1 Prologue

WHAT IS A PLANET?

> "When we think of a planet, our first conception is a body like Earth with an atmosphere, continents and oceans" [1].

This question is less important than one might suppose, given the uproar about the status of Pluto. Although labels are useful, trying to define a planet runs into the philosophical difficulty of attempting to classify any set of randomly assembled products. A bewildering array of objects form in the nebular disks around stars. These items include in our system, dust, asteroids, Trojans, Centaurs, comets, TNOs, our eight planets from tiny Mercury to mighty Jupiter and their 160 satellites. All differ from one another in some salient manner. A rational view would merely define our planetary system as having four planets (the gas and ice giants) with some assorted rocky rubble sunwards and icy rubble beyond. The significant question is how did they form and evolve, not what pigeonholes this variety of objects can be forced into. The strange varieties of exoplanets and brown dwarfs have added much extra complexity [2].

The views of astronomers and planetary specialists on what should constitute a planet have varied widely, but these often reveal as much about the commentator as the problem. Planets are not something to be tacked on to the bottom corner of the Hertzsprung–Russell diagram. If we use the three physical properties of orbital characteristics, mass and roundness, this leads to a total of 24 planets that includes many satellites. This classification is too broad to be scientifically or even culturally useful. As the New York Times has remarked "too many planets numbs the mind".

The definition of planet by the International Astronomical Union in 2006 ordained that in our solar system, a planet

(1) is in orbit around the Sun,
(2) has sufficient mass to assume a nearly round shape,
(3) has cleared the neighborhood around its orbit.

Any body, except satellites, that meets only the first two of these criteria is classified as a "dwarf planet". So the decision of the IAU that there are eight major planets and five dwarf planets in our planetary system seems an appropriate compromise. A further category of "minor planet" includes the asteroids, Trojans, NEAs (Apollos, Atens and Amors), Centaurs, comets, TNOs and KBOs. Brian Marsden made the useful observation that "it has rarely been scientifically useful to use the word [planet] without some qualification" and terms such as ice giants or terrestrial planets will always be needed. At least in our solar system, it is useful to recall the wise words of Confucius "The beginning of wisdom is to call things by their right names".

The problem with exoplanets is only apparently less acute, as we currently detect only planetary-size bodies. Nevertheless a problem soon arose of how to distinguish planets from brown dwarfs. By convention these bodies lie between 13 Jupiter masses, the lower limit for deuterium burning, and 80 Jupiter masses, above which hydrogen fusion becomes possible, so enabling red dwarf stars to form.

But confusingly, free floating objects down to about 3 Jupiter masses have been found and so are termed "sub-brown dwarfs".

Although the upper limit for giant planets was originally set at 12 or 13 Jupiter masses, strange new worlds continue to appear to confound those who wish for a tidy classification. To cloud the issue further, Corot 3b, a planet with over 22 Jupiter masses, has been found in a 4-day orbit. Other inhabitants of the brown dwarf desert have appeared. So the upper limit of 12 or 13 Jupiter masses for planets has now been changed to 25. Perhaps we need to retreat to a definition that planets are objects that form in disks around stars and arise by a different process (bottom-up) than stars and brown dwarfs that form in gas clouds (top-down). But the complexity of the problem of classification merely points up the message of this book: chaotic events rule the planetary world [2].

WHY CAN'T A PLANET BE MORE LIKE A STAR?

> "The brown dwarf desert . . . strongly suggests that the vast majority of exoplanets formed via a mechanism different from that of stars" [3].

Planets are individuals formed by stochastic processes. They resist generalizations and being placed into pigeonholes. The discovery of over several thousand exoplanets orbiting stars other than the Sun has brought the question of planetary origin and evolution into sharp focus, following from 40 years of exploration of our own solar system.

The detailed study of planets is in fact a very late development in science. It has required the earlier development of many other disciplines. The intellectual leap from the biblical chronology into deep time was mostly due to James Hutton, a member of the Scottish Enlightenment, in the late eighteenth century. The Hertzsprung–Russell diagram, fundamental to astronomy and astrophysics, dates from 1913. The robust OBAFGKM classification of stars (with recent L, T and Y additions for brown dwarfs that spoil the famous mnemonic) also appeared nearly a century ago. Al Cameron finally clarified the origin of the Moon in 1984, while the problem of the origin and evolution of the planets in the solar system is only now slowly coming into focus.

