Notes on sources and complementary information

exoplanet names (page 2)
The International Astronomical Union has decided not to attribute individual names to exoplanets. That seems prudent; I suspect that the day naming was allowed, the sky would instantly fill with women’s names and we would have to give scientific papers such titles as “Samantha much hotter than previously thought”. This impression was confirmed when in 2010 an astronomer named his most high-profile planet discovery (subsequently shown to be spurious) with his partner’s name. Catalogue names and numbers may not be ideal, but they become familiar quickly enough, and I don’t think the name 1644 has been a handicap for the French lager of that name.

Nevertheless, I found it impossible to write this book with the official planet names. The two most well-studied exoplanets are called HD 189733 b and HD 209458 b, and a paragraph filled with these two jumbles of digits quickly becomes confusing. That is why I used names – a sin that may bring the ire of the community on my head. For HD 209458 b, I was helped by Alfred Vidal-Madjar at the Institut d’Astrophysique de Paris, who in defiance of the IAU calls the planet Osiris in his papers about it. Alfred has been the first to identify atomic lines in the cometary tail trailing the planet. I made up the other names using the same Egyptian deity theme. The only objective is to make the text more readable, and I apologise to the reader if that means it will be more difficult to spot these planets in the news. The following table gives the correspondence.

<table>
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<tr>
<th>Name</th>
<th>HD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osiris</td>
<td>209458</td>
</tr>
<tr>
<td>Isis</td>
<td>189733</td>
</tr>
<tr>
<td>Nephthys</td>
<td>80606</td>
</tr>
<tr>
<td>Anubis</td>
<td>1214</td>
</tr>
</tbody>
</table>

the first exoplanet (page 2)
The first known exoplanet is usually said to be 51 Peg b, discovered by the team of Michel Mayor at the Haute-Provence Observatory in France in 1995. “The first exoplanet around a normal star” is the full statement, because three years earlier planets were found orbiting a neutron star by Aleksander Wolszczan and his team using the Arecibo radio telescope in Puerto Rico. A neutron star is the dead core of an exploded supernova, and these bodies would be very different kinds of planets. We may also have to add “first normal planet” to the 51 Peg statement, since in 1989 a team lead by David Latham at Harvard found an invisible companion to the star GJ 229 that they then labelled as a brown dwarf, but that we would today classify as a planet. It was none other than team member Michel Mayor who argued at the time that the companion of GJ229 could not be a planet, because its orbit was too eccentric. As we see in Chapter 8 of this book, it turned out that many planets have eccentric orbits, contrary to what was thought at the time.

There are several books on the early planet hunters, including Planet Quest by Ken Croswell.
The detection of the first planet outside the Solar System was announced several times before 1995. Famous examples include the case of Barnard’s Star. Fluctuations in the position of this nearby star were interpreted by Dutch Astronomer Piet van de Kamp as the signature of an unseen Jupiter-like planet. The community remained unconvinced, but it took a very long time to dismiss the hypothesis entirely. The double star system 61 Cygni was also at some point thought to harbour a massive planet. Spurious detections remain common today. It is a fact of science that seeing signals where there is only noise is easier than accumulating the much larger amount of high-quality data required to prove the absence of a signal.

This is a paper published in 1997 by Canadian astronomer David Gray in *Nature*, showing that the apparent velocity change in 51 Pegasi – interpreted as a planet signature – was associated with changes in the shape of the spectrum itself. This is not supposed to happen if the signal is due to a planet, but will happen when due to a pulsation of the star. The objection carried special weight because Gray was a top specialist of the spectroscopic technique, author of a reference textbook (*The Observation and Analysis of Stellar Photospheres*). The data used by Gray, though, was very noisy, and the analysis a bit shaky. As more hot Jupiters were discovered by the team of Geoffrey Marcy in California, Gray’s “exotic stellar pulsation” lost support. The hypothesis was never entirely disproven, it just gradually vanished over time the way incorrect scientific results tend to do.

