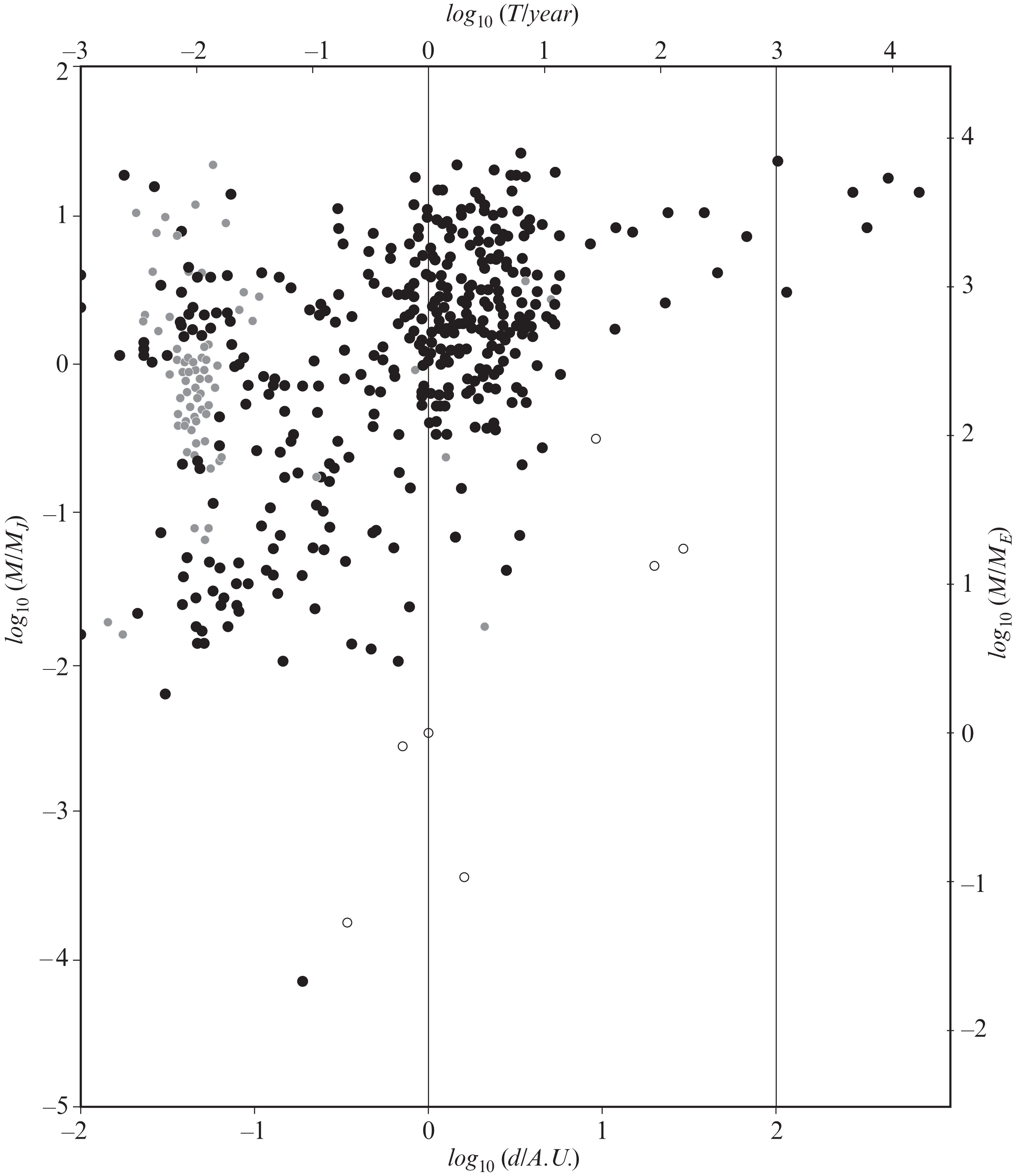
- **Pulsar timing**
  A pulsar (the small, ultradense remnant of a star that has exploded as a supernova) emits radio waves extremely regularly as it rotates. If planets orbit the pulsar, they will cause slight anomalies in the timing of its observed radio pulses. Four planets have been detected in this 13
  way, around two different pulsars. The first confirmed discovery of an extrasolar planet was made using this method.

- **Timing of eclipsing binaries**
  If a planet has a large orbit that carries it around both members of an eclipsing double star system, then the planet can be detected through small variations in the timing of the stars' 14
  eclipses of each other. As of December 2009, two planets have been found by this method.

- **Circumstellar disks**
  Disks of space dust surround many stars, and this dust can be detected because it absorbs ordinary starlight and re-emits it as infrared radiation. Features in the disks may suggest the 15
  presence of planets.

Most extrasolar planet candidates have been found using ground-based telescopes. However, many of the methods can work more effectively with space-based telescopes that avoid atmospheric haze and turbulence. COROT (launched December 2006) and Kepler (launched March 2009) are the two currently active space missions dedicated to searching for extrasolar 16
planets. Hubble Space Telescope and MOST have also found or confirmed a few planets. There are also several planned or proposed space missions geared towards exoplanet observation, such as New Worlds Mission, Darwin, Space Interferometry Mission, Terrestrial Planet Finder and PEGASE.

Orbital parameters
Scatter plot showing masses and orbital periods of extrasolar planets discovered.



