Destiny or Chance Revisited

Planets and their Place in the Cosmos

This exciting tour of our universe explores what we now know about exoplanets and explains the difficulty of finding another Earth-like planet.

Building on the remarkable story of our own solar system from his bestselling book *Destiny or Chance*, Stuart Ross Taylor now takes the reader further, comparing our solar system with the wider universe. How are planets made, and why are they different from stars? Why are exoplanets all different from one another and from our familiar eight planets? What can Earth's nearest neighbors tell us about planetary processes in the whole universe? Why does Earth harbor life?

Beginning with the basic concepts of planet formation and the composition of the universe, the book then summarizes our knowledge of exoplanets, how they compare with our planets, and why some stars have better habitable zones. Further sections provide a detailed study of our solar system, as a basis for understanding exoplanetary systems, and a detailed study of the Earth as our only current example of a habitable planet. The book concludes with a philosophical and historical discussion of topics surrounding planets and the development of life, including why our chances of finding aliens on exoplanets is very low.

This is an engaging and informative read for anyone interested in planetary formation and the exploration of our universe.

STUART ROSS TAYLOR is a trace element geologist and an Emeritus Professor at the Australian National University. His research has covered wide-ranging topics involving trace element geochemistry, from the composition and evolution of the Moon, to tektites and the continental crust of the Earth. He has a D.Sc. from the University of Oxford, is a Foreign Member of the US National Academy of Sciences, and has received the Goldschmidt Medal of the Geochemical Society, the Leonard Medal of the Meteoritical Society, and the Bucher Medal of the American Geophysical Union. Professor Taylor is the author of 240 scientific papers and nine books, including *Planetary Crusts* (with Scott McLennan, 2008), which won the 2010 Mary Ansari Best Reference Award of the Geoscience Information Society. He carried out the initial analysis of the first lunar sample returned to Earth at NASA, Houston in 1969, and Asteroid 5670 is named Rosstaylor in his honor. He is a Companion of the Order of Australia, the highest civilian honor.

Praise for this book:

"We live in an exciting era of discovery. Breakthroughs in solar system exploration, star formation studies, and extra solar planet searches have greatly expanded our horizon of the cosmic root of the Earth and her planetary siblings. A new conceptual paradigm of planetary ubiquity and diversity is firmly taking shape. This book is an encyclopaedic reference of the vast range of intertwining phenomena and processes which compete to shape the paths of planet-making. *Destiny or Chance Revisited* is comprehensive, thorough, and admirably up-to-date. With many intriguing historic anecdotes and vivid analogies, Stuart Ross Taylor lucidly conveys some deep concepts in layman terms without the distraction of intimidating formula or excessive jargon. It is a must-have for all amateurs or professionals who are fascinated by our place in the Universe."
– **Professor Douglas Lin**, *University of California Lick Observatory*

"In his highly-readable style, Ross Taylor describes the most recently discovered members of the solar system family, and the planets found to circle other stars. Anyone interested in planetary formation will be interested by his argument for their formation by chance and the laws of physics, not by destiny or design, and his conclusion that other peopled earths must be extremely rare."
– **Dr. John Wood**, *Senior Scientist (retired), Harvard-Smithsonian Center for Astrophysics*

"This book presents an interesting and novel view of the origin of the Earth and life upon it. It successfully covers the known fact about the main members of our solar system as well as fully covering the recent discoveries concerning other planetary system. It also looks the formation of planets and planetary system, placing the concept within the wider context of stars and galaxies. It is thoroughly readable account, accessible to a wide audience, with complex concepts being explained in an informative way. Readers of all levels will both enjoy and learn from this book."
– **Professor Iwan Williams**, *School of Physics and Astronomy at Queen Mary, University of London*

"Subject: nothing less important than the universe including its history. Author: nothing less than a world-renowned scientist of broad learning with an exceptional gift for exposition. Result: nothing less than a must-read for scientists, philosophers, and anyone interested in learning about some of the most dramatic advances in our understanding of the universe and our place in it."
– **Dr. Michael J. Crowe**, *Professor Emeritus, University of Notre Dame; author of* The Extraterrestrial Life Debate, 1750–1900.

