The Evolution of Stars

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From Birth to Death

By

Graham Hill

Cambridge Scholars
Publishing

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This book first published 2020

Cambridge Scholars Publishing

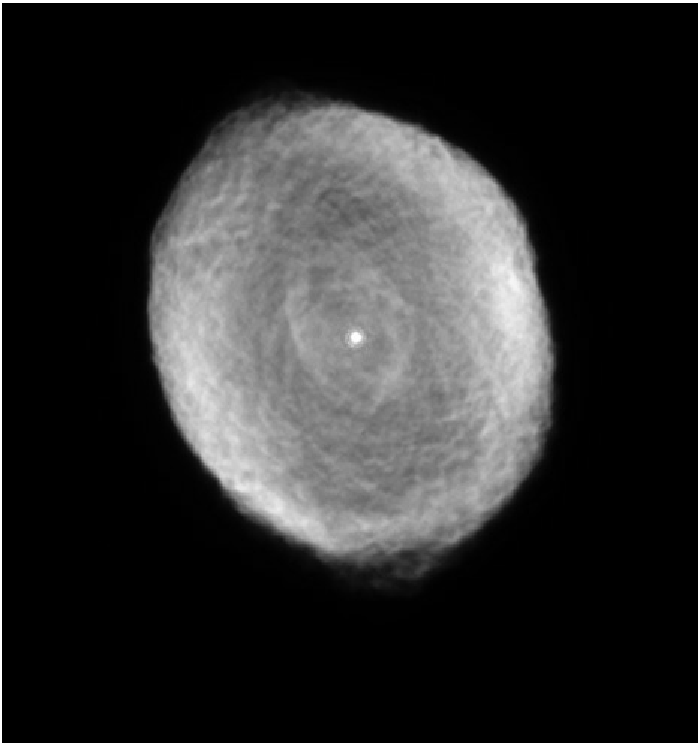
Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-5052-4
ISBN (13): 978-1-5275-5052-0

To Willem J Luyten who gave me the opportunity to become a professional astronomer and who, each day, demonstrated that age is no barrier to imagination and innovation.

And to my wife Joanie, who has been my rock over many years, particularly over this last year.



Frontispiece. See Centrefold. The Spirograph Nebula. Credit: NASA and The Hubble Heritage Team/(STScI/AURA)

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PREFACE

"Twinkle, twinkle, little star
How I wonder what you are
Up above the world so high
Like a diamond in the sky
Twinkle, twinkle little star
How I wonder what you are"

This book had its genesis more than sixty years ago when I read W. M. Smart's book "Some Famous Stars". It was, and still is, a wonderfully informative book on astronomy and was influential in setting me on my path to becoming an astronomer. Now, in my mature years, I've responded to the heeding of my wife who has long urged me to write about astronomy though not in a technical manner for I have authored and co-authored many papers on the subject. Her drive, and that of our children and close friends, was for me to write a popular book about the stars that might interest a public who have long been fascinated by astronomy. This is an interest only whetted further by the flow of results from the Hubble Space Telescope, the huge ten-metre-class ground-based telescopes such as the Keck twins on Mauna Kea, the quartet of eight-metre European telescopes in northern Chile and other more esoteric observatories currently in space.

Unlike Smart who wrote about a few specific stars, I have chosen to write the story of the evolution of stars from birth to death, but not just of single stars. About 50% of the stars in the sky come in pairs that are gravitationally linked, just as the Earth and Moon are linked, as is the Earth-Moon system to the Sun. Because of this physical connection between stars, the possibilities involved in their evolution take some curious and very interesting paths, much as in our own lives which are more complex when lived with a partner.

Most people know little about those little points of light out there we call the stars. Many don't even realise that the Sun is a star and differentiating between a star and a planet is often in the too hard basket. I hope that folk may find this book a stimulus that will entice them into this untouchable world, and further, heighten an interest in our Earth, both in its current form—damaged as it is—and also into its past, both physically and historically.

Astronomy, like all sciences, builds on the past from which much of its language is derived. Rather than present the past as a continuous historical survey I've chosen to interleave it with the narrative to introduce some of the underlying principles of astronomy. Additionally, I attempt to honour in a small way some of the early astronomer's accomplishments that were often based on rudimentary measurement but often capped by brilliant insight.

I've also appended a glossary to further aid the reader in understanding the language of astronomy. Words included in the glossary are initially written in boldface type. Further, I use the metric units of measurement along with the US definition of the billion.