A major problem in trying to understand planets is that, unlike stars, they are individuals that refuse to be placed into a tidy classification. While stars are relatively uniform in composition (except for metal contents from near zero to 4%) and differ mostly in mass, planets are assembled in the late stages of star formation from the leftover debris in nebular disks, and so resemble the products of a junkyard.

Jupiter is not simply a failed star and this illustrates the dilemma. Like the lament in *My Fair Lady*, "Why can't a woman

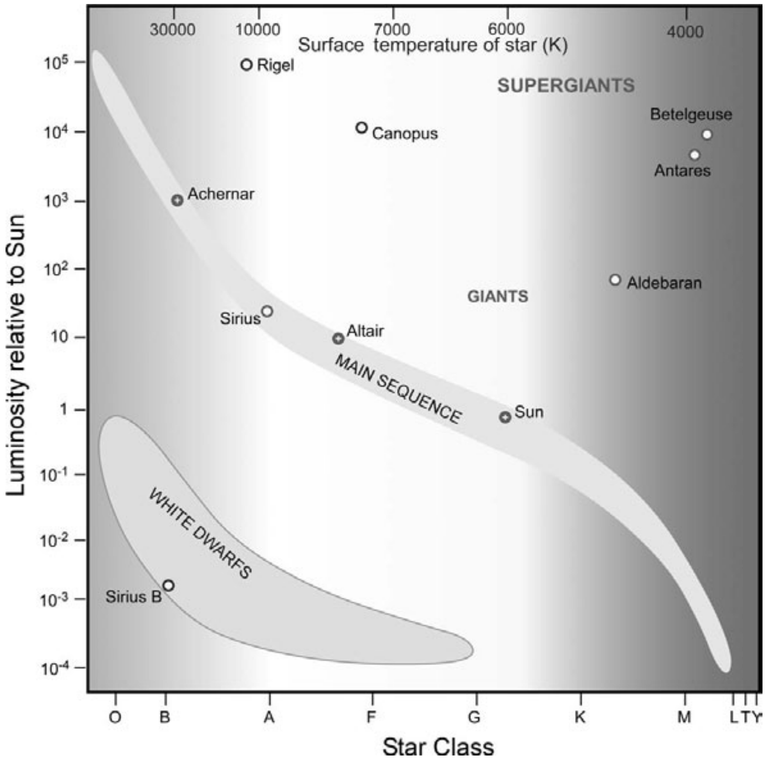

FIGURE 1 Hertzsprung–Russell diagram

The famous Hertzsprung–Russell diagram plots the surface temperature of a star (or class of star) against the luminosity of the star relative to the Sun on a logarithmic scale. The star classes include L, T and Y classes (brown dwarfs) that lurk in the bottom-right corner, as well as the classical OBAFGKM classes. Some well-known stars are identified. See also color plates section.

be more like a man", life would be simpler if planets were more like stars. But there is no equivalent of the Hertzsprung–Russell diagram (Figure 1) that might define the basic parameters for planets, nor much sign of one appearing and that's what makes the subject difficult. We are essentially dealing with individuals. It is even difficult to arrive at a satisfactory definition of a planet as noted; witness the furor over the status of Pluto, which is an eccentric dwarf when placed among the planets, but is one of the largest ice dwarfs in the Kuiper Belt in its own right.

In our solar system, we have eight planets, all different from one another in significant ways. This of course is a celebrated example of the statistics of one, but here we also have four major satellite systems and over 160 satellites. But the regular satellites of the giant planets could just as well belong to different planetary systems. If satellite systems are an inevitable by-product of building planets, the end products are startlingly diverse. Our limited sampling of the exoplanets shows few similarities to what we see in our own system in terms of mass and spacing of planets, while many are in highly eccentric orbits, unlike our tidy near-circular orbits.

So there is a philosophical difference between dealing with stars and with planets that requires a new type of scientist with a distinct mindset, somewhere between the mathematical sophistication of astrophysics and the geological sciences, whose detective-like approach Sherlock Holmes would recognize. As Clemenceau famously remarked: "War is too important to be left to the Generals", and the study of planets is too significant to be left to any one specialist group, either geologists ensnared by the properties of this unique planet, or astrophysicists beguiled by the physics of star formation.

The problem is typified at present by the two competing theories for the formation of the exoplanets: top-down by condensation from the nebula, or bottom-up, by gravitational collapse of gas around earlier-formed cores. Planets formed by the first process might be expected to have a similar composition to that of the Sun, but the giant planets in our own system do not have solar compositions and appear to have formed by the second mechanism. Among other evidence for the latter model is the very existence of the ice giants Uranus and Neptune, 14 and 17 Earth masses respectively, that are mostly composed of rock and ice (or metals) with only one or two Earth masses of gas. They thus constitute analogs for the cores of Jupiter and Saturn.