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STUART ROSS TAYLOR

Research School of Earth Sciences
Australian National University
Canberra, Australia

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"**UNIQUENESS, IT APPEARS, IS THE COMMON PROPERTY OF PLANETS**."

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Preface

We live in remarkable times replete with technical advances, a consequence of the great intellectual advances of the seventeenth and eighteenth centuries in Europe. *Destiny or Chance* in 1998 looked at the solar system to examine the question whether our planets were likely to be reproduced elsewhere. From the evidence then available, this was judged to be very unlikely, while the possibility of intelligent life resembling *Homo sapiens* [**1**] elsewhere was assessed to be zero. In the succeeding dozen years, major improvements in technology have resulted in the discovery of thousands of exoplanets. Has the situation changed? Yes, in the sense that it has gotten worse. Not only are the exoplanets "Strange New Worlds" as a popular book title has it, but our familiar solar system itself, with its tidy circular orbits, appears to be a rarity. The very architecture of the solar system, familiar to every schoolchild, appears to have arisen through chance collisions and migrations half a millennium after it formed.

Destiny or Chance was written following a close look at our solar system. The numerous planets, satellites, TNOs, asteroids, centaurs and other assorted debris that surround our Sun provided no evidence of design. The resulting array, strange enough when looked at objectively, was clearly the result of a series of chance events. Halfway through writing *Destiny or Chance*, the first exoplanets were discovered. These "Hot Jupiters" were totally unexpected by astronomers, although less surprising to students of the solar system. Lurking in the background is the expectation that something like the Earth, complete with its set of interesting inhabitants, might be discovered.

My excuse for yet another book is to examine this question. I had already concluded in 1992 in the first edition of *Solar System Evolution* that "The planets and satellites are rich in diversity and the difficulty in producing clones of our present solar system makes duplication as unlikely as the possibility of finding an elephant on Mars". Following the publication of *Destiny or Chance*, in an address to the Meteoritical Society, I discussed the problem of the difficulties of making Earth-like planets and came to the conclusion that "the odds of finding 'little green men' elsewhere in the universe decline to zero".

But science moves on. Now the search for Earth-like planets has intensified and numerous examples of Earth-mass planets residing in habitable zones have appeared. Among the reasons for revisiting *Destiny or Chance* is to try to place these in a cosmic perspective. I also wish to investigate the problems of forming an "Earth-like" rather than an "Earth-mass" planet. All have added new hope to the possibility that we are not alone, lost among the incomprehensible spaces that are extended with each new discovery.

I am a physical scientist, not a biologist. The emphasis in this book is on the physical development of habitable Earth-like planets. However major events on the Earth such as worldwide glaciations, the rise of oxygen in the atmosphere, the development of the continental crust, collisions with asteroids and other geological processes have all affected the development of life. The evolution of intelligent life is marked by several improbable events that seem to correlate with these changes and so are addressed here as appropriate.

Meanwhile we have developed a new understanding of the solar system, and of the place of the Earth in it. We understand much about the planets, how they were formed and how they evolved. This enables us to take another look at the idea of "one world or many"? How easy or difficult would it be to make a duplicate of our solar system, or of the Earth, complete with its interesting cargo of inhabitants? Are habitable planets, complete with "little green men (or women)" readily available and common elsewhere? This is one of "humanity's most exciting science projects" as a recent book explains [**2**]. This is a stupendous subject, becoming more complex daily. Here is my attempt to place the current excitement over exoplanets into perspective and to understand our place in the cosmos.

This book is organized into seven chapters, preceded by some notes on the terminology employed. Following the Prologue, I discuss our current understanding of the universe. The next chapter considers how planets are formed. This is followed by a discussion of what we know about the exoplanets. The considerable detail that we now know about the solar system is then summarized. Much of the available evidence about planets is inevitably derived from this source so that there is an unavoidable bias towards our own planets that I have tried, not always successfully, to minimize. The familiar Earth and Moon require yet another chapter. Then I conclude with some perspectives about what it all means.