Graham. Hill
Auckland
New Zealand
1 November 2019

PROLOGUE

To set the stage, what follows is an outline of the birth, life and death of our solar system.

And then there was **light**. A gigantic point of energy bursts forth out of nowhere (the **Big Bang)** and in its bursting comes expansion and space. Where there was nothing expansion creates space within a universe that expands into nothingness. Amid the high-energy soup of **radiation** there is little matter and what there is, continues to be annihilated into energy and subsequently renewed as matter. With its expansion, the fireball cools. Atomic **nuclei** form out of the radiation, creating Nature's building blocks—**electrons**, **neutrons** and **protons**. Minutes pass—time as measured one day by the motion of a rotating planet revolving around a yellow star called the Sun—and more and more radiation converts into matter. Cooling further, protons and neutrons are thrust together past the repulsive forces that keep them apart to form the **nuclei** of light elements known in their time as **hydrogen**, **deuterium**, **tritium**, **helium**, **lithium** and **beryllium**. Dominant among these elements are hydrogen and helium, with hydrogen contributing three times the total mass of helium to the stew of radiation and matter, with the remaining elements being inconsequential contributors. In this process of element building, only a few simple stable combinations of protons and neutrons result, for conditions are limited in the cooling high-pressure furnace that is the early universe. As these atoms form, radiation lessens.

After a few million years, temperatures are cool enough so the positively charged nuclei can capture the negatively charged electrons. **Atoms** form, allowing a world previously opaque to sight to become more visible for matter now dominates rather than radiation. Gigantic clouds of gaseous hydrogen and helium become visible, linked by long filaments of matter, and dominate a universe bathed in the primal radiation which slowly ebbs away as the universe expands.

Over millions of years, within this expanding universe, clouds of matter clump together under **gravity**, collapsing and forming giant flattened pinwheels of rotating gas. Within these pinwheels—these embryo

galaxies—smaller clumps of gas collapse to form brightly shining objects called **stars**. The pinwheels gain form, rotating and trailing three or four spiralling arms defined by hot, blue, young stars. Overlaying this image are myriads of stars that are cool and red but their light is hard to see against the glorious overwhelming light of these young stars and the remains of the clouds from which they sprung. Small numbers of spherical objects containing hundreds of thousands of stars orbit these galaxies; dipping in and out of the flattened disks, which are rich in stars, but not sharing the general motion of the spiral arms and their attendant stars and gas.

The universe is a crowded place amid these gigantic pinwheels or **spiral galaxies** as they will be known one day. Collisions occur, for the universe is small and the galaxies are large. Galaxies collide and merge. Their gases intermingle, forming even more stars which interact with each other creating diverse orbits as the colliding galaxies go through a huge mixing process. At its end, the mixing may result in an oval shaped object vastly different from the parent spiral galaxies. In this way **elliptical galaxies** form, which are notably different from their progenitors in their shape and in the absence of gas. Other galaxies brush by each other drawing matter away in vast, long tendrils of stars and gas.

But as the universe expands, these galaxies gain more space in which to move. There are fewer collisions. **Billions** of years pass. A pattern emerges, revealing a vast latticework of matter linking the galaxies and surrounded by enormous holes of empty space. The galaxies also clump together under mutually felt gravity to form giant rotating conglomerations, themselves part of even higher groupings. Long-born galaxies grow dim with the passage of time. New galaxies form from gaseous material that slowly clumps together over the eons. Within these giant rotating spirals, stars continually form while others die away. Some stars die in such a blaze of glory that the light from the explosion drowns the light of the galaxy's other 100 billion stars.

Within one of a spiral galaxy's arms there is a star ripe for destruction. It is huge, so large that light takes tens of minutes to traverse it. And it is red and bloated, its density a billionth of what it was when its **nuclear furnaces** started only 10 million years ago. Suddenly, with not a tremor of forewarning, it explodes in a blaze of light that would in time be seen clearly at the outer reaches of the universe. Once the glare subsides, a shell of gases moving at unbelievable speeds expands outwards from where the star ***had*** been. For it is no more. Well, almost no more, for a tiny object remains, it too racing outwards as if to keep in touch with the other remnants of its parent. This object, this dead star, a **neutron star**, contains only a fraction of its parent's mass. It is almost as dense as an atomic **nucleus** and spins as it races through space emitting a narrow beam of light from its polar regions as it rotates. When viewed it is called a **pulsar**. Even then it is hard to detect because it flickers on and off in thousandths of a second. This neutron star keeps on its path inside a gaseous shell that expands rapidly into interstellar space and is soon lost to view.