The transit of HD 209458b (Osiris in this book) across its star was first measured by David Charbonneau and Timothy Brown with a four-inch telescope (this is no misprint, four inches only) at Harvard, or by Gregory Henry from Arizona. The story is entertaining, at least in the fictionalised account which was written in French as a novel by Elisa Brune, in *Les Jupiters chauds*.

The planet itself was first detected using the Doppler-wobble method by Tsevi Mazeh from Tel Aviv University, working with planet-search specialists Dave Latham and Michel Mayor. The one percent dip in luminosity is relatively easy to detect even with a small telescope if you know when to observe (when the planet is aligned with the star), and that is what the two teams of observers did. Charbonneau and Brown then went on to observe the transit with the Space Telescope, thus obtaining the first measurement of an exoplanet atmosphere with the detection of the sodium line in the atmosphere of Osiris. David Charbonneau is now professor at Harvard University and Tim Brown leads a network of privately funded telescopes based in Santa Barbara, California.
Notes on sources and complementary information

**MOLA (page 3)**
The MOLA altimeter is an instrument aboard the NASA Mars Global Surveyor mission. Between 1996 and 2001, it has measured the altitude of the Martian terrains with a vertical resolution of 30 metres, producing a detailed relief map of the whole planet. The maps are available online on the MOLA website. There are many fantastic books on the mapping of Mars, including *Mapping Mars* by Oliver Morton.

**Talk by Raymond Pierrehumbert in Oxford (page 4)**
This was the *Halley lecture*, an annual event at the University of Oxford. Raymond Pierrehumbert is the author of a wonderful textbook on planetary atmospheres, *Principles of Planetary Climate* (for scientists), and gives very inspiring conferences.

**Exoclimes conferences (page 4)**
The first “Exoclimes” conference was organised by the author, together with two fellow astrophysicists, Suzanne Aigrain (now at Oxford University) and Isabelle Baraffe, in Exeter in September 2010. Webcasts of the review talks and the slides of all talks are available online at [www.exoclimes.org](http://www.exoclimes.org). The organisation of the second Exoclimes conference was lead by Nick Cowan at Northwestern University (Chicago). It took place in January 2012 in Aspen, Colorado. The slides from the talks are available on the same website. The third Exoclimes conference is scheduled for February 2014 in Davos, Switzerland. On the associated [www.exoclimes.com](http://www.exoclimes.com) website, researchers from Exeter and Oxford provide short summaries of the latest research developments in the field of exoplanetary atmospheres.

**Bertrand Piccard (page 10)**
Bertrand Piccard is the latest in a distinguished dynasty of adventurous scientists. His grandfather was Auguste Piccard, who inspired the Professor Calculus character in the Tintin stories, and his father was Jacques Piccard, who built the Bathyscaphe submersible to reach the deepest point in the oceans. We can expect one of his three daughters to be the first human to explore an alien atmosphere.

**Global conveyor belt (page 20)**
The global circulation of the ocean currents is also called *thermohaline circulation*, from the Greek thermo for heat and haline for salt. Although the difference of heat between the Equator and the poles is the main driver, the injection of salt-free water from the melting icecap in the Arctic plays a key role. Salty water is heavier than freshwater, so the warm but salty water from the Equator sinks below the cold water from the poles, closing the loop of the current around Iceland. Thus the pattern of global ocean currents depends not only on the Equator-to-pole heat transfer, the shape of the continents and the Coriolis effect, but also on the extent and position of the icecaps at the poles.
Fig. 2.8 (page 33)
This reconstruction is due to Don Mitchell, from his blog/website called Mental Landscape.

Carl Sagan (page 49)
The “nuclear winter” simulations were published in Science by five US scientists (Richard Turco, Owen Toon, Thomas Ackerman, James Pollack and Carl Sagan) in 1983.