The sources of various quotations and comments that are identified by numbers in the text (e.g. [8]) are listed by chapter in the Notes at the end of the book. The illustrations are divided into figures, which occur throughout the text, and color plates that can be found in a central section.

Acknowledgments

Much of this book was written while I was a Visiting Fellow in the Department of Earth and Marine Sciences, now part of the Research School of Earth Sciences at the Australian National University. I remain grateful for their hospitality.

I owe a deep debt to many of my scientific colleagues for advice and encouragement that has extended over many years as I have contemplated the problems of planets and our solar system and of our place among all these wonders. The list is far too long to include here. It begins with my schoolteachers of English in New Zealand and concludes with most of the current workers on the problems of planets and the solar system.

I thank Laura Clark, Emma Walker, the production team and particularly Susan Francis of Cambridge University Press for long and continued support in producing this book. Anonymous reviewers for Cambridge University Press made many useful suggestions.

I owe a great deal to Brian Harrold, RSES for much help with computers and who also prepared the color plates. I am also indebted to Dr Judith Caton, ANU, who skillfully turned my rough sketches into polished figures.

I owe much to my patient wife, Dr Noël Taylor for her unstinting support over many years.

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Terminology

Planets found outside our solar system are referred to throughout as "exoplanets" as in current usage, rather than as "extra-solar planets". They are generally designated in the literature by the letters b, c, etc. following the name of the star, thus Gliese 581b or HD 149026b. Sometimes the planet is identified by the mission that discovered it; thus Kepler 22b or Corot 3b. I use the term "geology" throughout the text to refer to processes on Earth-mass planets, as it makes for simpler sentences.

Time and distance are particularly difficult to deal with when discussing the universe because both concepts extend far beyond our daily experience. The great contribution of geology to philosophy was to establish the immensity of time or "Deep Time". Comments about intervals of time "as brief as a million years" are common in scientific literature. I avoid the modern scientific convention that refers to the passage of 1 billion years as a gigayear (or the even more appalling abbreviations, Ga or Gyr) because it reduces this stupendous period of time to a trivial level. The origin of the universe as it is currently understood dates back around 13.7 billion years, the time of the Big Bang.

The universe had been around for a long time before the Sun and planets appeared. The time of formation of the solar system has been dated rather precisely. The term ($\mathbf{T_{zero}}$) appears frequently in these pages. It is the earliest reliable date, 4567 million years ago, accurate to within 2 million years that we have in our solar system. What it measures is the earliest formation in our solar system of crystalline material, now preserved as refractory minerals in meteorites. These minerals formed at high temperatures near the early Sun, as dusty grains were recycled through many stages of evaporation and condensation before being spayed out into the solar nebula. Many were trapped in meteorites, where they form a few percent. Some went much farther out and have been found as grains in dust from comets.

They contain minerals formed at high temperatures so these mm-size fragments are thus called "Refractory Inclusions" or "CAIs" (after calcium, Ca and aluminum, Al, two principal components). The significance of the date is that by that time, the Sun had already reached its present mass and was driving gases and volatile elements out from the inner nebula. Perhaps a million years had elapsed since a mass of gas with 1 or 2% of ices and rock had separated from a molecular cloud and started to condense into a star.

Life apparently appeared over 3 billion years ago on this planet. In contrast, it is only 10,000 years since the last ice age ended and the ice that had covered much of Europe and North America, retreated. The whole of recorded civilization is compressed into the past 6000 years.

Distances within the solar system are usually given in terms of the Astronomical Unit. This is the average distance between the centers of the Sun and the Earth, around 150 million kilometers. This useful unit is abbreviated to AU throughout the text. It should not be confused with Au, the chemical symbol for gold, nor with Å, the Ångstrom (10^{-8} cm), another useful measure that is about the size of an atom. The planets extend out to the orbit of Neptune at about 30 AU. The outer boundary of the solar system is at the edge of a spherical cloud of comets that extends to about 50,000 AU. Light takes almost a year to reach us from that distant region.

All these immense expanses are trivial on an astronomical scale. For these vast regions, the distance travelled by light in a year, the so-called "light year" which is about 63,000 AU, now becomes a more useful measure. The nearest star is about 4 light years away. A more frequently used unit in astronomy is the parsec, 3.26 light years.