The observation that the extra-solar gas giant planets preferentially form around metal-rich stars implies that metal-rich cores are also needed to build gas giants elsewhere, at least to followers of William of Occam.

In contrast with the gas giants, the existence of Earth-like exoplanets cannot be addressed directly in the absence of current examples, and so resembles astrobiology. Information from our own system reveals the obvious requirements for metals, orbits of low eccentricity and the avoidance of giant planet migration into the inner nebula that would have cannibalized the terrestrial planets. We also know from their diversity of chemical composition that the formation of our rocky or terrestrial planets (Mercury, Venus, Earth and Mars) was essentially stochastic.

The formation of the Moon provides some clues. Although several people, notably Bill Hartmann, were beginning to understand that collisions were involved with the origin of the Moon, it was Al Cameron who produced the smoking gun in the form of angular momentum conservation. One had to hit the Earth with something the size of Mars, to account for both the rapid spin of the Earth–Moon system and to splash off the rocky mantle of the impactor, to form the low density Moon. But even if the Moon is a special case, it provides the evidence from its pockmarked face of the validity of the planetesimal hypothesis (the accretion of the terrestrial planets from a multitude of smaller rocky bodies) and so tells us, as do the meteorites, much about early events in the inner solar system.

But making these planets in our system is not just a matter of accumulating the rocky fraction from the primordial nebula. The inner nebula, from which the rocky planets formed, was also depleted in elements whose sole common property is volatility. Ironically, this depletion, which has occurred out to several AU, also depletes the habitable zone around the Sun in biologically important elements, such as C, N, P and K. The inner nebula was also bone-dry, as shown by the anhydrous nature of the primary minerals of meteorites (olivine, pyroxene and plagioclase), so that the splash (500 ppm) of water in our planet had to come in later from the neighborhood of Jupiter.

Even when nature gets around to building two similar planets, it finished up with the Earth and Venus. These twins, unlike Mars and Mercury, are close in mass, density, bulk composition and in abundance of the heat-producing elements (potassium, uranium and thorium), but the geological histories of these "twin" planets have been wildly different. Thus plate tectonics, which has the useful property of both building continents and forming ore deposits useful for advanced civilizations and so enabling this discussion to take place, appears to be unique to the Earth.

Venus, in contrast, is a one-plate planet and appears to undergo planetary-wide resurfacing with basalt perhaps every billion years. What is the difference due to? The short answer is water, recalling the aphorism "no water, no granites, no oceans, no continents". As the study of Venus shows, similarity does not mean identity.

So the problem of forming planets elsewhere would seem to depend on repetition in detail of the essentially random processes of planetary accretion and subsequent geological evolution that have characterized the formation of planets in our solar system. As it is very difficult here to form a clone of the Earth, it would seem difficult to make Earth-like habitable planets elsewhere. One must recall the difference between necessary and sufficient conditions for the emergence of life. Much more is needed than metals, orbits of low eccentricity within the habitable zone, water and plate tectonics. The concept that Earth-like planets are rare is not a conclusion that one might wish for, but like much in science, this is what can be read from the observations.

So the study of planets remains in its infancy, beset by the random nature of planet-forming processes and of their subsequent evolution, with the problems requiring the collaboration of many disparate scientific disciplines. This has resulted in a torrent of literature, heavy with speculation. This deluge is reminiscent in many

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ways of the flood of papers, now mercifully forgotten except by those old enough to remember, that appeared in the 1960s, prior to the Apollo landings on the Moon. It is curious to record that at that time, nearly every possible composition was suggested for the surface of the Moon, except what was revealed by the returned lunar samples.

ANCIENT PERSPECTIVES

It has taken us a long time to discover where we are. Primitive tribes living in remote jungle valleys have often been astonished to discover that the Earth extends far beyond their limited horizon and that they are not its only inhabitants. Before Copernicus, it was generally believed in the civilized world that the Earth was the center of the universe. However, it has slowly been realized that we live in a bigger arena. When you look up at the sky on a dark night in the country, the most striking feature, when the Moon is down, is the glowing band of stars, referred to as the Milky Way, a term first used in English literature by Geoffrey Chaucer (1342–1400) in 1384. This glowing band of stars spreading across the heavens is an edge-on view of our galaxy from the inside.