Fig. 3.14 (page 51)
This figure comes from the work of François Forget and his group, published in Science in 2006. François Forget, from the Laboratoire de Météorologie Dynamique in Paris, is one of the pioneers of using climate models for planets other than Earth.

uniquely among moons, Titan possesses an atmosphere (page 55)
Some other bodies in the Solar System have very tiny amounts of gas around them that can be called an atmosphere in some contexts. Pluto and Triton for instance have a few millionths of a bar of gas above their surface. This is sufficient to show winds and even clouds. But in the context of exoplanets such tiny amounts of gas do not have a sufficient effect on the planet as a whole to qualify as real atmospheres in the sense of this book.

the GAIA view of the Earth as a system (page 65)
The “GAIA” concept is a stimulating and controversial way to consider the atmosphere, ocean and biosphere of the Earth as a whole, introduced by British scientist James Lovelock. The basic idea is that the system has become complex enough to react like a giant living organism and regulate its own environment to ensure its continued existence. Lovelock elaborated on his concept for the general public in a series of books: Gaia, the ages of Gaia, the revenge of Gaia and the vanishing face of Gaia, with titles reflecting increasing alarm at mankind’s assault on the ecosystem.

The Daisy World computer simulation was introduced in 1983 by Lovelock and his then student Andrew Watson (now professor at the University of East Anglia).

in the Iliad (page 68)
The passage is in Book 8:
You will see how much mightier I am than you immortals. Go on: attempt it, and see. If you tied a chain of gold to the sky, and all of you, gods and goddesses, took hold, you could not drag Zeus the High Counsellor to Earth with all your efforts. But if I determined to pull with a will, I could haul up land and sea then loop the chain round a peak of Olympus, and leave them dangling in space. By that much am I greater than gods and men.
Fig. 5.13 (page 79)
This figure comes from the work of Peter Read at Oxford University, a planetary scientist who studies the climates of Venus and Mars, and in particular the effect of rotation on the flow in planetary atmospheres.

the NASA Kepler planet search mission (page 83)
Kepler is a space mission launched by NASA in 2009 to conduct the census of exoplanets down to Earth-sized planets using the transit method. The Kepler probe is orbiting the Sun some distance behind the Earth (it is therefore not orbiting the Earth directly, but slowly drifting away from us). Its array of cameras is taking an image every fifteen minutes of the same area of the sky, a field of around 150,000 stars in the direction of the constellation Cygnus. The Kepler mission has detected thousands of transiting planets, and has established the frequency of planets around stars like the Sun, depending on size and orbital distance. More details can be found on the mission’s website.

Hot Jupiters (page 84)
There is no official definition of the term hot Jupiter. The term usually designates gas giant planets with orbital distances below 0.1 AU, i.e. nearer to their star than a tenth of the Sun-Earth distance. The temperature of a planet at this distance will depend on how hot the host star is. Some researchers attempted to introduce other names for such planets, including “Roasters” and “Vulcans”, but only the simple and descriptive term “hot Jupiter” has gained general use, with its remarkably unpoetic extension “very hot Jupiter” for extreme cases with periods shorter than around two days.

shockwaves (page 85)
The question of shocks in the atmosphere of hot Jupiters is still unresolved. I take my cues from the work of Kevin Heng at Bern University and Adam Showman at the University of Arizona, but not all specialists would agree, and there are yet no direct observations of the effect of shocks in hot Jupiter atmospheres.

cometary tail (page 86)
The notion of an extended tail of escaping gas around Osiris comes from the work of Alfred Vidal-Madjar and his team at the Institut d’Astrophysique de Paris. In 2004 they used the Hubble Space Telescope to observe the lines of hydrogen, oxygen and carbon in the ultraviolet, and found that these lines were enhanced during the transit, which could be interpreted as the signature of a large amount of gas escaping from the planet. At first, this was thought to imply that hot Jupiters were doomed to evaporate over the life time of stars. With more hot Jupiters known, better measurements and more detailed models of atmospheric escape, it is now thought that the amount of gas escaping from planets such as Osiris is not sufficient to affect the planet as a whole.
Alkali metals (page 88)
There are many great books about the periodic table, including *Periodic Tales* by Hugh Aldersey-Williams and the classic *Uncle Tungsten* by Oliver Sacks. Also check out the fantastic *periodic table of videos* produced by the University of Nottingham’s chemistry department, for vivid first-hand experiences with the elements.