One of the most striking features of our planetary system is that the planets orbit close to a plane. This is defined by the orbit of the Earth around the Sun and is generally called the plane of the ecliptic. The tilt or obliquity of the planets refers to how far the spin axis of the individual planet is tilted relative to this plane. Thus the tilt of the axis of rotation of the Earth varies around 23°, a feature that provides us with the seasons that we so greatly admire, as the northern or southern hemispheres receive more or less sunlight.

Two other terms dealing with the orbits of planets need to be mentioned. These are the inclination and the eccentricity of the orbits. Inclination is the angle that the orbit of the planet, asteroid, comet or whatever makes to the plane (ecliptic) in which the Earth rotates around the Sun. Except for Mercury with a 7° tilt, our planets have inclinations within a few degrees of the plane of the ecliptic. Other bodies like Pluto (17°) and many of its companions in the Kuiper Belt, along with many comets, have high inclinations. Those exoplanets that are observed to transit, or cross in front of their parent star likely have low inclinations.

How far the orbit of a planet departs from a perfect circle ($e = 0$) and becomes oval or elliptical is measured by its eccentricity. Kepler established that the orbits of our planets are elliptical, although they do not in fact deviate very far from circular. Many bodies in the Kuiper Belt, including Pluto ($e = 0.25$), have eccentric orbits. An extreme case in our system is the TNO Sedna ($e = 0.85$) which has an extremely eccentric orbit that takes it from 76 AU at its closest approach to the Sun, out to 960 AU at the farthest point. Many exoplanets have similar highly eccentric orbits.

Another important feature of orbits, resonance, needs to appear here, as it is significant in many aspects of planetary dynamics, for example, as in the strange orbit of Pluto. This icy dwarf along with companions orbits the Sun two times for every three orbits of Neptune and so it is referred to as being in a 2:3 resonance with Neptune. The importance of these simple whole number resonances is that, in each orbit, the two bodies return to exactly the same relative positions in space. So their minute gravitational interactions accumulate, rather than being evened out. Sometimes this results in stability, as with Pluto, but other resonances clear out gaps, as in the 2:1 resonance of asteroids with Jupiter.

Bodies in close orbits, like our Moon, may become tidally locked, always presenting one face to their companion. If this happens to be a planet near a star, unfortunate consequences follow with one side too hot and the other too cold.

Another convention I have to mention deals with temperature scales. In addition to the familiar Centigrade (or Celsius) and Fahrenheit scales, the Kelvin scale is commonly used in science. It uses the same intervals as the Centigrade scale but is expressed simply as K (not to be confused with the same symbol used to indicate 1000, nor with the element symbol for potassium (aka kalium)). Absolute zero on the Kelvin scale is the temperature at which all motion of molecules ceases. It is 273° below zero on the Centigrade scale which is set by the freezing point of water. One of the coldest places in the solar system is the surface of Triton, the satellite of Neptune, which has a surface temperature of a mere 38 K.

Percentages are the unit that is commonly used in talking about the abundances of the common chemical elements. Another convenient unit is "parts per million" (one part in 10^6), usually abbreviated to "ppm". One percent (one part per hundred) is 10,000 ppm. Ppm is a useful unit for comparing the abundances of trace elements, mainly because it enables us to use small numbers and so avoid long strings of zeros that easily allow errors to creep in. For example, the concentration of uranium in the crust of the Earth is usually referred to as 3 ppm (rather than 0.0003%), while the total amount of water in the Earth amounts to about 500 ppm, less easily confused than 0.05%.

Parts per billion (or ppb, one part in 10^9) is employed for abundances 1000 times lower than ppm. Thus the amount of the element iridium in the Earth's crust is only one tenth of a ppb. In contrast, this element is 5000 times more abundant in meteorites,

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where it is present at 500 ppb or 0.5 ppm. Because of this extreme difference, concentrations of iridium in the crust as low as 10 ppb are 100 times more than the average and so are commonly signatures of the impact of a meteorite on the Earth. The most famous example is that of the asteroid collision that destroyed the dinosaurs. This event left a measurable spike of iridium at the Cretaceous–Tertiary boundary around the globe from Denmark to New Zealand.