At speeds of many millions of kilometres/hour (km/hr) the debris races outward with little to impede its motion. The debris is not just hydrogen and helium but oxygen, iron, silicon, carbon… elements which were created in the blazing cauldron that resulted from the star's detonation. Over millennia the cloud crosses the spaces between the stars until it collides with a similar random giant cloud of gas and dust. The cloud itself, the product of long dead stars or part of the enormous gaseous residue from the universe's formation nine billion years previously. Within the merged cloud, the balance between natural internal motions of the individual atoms and the force of gravity wanting to collapse the system is sundered as the impacting gas increases the local density of gas. Now this denser material acts as a gravitational magnet that pulls the cloud together in one huge gaseous mass **trillions** of kilometres across. The cloud collapses under the effects of gravity, and, over time, motions that might be only metres/second (m/s) are accelerated into speeds of 100s of km/s. Because of asymmetries in the way that the cloud collapses, it begins to rotate. With this rotation it flattens, swirling into a planet-forming pinwheel with a compact mass of gas at its centre. The centre compresses more under the inexorable force of gravity, and, consequently, it heats up and begins to glow, first a dull red then a more brilliant red. But initially, not much can be seen for the pinwheel is shrouded in gas and dust. Outside the central mass of gas, rotating material collides, often sticking under the local effects of gravity. Nodes of matter form. Under gravity, the nodes grow and they too begin to rotate. These nodes, later to be known as planets, sweep around the embryo star—our Sun—colliding with any material in their path. Sometimes other nodes of material are captured. Most often the material falls onto an existing host but some go into orbit about the host providing a seed upon which other material may accumulate.

Amid this mayhem the central star shrinks and shrinks under gravity's relentless imperative, getting hotter and hotter until it is decidedly yellow in colour. This radiation slowly drives the gases out of the embryo **solar system**. By now the central star is a nuclear furnace, fuelled by converting hydrogen gas into helium, a process switched on by the enormous temperatures and pressures in its central core. Its fuel will burn for billions of years. But out of this seeming chaos order comes. Over time, the Sun and its retinue of planets, many with moons and rings, emerge from the gaseous remnants of their creation. Eight planets, among a plethora of debris, remain. All these planets start out surrounded by massive atmospheres of hydrogen and helium, either in liquid or gaseous form, the very building blocks of the Sun. A tug-of-war occurs between the planet's own gravitational pull and that of the heating, vaporising radiation from the Sun. The innermost planet loses the fight and slowly its heated atmosphere evaporates. The other nearby planets fare better in retaining their atmospheres, except the fourth one whose atmosphere is thin because its gravity is not as strong as the two planets immediately interior to it. The moons, associated with many of the planets, fare less well too but four moons, orbiting the outer planets, retain cold, gaseous atmospheres.

The four inner planets are small rocky places, one hosting a giant moon, and another with two tiny moons probably captured in the early days of formation. The innermost one is scarred by **impact craters**; a permanent reminder of the history of the planet as it did its part in sweeping the flotsam and jetsam remaining from the birthing of the solar system. The surface of the second planet is totally obscured by a white veil of clouds that traps the heat from the Sun, creating an arid place of enormous pressure and heat. Its surface is pockmarked by volcanoes and covered in magma flows. The third planet is brilliant blue and white with seas starting to teem with life, its moon a carbon copy of the innermost planet. The fourth planet is red, coloured by iron oxides, a reminder of the fact that iron provides a critical pathway in the way stars live and end their lives. There may be large masses of water still there but hidden underneath the polar ice caps. Its thin atmosphere is revealed by clouds and gigantic dust storms that sweep across the planet's surface, making the surface detail all but invisible for many of this planet's days. Other planets are huge rotating spheres of hydrogen and helium modified by the presence of carbon compounds. All have moons and rings though one is particularly spectacular. One moon reveals intense volcanic activity caused by a "push-me pull-me" gravitational effect from its giant master and another nearby moon. The original ninth and outermost planet-like object is different from the rest. It is really two objects of almost comparable size moving in a path that loops inside the orbit of its immediate interior planetary neighbour. Another more remote and smaller object takes its place as the ninth planet. More are out there.