Sunsets (page 89)
I was part of the team that discovered the planet Isis in 2005, and when the different types of follow-up observations were divided up, I took charge of the measurement of the transit with the Hubble Space Telescope, to measure the size of the planet precisely. As a by-product of these observations, we could check whether the size of the planet varied with wavelength because of the signature of the atmosphere. Models predicted that the spectroscopic features of the atmosphere would be too small to be detectable, but I carried out the analysis anyway – it is a general rule for scientific observation never to trust the models prediction entirely.

What I found instead, after much work to account for the variations of the star itself due to its spots, was the clear and unexpected signature of scattering by a haze of small particles. Alain Lecavelier at Paris Observatory then calculated that the most likely constituent of this haze was transparent grains or drops of enstatite, a type of magnesium silicate.

Later on, with David Sing at the University of Exeter and other specialists of exoplanet atmospheres from the United States (Ronald Gilliland at NASA, Heather Knutson at Caltech and others), we collected more observations with the Space Telescope that confirmed this picture, and gathered the information to reconstruct the visible colours of a sunset seen through the atmosphere of the planet. Most recently, with Tom Evans at the University of Oxford, we detected the direct reflection of the planet in visible light (as opposed to the transmission spectrum obtained during the transit). These observations suggest that the planet has a deep blue colour when seen directly.

More details can be found on www.exoclimes.com, or with search terms like “sunset on HD 189733b” or “exoplanet color” on the internet.

A telescope (page 98)
The planet mentioned here was identified by the OGLE transit search. OGLE is an observation programme set up by the late Bogdan Paczynski, professor of astrophysics at Princeton University, to detect dark matter in our Galaxy. The method is to monitor a very large number of stars in search of the very rare events in which lumps of dark matter would focus the light of a star and make it shine brighter for a few days, an effect expected from Einstein’s theory of general relativity, called “gravitational lensing”. As a by-product of this programme, the OGLE telescope at Las Campanas Observatory in Chile was also used to look for transiting planets. It detected the first exoplanet identified by its transit, OGLE-TR-56b, then five other planets, before being overtaken by transit surveys specifically designed to look for planets, such as *HATNet* and *superWASP*.
**brightness map (page 99)**
The brightness map of Isis was obtained by a group led by David Charbonneau and his PhD student Heather Knutson at Harvard University. In 2007 they used the infrared camera aboard the Spitzer space telescope to follow the phases of Isis over a full orbit, and reconstructed the distribution of brightness on the surface of the planet from the brightness variation along the phase curve.

**HR 8799 (page 101)**
The system HR 8799 was discovered in 2008 by a team led by Canadian astrophysicist Christian Marois using the Keck and Gemini giant telescopes in Hawaii. They obtained very precise images of the star and its immediate neighbourhood by a technique known as “adaptive optics”, whereby ultra-rapid motion of mirrors in the telescope compensate for the turbulence of the atmosphere to produce images almost as sharp as those taken from space. They then needed to post-process the images with computers to remove the dominant light from the star and detect the tiny dots of light from the planets. They could prove they were planets because the dots moved around the star with time in the manner predicted by Kepler’s laws.

**upheaval in the Solar System (page 106)**
This model of the orbital evolution of the Solar System is presented in a series of papers by A. Morbidelli, K. Tsiganis, R. Gomes and H. F. Levison in *Nature*. An animation in this scenario is available online. Not all specialists consider that the scenario has been proven yet.

**we seem to be safe (page 106)**
The calculations about the orbital evolution of the Solar System are by the group of Jacques Laskar at the Paris Observatory. These calculations take enormous amounts of computer time, and as far as I know the Paris group does not have direct competitors, which is never a good thing in science. So these conclusions may still change, as they have done in the past. One can argue that predictions about the future of the Solar System in billions of years time do not belong to the realm of science anyway, since they will remain untestable.