In the astronomical world, all elements heavier than helium, including such distinct elements as chlorine, nitrogen, oxygen and sulfur and the rest of the Periodic Table, are referred to as "metals". This has become standard usage for astronomers, who have much more serious problems to think about than the details of chemistry. The easily measured ratio of iron to hydrogen (Fe/H) is commonly used as a measure of the "metallicity" of the star, although it is only an approximation as low-mass elements such as oxygen form by different nuclear processes. The convention has arisen because iron is a common and readily measured element in stars and so proxies for everything else in the Periodic Table. The story of the formation of the chemical elements, worked out through a combination of nuclear physics, astrophysics and astronomy in the 1950s, is one of the great triumphs of human understanding of the universe, which can only be mentioned here in passing (See Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F. Synthesis of the Elements in Stars, *Reviews of Modern Physics*, Vol. **29**, 547–650, 1957).

The point of emphasizing the use of the term "metals" here is that planets commonly form around metal-rich stars. Metal-rich is perhaps a misnomer as the metal content of stars ranges from near zero with 10,000 times less metal than our Sun to a maximum of 3 or 4%, our Sun containing about 1.4%.

Throughout the book I refer to the Edgeworth–Kuiper Belt of icy planetesimals beyond Neptune as the Kuiper Belt although this is historically incorrect. However it has become common usage and certainly makes for simpler sentences. Icy bodies in the outer reaches of the solar system are referred to as Kuiper Belt Objects

(KBOs) if they inhabit the Kuiper Belt. A more general term, Trans-Neptunian Objects (TNOs) includes both the Kuiper Belt bodies and those further out in the Opik–Oort Cloud, here again referred to as the Oort Cloud.

The famous astronomical classification of stars, dating from 1920, of OBAFGKM (with newly added L, T and Y classes) covers the range from very hot giant stars (O class) to the cooler red dwarfs (M class) and brown dwarfs (L,T,Y). The Sun is a G class star and F, G and K stars are thought most likely to harbor planets on which life might develop (Figure 1).

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Abbreviations and symbols

AA	Astronomy and Astrophysics
AAR	Astronomy and Astrophysics Review
Al	Aluminum
Ag	Silver
ApJ	Astrophysical Journal
ApJ: L.	Astrophysical Journal Letters
ASP	Astronomical Society of the Pacific
Au	Gold
AU	Astronomical unit
Ba	Barium
BJOG	An International Journal of Obstetrics and Gynaecology
Ca	Calcium
CAI	High temperature (calcium–aluminum) mineral inclusions in meteorites
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Cu	Copper
D/H	Deuterium/hydrogen ratio
ESA	European Space Agency
ESO	European Southern Observatory
Eu	Europium
Fe	Iron
GRL	Geophysical Research Letters
HARPS	High Accuracy Radial Velocity Planet Searcher
HD	Henry Draper, who funded a star catalog
Hf	Hafnium
HR	Hertzsprung–Russell

IAU	International Astronomical Union
Ir	Iridium
K	Potassium
K/U	Potassium–uranium ratio
K-T	Cretaceous–Tertiary
KBO	Kuiper Belt Object
LHB	Late Heavy Bombardment of the Moon, 4000 million years ago
M_E	Planetary mass relative to Earth
MER	Mars Exploration Rover
Mg	Magnesium
M_{Jup}	Planetary mass relative to Jupiter
Mo	Molybdenum
MORB	Mid-Ocean Ridge Basalt
NASA	National Aeronautics and Space Agency
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
Pb	Lead
Pt	Platinum
QJRAS	Quarterly Journal of the Royal Astronomical Society
SETI	Search for extraterrestrial intelligence
Sr	Strontium
REE	Rare Earth elements
Sn	Tin
Th	Thorium
TNO	Trans-Neptunian Object
T_{zero}	4567 million years ago, derived from the earliest dated minerals in our solar system
U	Uranium
USGS	United States Geological Survey
W	Tungsten
Zn	Zinc
Zr	Zirconium