The solar system revolves under the immutable laws of physics, and interlopers, arising from the vast reaches of space beyond the last planet, sweep in towards the Sun. At first, their motion is slight, but the Sun's gravity accelerates them, and in time, as they approach closer to the Sun, its heat begins to evaporate the cold gaseous envelope that encapsulates these objects. Ices turn to gas and the pressure of radiation—the same force that expelled the last of the gases from the solar system billions of years earlier—creates a bright reflecting gaseous tail that always points away from the Sun. But the Sun pours out more than radiation, it accelerates nuclei of its own material into space. Hydrogen, helium, **iron** and other nuclei beat on the onrushing interloper driving forth the dust that is mixed with the evaporated gases into another tail. The **comets**, for that is what they are, increase speed the closer they get to the Sun, quickly curving around it then racing outwards, slowing as they go back to the place from where their journey began tens, hundreds, or thousands of years earlier. From this place they will return, for they are in the immutable grip of gravity that holds them in their orbit. Occasionally, they don't make a return to the unfathomable cold of the outer solar system, but are captured by the gas planets, in particular, the giant one, either claiming it as another satellite or more likely gobbling it up in the seas of liquid **hydrocarbon compounds**. Sometimes the Sun's gravity breaks up the interloper so that it exits the Sun's environs trailing material. Occasionally these parts will strike the third planet shrouding it in dust for millennia. Within that shrouding cloud, species die, notably the dinosaurs, but upon its inevitable dissipation life reasserts itself.

Eons pass until other interplanetary interlopers are seen. All arise from the third planet—our Earth—which seems to be producing its own version of what had previously been seen arising in the outer reaches of the solar system. These new interlopers circle and perhaps pass by each of the planets at times, sometimes disappearing outward into **interstellar space**—the space between the stars. A number of these objects land on the Earth's moon and the fourth planet, or circle two of the next outer planets.

Over billions of years the Sun gets larger and slightly cooler. Though its growth is slow, it is steady and inexorable. Its outer atmosphere enlarges until the radiation melts and evaporates the inner planet and clears the atmosphere of the cloud-shrouded second planet. Then its evaporation begins. The seas boil on the third planet and then it too meets its fate. The fourth planet follows. After ten billion years from their formation these planets are finally consumed by the source that birthed them. Yet the process is not yet over…

The foregoing outlines the birth, life and death of our solar system. We must deal with the fact that Earth is doomed. Our present notion that we can't travel between the stars because of the distances involved is false. Many science fiction writers have dealt with the imperative for us to reach the stars. We have no choice in the matter. Yes, the Earth's destruction is billions of years into the future and how we get to the stars is unknown, but we will have to accomplish the leap. Currently, telescopes are investigating our stellar neighbours looking for evidence of life. Given its discovery, maybe we'll find our future home, or 'life" will find us!

In this book I'll finish the story of our Sun and other stars too, for the stars come in all sizes, chemical compositions and associations—single and double or more. These factors mean that their evolution is all different. Don't think for a moment that the story is clear-cut—it isn't. This can be seen from the confessions, contradictions and the omissions in this narrative. I'll talk about the way astronomers practice their science, the tools they use and the general limitations of the process, from the point of view of someone who has had the marvellous good fortune to be still doing research after more than five decades.

CHAPTER 1

BACKGROUND

1.1 What's with astronomy? Who cares?

The world of the astronomer, which I call the night-time world, is one of mystery and excitement. Regardless, whether one is a stellar astronomer (one who studies stars) or a cosmologist (one who studies galaxies and the structure of the universe), we view this world with the same wonder. The mystery is easy, for we have all looked up at the sky at some time or another and wondered "What is out there?" The list of queries I've encountered from the public about the night-time sky is endless and the answers are as interesting as they are diverse. What are those points of light we call stars? And those streaks we see burning across the sky—the shooting stars (**meteors**), are they stars? What about the comet things that are played up in the newspapers as promising to be spectacular to look at and, upon viewing, always seem to let us down? Is the Sun a star? Where does the Sun, and the storms that erupt on its surface that somehow disrupt communication here on Earth, fit in the scheme of things? How do events taking place within the Sun affect the long-term climate on Earth, producing ice ages and more recently a mini-ice age within the last five centuries? How come barley was grown in Greenland a thousand years ago? Why is the Moon bright? What is the difference between a planet and a star? For some, this latter question is ridiculously easy and yet there is a real issue about what a planet is and what is a star! What about life out there? And of course, what about UFOs? What we ***don't*** know is endless. At other times I've had a different point of view expressed. "Why should we waste our money on studies that have no relevance to me? The stars don't affect me one bit." True. One cannot justify the case for studying astronomy based on utility. But there is one exception. As we will discover, there is a strong case for us to study the Sun for what happens around and on it, impinges directly on Earth and some of its effects can be mitigated if we receive enough warning. I'm talking here about global warming and catastrophic communication failures caused by particles emitted from the Sun running down the magnetic lines of force in the polar regions. But my real answer is buried in the responses people make when, in my adult education classes, I ask them why they enrolled in the course.