**Anubis (page 108)**
GJ 1214 was observed by many teams using telescopes in space and on the ground to try to measure its atmosphere, but the task is difficult. Most results converge on the conclusion that the atmosphere is not detected at any wavelength, which tends to indicate that it is either heavy or clouded. But negative proofs such as this one are never as good as positive evidence, and we probably will have to wait for the next generation of telescopes and instruments, around the year 2020, to draw definite conclusions. See *Exoplanet Atmospheres* by MIT Professor Sara Seager for a technical book on this topic.
Steppenwolf (page 113)
Steppenwolf is a 1927 German novel by Herman Hesse, where the main character is a loner who feels cut off from everybody else. It was chosen to designate free-floating planets with buried oceans by Dorian Abbot at the University of Chicago. Planets can be ejected from systems by gravitational interaction with other planets or with another star. While no such case has been established with certainty, it is likely to be quite common if our current understanding of planet formation as a very violent process is correct.

tidally synchronised Earth (page 115)
To produce Fig. 7.13 I have used the output of a circulation model of a tidally synchronised, Earth-like planet by Kevin Heng (astrophysicist at the University of Bern), and superimposed it on the map of Earth in the absence of rotation according to Witold Fraczek at ESRI (a technology company based in New York). For the longitude of the centre of the day side I have used the heaviest region according to measurements of the local gravity anomalies on the globe. I have estimated the influence of humidity by eye (i.e. more humid implies less extreme temperatures).

pool planet (page 116)
The “pool planet” case was calculated by Raymond Pierrehumbert from the University of Chicago (who now calls it eyeball planet). It corresponds to a tidally locked Earth that becomes cool enough for a global glaciation to take hold, except near the centre of the day side. If ocean planets are common, such cases could be frequent as well, around stars cooler than the Sun (which are the most common type of stars). In such cases, a planet would have to be closer to remain warm enough to sustain liquid water, close enough for tidal locking to operate.

Nephthys (page 117)
HD 80606b was identified in 2001 by Dominique Naef, a student of Michel Mayor, at the Haute-Provence Observatory in France. Its extremely elongated orbit made the detection challenging: it barely tugs on its star for most of its 111-day orbit, then furiously pulls it during a few days at closest approach, before resuming its stately journey. Checking whether the planet was transiting was another challenge, because of the long period: just one short event every 111 days. On 13th February 2009 I was at Haute-Provence Observatory with one of the team who caught the event. A memorable night.

in the sky of Nephthys (page 118)
I have used a plot of the orbit of HD 80606b by US astrophysicist Greg Laughlin to calculate the figure. For some years Greg kept a very entertaining, extremely reliable and beautifully illustrated blog on exoplanets (oklo.org). It is still worth a visit.
diamond planets (page 119)
The ‘diamond exoplanet’ idea was introduced by NASA astrophysicist Mark Kuchner, who explored the consequences of a higher abundance of carbon than oxygen on the internal structure of a terrestrial planet. It was taken up by the press with the usual mixture of enthusiasm, simplification and short attention span, and the idea of “diamond planets” briefly circled the world, with a few shiny illustrations.

exo plate tectonics (page 120)
Work on the behaviour of plate tectonics on planets larger than Earth was initiated by Dimitar Sasselov at Harvard University. Geophysicists are quick to point out that on Earth the behaviour of tectonic plates can depend very sharply on details, such as the presence of tiny amounts of water in the mantle to “lubricate” the motion of plates, and that it is therefore probably vain to try to derive some general behaviour for exoplanets. Exoplanet researchers would argue that pushing the models out of their comfort zone is often a good way to test our understanding, even in the absence of data.

life (page 121)
The two mission concepts from the 1990s to measure signs of life in the atmosphere of an exoplanet are NASA’s “Terrestrial Planet Finder” and ESA’s “Darwin”. There is, of course, plenty of literature on the topic of the search for exo-life, including the wonderful Lonely Planets by David Grinspoon.