Many exoplanets have orbits with very small radii, and are thus much closer to their parent star than any planet in our own solar system is to the Sun. Astronomers were initially very surprised by these "hot Jupiters", but it is now clear that most exoplanets (or, at least, most high-mass exoplanets) have much larger orbits, some located in habitable zones - suitable for liquid water and life. 17

Mass distribution

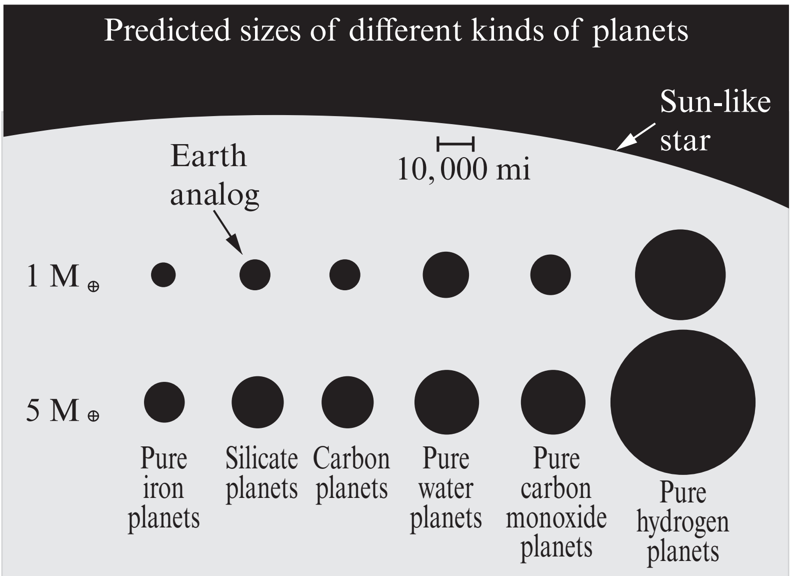
The vast majority of exoplanets detected so far have high masses. Many are considerably more massive than Jupiter, the most massive planet in the Solar System. However, these high masses are in large part due to an observational selection effect: all detection methods are much more likely to discover massive planets. This bias makes statistical analysis difficult, but it appears that lower- 18
mass planets are actually more common than higher-mass ones, at least within a broad mass range that includes all giant planets. In addition, the fact that astronomers have found several planets only a few times more massive than Earth, despite the great difficulty of detecting them, indicates that such planets are fairly common.

The results from the first 43 days of the Kepler mission "imply that small candidate planets with periods less than 30 days are much more common than large candidate planets with periods less 19
than 30 days and that the ground-based discoveries are sampling the large-size tail of the size distribution".

Temperature and composition

It is possible to estimate the temperature of an exoplanet based on the intensity of the light it receives from its parent star. For example, the planet OGLE-2005-BLG-390Lb is estimated to have a surface temperature of roughly -220 °C (roughly 50 K). However, such estimates may be substantially in error because factors such as the greenhouse effect may introduce unknown 20
complications. A few planets have had their temperature measured by observing the variation in infrared radiation as the planet moves around in its orbit and is eclipsed by its parent star. For example, the planet HD 189733b has been found to have an average temperature of 1205±9 K (932±9 °C) on its dayside and 973±33 K (700±33 °C) on its nightside.

If a planet is detectable by both the radial-velocity and the transit methods, then both its true mass and its radius can be found. The planet's density can then be calculated. Planets with low density are inferred to be composed mainly of hydrogen and helium, while 21
planets of intermediate density are inferred to have water as a major constituent. A planet of high density is believed to be rocky, like Earth and the other terrestrial planets of the Solar System.



Unanswered questions

Many unanswered questions remain about the properties of exoplanets. One puzzle is that many transiting exoplanets are much larger than expected given their mass, meaning that they have surprisingly low density. Several theories have been proposed 22
to explain this observation, but none have yet been widely accepted among astronomers. Another question is how likely exoplanets are to possess moons. No such moons have yet been detected, but they may be fairly common.

Perhaps the most interesting question about exoplanets is whether they might support life. Several planets do have orbits in their parent star's habitable zone, where it should be possible for liquid water to exist and for Earth-like conditions to prevail. Most of those planets are giant planets 23
more similar to Jupiter than to Earth; if any of them have large moons, the moons might be a more plausible abode of life. Gliese 581g, thought to be a rocky planet orbiting in the middle of its star's habitable zone, was discovered in September 2010 and, if confirmed, could be the most "Earth-like" planet discovered to date.

Various estimates have been made as to how many planets might support simple life or even intelligent life. For example, Dr. Alan Boss of the Carnegie Institution of Science estimates there may be a "hundred billion" terrestrial planets in our Milky Way Galaxy, many with simple life forms. He further believes there could be thousands of civilizations in our galaxy. Recent work
by Duncan Forgan of Edinburgh University has also tried to estimate the number of intelligent 24
civilizations in our galaxy. The research suggested there could be thousands of them. Apart from the scenario of an extraterrestrial civilization that is emitting powerful signals, the detection of life at interstellar distances is a tremendously challenging technical task that will not be feasible for many years, even if such life exists.

Sources:

page 5 - http://en.wikipedia.org/wiki/File:Exoplanet_Period-Mass_Scatter.png

page 6 - http://en.wikipedia.org/wiki/File:Planet_sizes.svg