Are we alone? There is a deep drive within us that wants an answer to this question. “Is the Sun and its planets simply an accident of fate?” In coming to grips with an answer, we first must find planets circling other stars. Thousands of planets are now known to orbit stars (we call these objects **exoplanets**). Some planets have been found in the “**Goldilocks zones**”, orbiting in places where the temperature is neither too hot nor too cold to preclude life as we know it. Given this, the likelihood of an answer to the larger question increases, such that one day we will know for sure.

There is the wonder involved when looking into the heavens on a moonless night out in the country that is totally absorbing. Everyone who has done so has, at one time or another, wondered about Life, our existence, whether the universe is endless or not, whether sentient beings are out there and whether these beings are already among us or spying on us in some way. Just as if we ever learn to travel forward and backward in time, we’ll have those beings with us right now. These cogitations feed the human spirit. When I look upon the images from the **Hubble Space Telescope (HST)**, I recognise their beauty and am moved. The images in Figure 1-1 are two of many in the Hubble website that take my breath away.

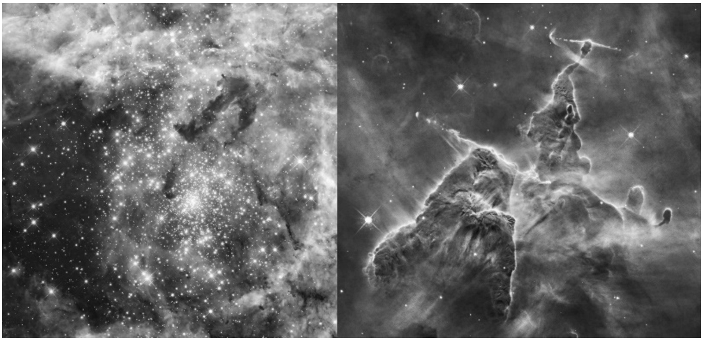

Figure 1-1. See Centrefold. Left panel. The star cluster, 30 Doradus, an **open or galactic cluster** made up of young, hot blue stars with an age in the millions of years. The right panel shows a star-forming region with the unlikely name Mystic Mountain. Credit: Left panel. NASA, **ESA**/Sabbi (ESA/**STScI**). Right panel. NASA, ESA/Livio, and the Hubble 20th Anniversary Team (STScI).

To answer the question about **extra-terrestrials,** we need to discover their base or realise the potential that they could already be here. And how can astronomy help in this regard? Believe it or not there is a branch of astronomy where questions are posed and conclusions reached about the feasibility that sentient beings could populate the galaxy even when limited by the speed of light, the maximum velocity a spaceship can attain. People suggest that in the billions of years available—remember the Sun has been around for 4.5 billion years—even at sub-light speeds sentient beings could have explored the whole of our Milky Way Galaxy! If so, perhaps they have reached our solar system, leading to the question, “Where are they?” In turn, this leads one to wondering about the places where their listening posts might be set up. The backside of the Moon? Maybe in the **asteroid belt**, the space between Mars and Jupiter where debris called **asteroids** are found. We have investigated the backside of the Moon and find no trace of some far-flung outpost. Investigating the asteroids is another issue—there are thousands of them. Perhaps they are under the sea in its deepest reaches. When the Viking Explorer took a picture on Mars that appeared to show a sculpted face, it generated immense interest and an excessive over-interpretation of the limited data available. Unfortunately, follow-up data showed that the face was a chance illumination and the unseen side of the mesa was quite different from Viking’s original view. The point of all this is that the practicalities of another race exploring the galaxy lead to a consequence, a listening post of some sort—at least in the way ***our*** minds work. This is the essence of the **scientific method**. Reach a conclusion and make a prediction. Your theory then rises or falls on the prediction being found correct or not. The lack of evidence does not negate the possibility that such beings have visited us, establishing a lookout amongst the jumble of the asteroids or hidden within our moon’s surface. There is a surfeit of potential hiding places. Related to this is the ever-intriguing notion of time travel, because, if it is ever possible, then those beings, our distant descendants, could be here now—our neighbours perhaps. And if one of the travellers told you that they were from the future, even if they ***could*** prove it, would you believe them?