Epoxi (page 124)
Epoxi is a reincarnation of NASA’s Deep Impact mission. If you missed it, Deep Impact was a movie in which Mel Gibson uses a big drill to fight a comet and save the world. The Deep Impact probe travelled to a comet called Tempel 1 and on July 4 (sic) 2005 dumped a fridge-sized load onto the comet to observe the explosion and study the composition and porosity of the surface. Its mission accomplished, the probe was then redirected towards another comet, which it reached in 2010. NASA scientist Drake Deming and others proposed to use the probe’s camera during the trip between the two comets to study exoplanets. This included observing the Earth as an exoplanet – the probe was by that time so far from our planet that it only saw Earth as a point of light in the sky. The brightness of the Earth was measured over two days in two colours, and Nick Cowan at Northwestern University led a study of this data, showing that it enabled a reconstruction of the broad distribution of landmasses and oceans on Earth, in a paper enigmatically entitled Alien Maps of an Ocean-Bearing World.

Earth as a snowball planet (page 130)
The extent and duration of the “snowball episodes” for Earth are hotly debated in the scientific community. While most researchers would agree that the geological records indicate periods of glaciation much more severe than the recent Ice Ages, the idea of an entirely frozen planet is not accepted by all. A large swathe of the oceans near the
Equator could have remained ice-free. The number of cold episodes is also debated.

**Hydrogen atmosphere (page 127)**

It is very difficult to reconstruct what the earliest states of the Earth’s atmosphere might have been. The earliest rocks dated by geologists are around four billion years old, a full 500 million years after the formation of the planet. They have not conserved inclusions of bubbles of air (the way Antarctica ice cores allow us to trace the composition of the air in the more recent geological past), so that the composition must be inferred from very indirect clues. Hydrogen in the early atmosphere has left no trace, and is only inferred from our present understanding of the formation of terrestrial planets. Every aspect of the composition of the early atmosphere is highly speculative, including the total amount of carbon dioxide. As usual for this book I have used what I take to be the “reasonable current best-guess”.

**Earth at 40 (page 132)**

Nice drawings of the reconstruction of the Earth’s map in the deep past can be found at the Paleomap Project of Christophere Scotese. These reconstructions are based on a very large number of geological studies, using a wide variety of techniques ranging from recognising common rocks in presently widely separated regions, and tracing the distribution of fossil species, to the measurements of the magnetisation of rocks that keep a memory of their ancient position relative to the magnetic field. The usual disclaimers apply: many details are speculative, and the more we go back in time, the hazier our knowledge becomes. Nevertheless, geologists have now become extremely good at that peculiar type of spherical puzzle-solving.

**soiling the pool (page 133)**

The concentration of CO₂ in the atmosphere has been monitored by the Mauna Loa Observatory in Hawaii since 1958. It has risen from 315 grams per tonne in 1958 to 390 grams per tonne in 2012 and keeps rising at an increasing rate. This number was around 200 during the ice ages, about 760 at the dawn of the age of mammals, and 1000 to 3000 during the age of the dinosaurs.

**Earth’s future (page 134)**

Conclusions about the future of the Earth are very speculative, and venture close to the limits of science because there is no way to verify them with experiments. I have based my remarks on the talks presented on this topic during the Exoclimes conferences, and at the NASA conference on planetary climates in 2012 in Boulder, Colorado. Opinions have been shifting, particularly on the issue of how much time will elapse before our planet becomes uninhabitable because of the increased solar luminosity.

**Venus timeline (page 134)**

The Venus timeline comes from the talk by David Grinspoon at the Exoclimes 2010 conference. Dr Grinspoon is curator at the Denver Museum of Natural History and a specialist on the atmosphere of Venus. His book *Venus Revealed* on the topic can be highly recommended.
Moon-forming impact (page 128)
Although the impact scenario for the formation of the Moon is considered likely, other scenarios are still posited by the scientific community. The main argument for the impact scenario is that the composition of Moon rock is similar to that of the Earth’s crust, and that the Moon’s total weight indicates that it lacks a heavy metallic core, as expected if it formed from ejected bits of the Earth’s crust.
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