Although there is a place for the Milky Way in most mythologies, before recent times only Kant seems to have realized what we were looking at. From a nearby galaxy, a few hundred thousand light years away, the magnificent spiral structure that is obscured by our edge-on view would be revealed in its entire splendor. But even this enormous spiral system is only a tiny portion of the universe. Each new telescope reveals a larger universe than our imagination had conceived. Like travelers lost in a desert wasteland, we urgently seek for signs that we are not alone.

THE VIEW BEFORE COPERNICUS

Here I summarize what the ancients made of the world in which they found themselves, as civilization slowly arose following the melting of the great ice sheets about 12,000 years ago. Many of our present notions were formulated in the great flowering of civilization in Greece and Rome. Indeed it has been suggested that the rise of scientific enquiry was not an inevitable development, but an accident, possible only in societies such as ancient Greece and Western Europe in the seventeenth and eighteenth centuries [4].

Babylonian and Greek astronomers observed the strange motion of the planets against the fixed positions of the stars. In this manner, they became aware that there were two classes of heavenly objects in addition to the Sun and the Moon. The term "planet" is derived from the Greek word meaning "wanderer". Curiously there is no mention of planets as distinct from stars in the Old Testament of the Bible. The "Star of Bethlehem", famously depicted on Christmas cards, is recorded only in the gospel according to St. Matthew in the Authorized Version of the New Testament. The most credible explanation, if it is more than a myth, is that it was a conjunction of Jupiter and Saturn that occurred three times during 7 BCE [6].

It is curious that, although the ancient astronomers devoted much study to the movements of the planets, they did not spend much time considering the origin of the solar system. The planets were mostly distinguished from the other heavenly bodies by their wanderings. The whole question of origins seems to have been the province, not of the astronomers, but of the philosophers. There was no shortage of these, or of their ideas.

Some astronomers, however, took up the challenge. Among them was Anaxagoras (*c.* 500–428 BCE) who considered that the Moon was a stone. He thought that the Sun was a red-hot mass of iron, bigger than the Peloponnesus, the southern region of Greece that is about the size of Sicily. This idea that the Sun might be made of iron was based on a reasonable interpretation of the available evidence. An iron meteorite had fallen in about 467 BCE in ancient Thrace and Anaxagoras concluded that the visitor had come from the Sun. He was banished from Athens because his views about the composition of the Sun and the Moon were considered to be heretical. Little of his work has survived, but apparently he pictured the Earth at the center of a sort of large cosmic whirlpool. In this he anticipated the notions

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of Descartes in the sixteenth century, demonstrating the truism that few ideas are truly original.

The great Greek philosophers, Plato and Aristotle, whose philosophy has formed much of the basis for western culture, were mostly concerned with questions of purpose. Four elements, earth, air, fire and water, sufficed to make up the Earth. The heavenly bodies, in contrast, were composed of shining crystal, a perfect fifth element, or quintessence. The Moon was also made of this. The dark patches that one could easily see on the face of the Moon were thought to be the reflections in this perfect mirror from the mountains and oceans on the Earth. The doctrine of Socrates (*c.* 470–399 BCE) left no room for any changes or evolution and so did little to encourage scientific investigation. Plato (*c.* 428–347 BCE) concerned himself with the motions of the planets rather than their origin. In his scheme, the heavenly bodies were supposed to move in perfect circles.

The problem of perfectly circular orbits continued to haunt astronomers as late as Copernicus, over 1000 years later, until Kepler finally broke the spell. Aristotle (384–322 BCE) also thought that the heavens were permanent and thus not subject to the Earthly laws of physics as he perceived them. Both Aristotle and Plato did not believe in the plurality of worlds nor of life outside the Earth. The speculations of Aristotle were to dominate Western culture for two thousand years because they became theological dogma, something that was not the fault of the philosopher. The Ancient Greeks had discovered both inductive and deductive reasoning, Plato in particular favoring the latter approach, reasoning from first principles. These are, however, somewhat difficult to establish as any scientist soon discovers. Empirical observations dominate most planetary studies and uncomfortable facts destroy the most beautiful of theories.

Aristarchus of Samos, who lived around 250 BCE, proposed a refreshing contrast to the views of Aristotle. He placed the Sun at the center of the solar system, and included the Earth with the rest of the planets. He realized that the Earth was small in relation to the Sun. Not everyone today has made that intellectual leap. Aristarchus