When you glimpse the heavens on that starlit night in the country you become aware of what we have lost in the cities. Just as looking at a flower brings a sense of joy, looking at the sky engenders similar awe. Environmental issues are now front and centre in our consciousness as the days of mindlessly raping our Earth are slowly becoming limited. We rape our night sky with notions of placing huge reflectors that will illuminate the icy, northern latitudes of our planet in winter. Do we want to live on an Earth where day follows day follows day…? Think about your neighbour’s security lights that blaze throughout the night, or the light spilling over into neighbourhoods from sports field, malls and business security lighting.

Mulling over the night sky brings the notion that perhaps we may be able to give ourselves downward-oriented lighting that does the job yet is less intrusive in our lives and will save a dwindling resource—energy!

Contemplating the night sky should give us a proper perspective on our importance, putting our tribal tribulations and pomposity into humble perspective. This is summed up for me in Shelley's poem Ozymandias:

> "…And on the pedestal these words appear:
> 'I am Ozymandias, King of Kings.
> Look on my Works, ye Mighty, and despair!'
> Nothing beside remains. Round the decay
> Of that colossal Wreck, boundless and bare
> The lone and level sands stretch far away."

A more contemporary view is offered by Hobbes, in response to Calvin's observation about the Universe.

> "Look at all the stars! The Universe just goes on forever and ever!"
>
> "It kind of makes you wonder why man considers himself such a big screaming deal."

Thank you, Waterson!

By our study of the stars and galaxies we may learn there was a beginning to our universe, about 14 billion or so years in the past. Naturally, we ponder about this beginning and why the universe came into being and hence to the question "Is there a God behind all this?" My science has made me a believer, but what we believe is highly personal and we aren't going to change our belief because some scientist comes to a particular conclusion. But we can talk about what appears to be the fate of the universe and our uniqueness.

Looking at our lives here on Earth we are like grubs looking at the ground underfoot as we grasp and seek sustenance. It is a hard life for most of Earth's inhabitants, only made bearable by our children succeeding where we failed. For us, it is to be able to roll over onto our backs on a magical night where the sky is black and the stars and the Milky Way burn into our consciousness, and be reminded that out there perhaps, there is a world untrammelled by lust and greed and hate; that for the pain and penury we may, and do, experience here on Earth, there is indeed a larger world, unknown for sure, that is beautiful beyond description and imagination. For me, the gaze and the dream are of the symbolic craft that took a mortal

Arthur to the promised land, a place in which we all deserve to be. When I am observing, I look up at the night sky with wonderment and never more so when I was in Chile where the sky was clear and the firmament gloriously exposed above me. A photograph from the **European Southern Observatory (ESO)** at Cerro Paranal in the Atacama Desert in northern Chile included here (Figure 1-2) might remind you, the reader, a feeling that everyone has experienced who has seen the **Milky Way** in all its splendour from outside a city's environs.

Figure 1-2. See Centrefold. A view of the Milky Way from Cerro Paranal, Chile. The Magellanic clouds, the smaller (**SMC**) and larger (**LMC**), are our nearest galaxy neighbours, identified by Magellan on his circumnavigation of the globe in the early 1500s, are to the right of the dome. The galactic centre is down to the left of the dome. Credit: ESO/Tafreshi.

If the previous comments regarding astronomy feeding the human spirit are unconvincing, let me take another tack. There are two answers I give to those who think that astronomy, and by extension, pure research, is of no value. The first is the **calculus** that Isaac Newton (1643-1727) developed independently with Leibnitz (1646-1716) and which Newton later used in his theory of gravitation. The calculus was developed as an academic exercise and yet no modern aircraft flies and no skyscraper stands without it. The second is the notion of imaginary numbers, which are based on exploring what might happen if you ***can*** take the square root of a negative number, which is impossible. Consider this example. Four is the square root of 16—the number when multiplied by itself gives 16—the square root of -16 does not exist as -4 times -4 is 16! Despite this impossibility, our communication system depends entirely on an analysis that has imaginary numbers at its heart. Both practical examples are entirely based on pure or "**blue sky research**" embarked on centuries ago. As I write these words, I'm reminded of a subject that I took at university and gave up on, writing the final exam on only two of the three subjects required. I was a "**flat-earther**" with respect to projective geometry which is based on the question, "What happens if parallel lines ***can*** meet?" We see this fact all around us, the railway track and roads that come to a point in the distance. Well, I don't know, but I guess that theorems from those mathematics are at the heart of the gaming of which our kids are enamoured.

Lastly, we want to explore the universe with our **telescopes** and space probes because of sheer inquisitiveness, just as the early explorers carried out expeditions to explore the Earth with wide-eyed interest and amazement and so catalogued the Earth's fauna and flora. One of the greatest of the western world's navigators Captain Cook, travelled to Tahiti to observe, of all things, Venus traversing the face of the Sun! We want to investigate because it is there and because knowledge of one thing leads to another! The same with space, and further abroad—the universe.

The newspapers routinely report that astronomers have observed the most distant galaxies yet (again). Their light has taken thirteen billion years to get here. How do astronomers know this and what has time got to do with distance? We see pictures of a star that has suddenly appeared in a distant galaxy and it is referred to as an exploding star—a **supernova** (super new star)—well, how do astronomers know this and what does it signify? What about these black holes from which not even light can escape? How do we examine them when they prevent light from reaching our eyes? Other reports tell us that the universe is expanding, but even more, it is accelerating as it expands—itself a major problem for those who try to explain the universe and its evolution since the acceleration requires a force. Where, and what is it? They say supernovae tell us this. What does this mean and why are exploding stars useful in this regard?

Beginning to answer these questions gets to the heart of astronomy which has its origins thousands of years ago when the first measurements of distance and size were made. Then, the world was pristine and life was hard. Ideas of democracy and great thoughts were in flower but what was known then was lost for more than two millennia. I often think back and imagine those people living before the advent of telescopes, trying to get a handle on the strange world out there. Knowledge has come to us incrementally over the centuries because the ancient scientists were limited by their equipment and hence their acquisition of data. But they were not limited by their imagination, as a study of the ancients and the diverse ways they gained insight soon reveals.

What are data? What sort of things did the ancients measure? What do we measure today? It is easier to start the discussion by talking about the ancients. Data are compilations of measurements. The early Greeks measured angles of the Sun, stars, and planets against some reference line, maybe a vertical plumb bob or against the horizon, recording the seasonal changing positions of these celestial objects. They recorded times and places of eclipses, times of the rising and setting of the Sun, Moon, planets, and selected stars. In the process they learned to predict the seasons and long-term cycles of solar and lunar eclipses. Note that a solar eclipse occurs when the Moon blocks out the light of the Sun and a lunar eclipse is when the Earth blocks out the Sun illuminating the Moon. Other peoples distilled similar information and presented it in the form of stone circles used as observatories to give them practical information regarding the seasons and their onset. They measured the period of revolution of the planets known to them—Mercury out to Saturn. They measured the brightness of stars, admittedly crudely, but their system of measurement we call **magnitudes** we still use today—and they recorded it. Libraries of data ***must*** have been available so that predictions using these data could be made. Given these data, Hipparchus (190-120 BCE) then tried to make sense of these observations and in doing so, discovered the **precession** of the equinoxes. or the rate at which the Earth‘s rotational axis **precesses** about the North-South axis—precession is what we see when we spin a top onto the ground. The period of this precession is about 26,000 years and was derived by Hipparchus in the second century BCE! The early names, positions and brightness of prominent stars were recorded by Hipparchus and later reproduced by Ptolemy (100-170 CE) in the Almagest in the second century CE and later developed by Arab astronomers.

Like us, they needed a framework upon which to interpret their observations. Initially, they would have interpreted the motions of the planets, a word that means “wandering star”, in terms of the Sun and planets moving around the Earth. Wise in the use of geometry, they understood that the Moon got its light from the Sun because it was the simplest explanation for the phases we see. And so, their interpretations went on, culminating in the notion that their data were best served if the Sun was at the centre of our solar system and that the Earth and planets revolved about it. The Greeks knew this more than a thousand years before Copernicus (1473-1543) proved it, yet it was Aristotle’s acolytes who shot down this notion of the

Earth revolving around the Sun because seasonal shifts in stellar positions are predicted by this assertion. This was early science in action, the logic being, that if the Earth revolves around the Sun, the closer stars should move backwards and forwards over six months with respect to more distant stars. This was not observed. The prediction failed, so the assertion was false. But nobody had any idea just how far away the stars were.

To this day, we measure positions of objects in the sky with ever-increasing accuracy and note any positional changes with time. We draw maps of the sky showing the positions of stars and the gas clouds in our galaxy. Satellites detect **X-rays** and **gamma rays** from space, recording, for each object, the picture or image, the time of the observation and the location of the source, comparing these data against objects at the same position in order to identify them. We time the moments when we make our observations. We measure the brightness of stars and galaxies, often recording times and brightness of thousands of stars at a time. We spread out the light from stars and galaxies into rainbows and measure the strength and positions of the features in these so-called **spectra**. The colours of celestial objects are measured and so it goes on. But, as with the ancients, we still need a framework—a model—with which to interpret what we see, but more of this later.

Nowadays, we are limited because of too much information. Knowledge is expanding **exponentially**, like our debts did when the mortgage rates were up at 18% or so. Under these financial circumstances, managing a debt was (thank heaven it is in the past) difficult and so it is when I try to assimilate the exciting information about the stars that are flooding across the Internet from the Hubble Space Telescope (HST) and other groups pushing the boundaries of astronomy and astrophysics. A book like this cannot keep up with the exponential flow of data and results that are currently flooding the literature. A glance at Figure 1-3 illustrates this through the output of many observatories. The numbers of paper include results for engineering, optical, electronic and astronomical research because the designers and builders of these wonderful telescopes and instruments are forever breaking new ground, just as astronomers are now breaking new ground as the universe is being plumbed by new technology in an ever-expanding subject. I'll talk more about this in Chapter 15. I can't nibble at the material as it flows by but periodically take large chunks to digest and hope that I haven't missed some juicy morsel. But in interpreting what is going on in the sky, specifically among the stars, I take a long-view knowing that this plethora of information will have its chaff, for winnowing is a natural process when these exciting front-page discoveries are critically examined on their way into print in an astronomical journal. Trying to navigate within this material

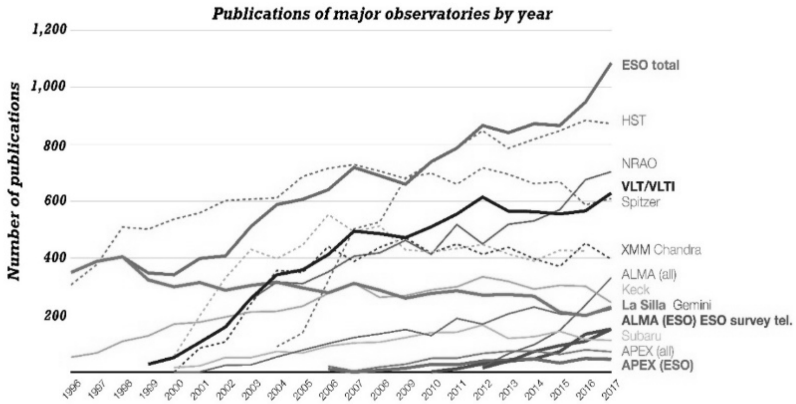

Figure 1-3. This graph shows the difficulty in being current with the science and I make no excuse for failing in this regard. The codes along the side refer to the various major observatories producing papers. Most of the abbreviations, are described in the glossary. Credit: ESO.

is like getting lost in some strange city where contradictory information is fed to you from imperfect street signs and inadequate maps. My caution therefore is to go "ooh", "ahh", but take the first announcements with a grain of salt. Like good wine, knowledge will mature with age. If the same story is around a year from now then chances are it is more than an astronomer's fanciful theory, but sometimes the stories are unfortunately aimed at getting an individual a moment's instant fame. What is included in this book however should give the reader some worthwhile framework within which the inevitable new discoveries may be understood and evaluated.

While words might be suspect—extravagant even—the images coming from the HST and the **Very Large Telescope (VLT)** cannot be ignored. Universally stunning, they are the fast food of astronomy, totally satisfying but also intriguing in what they are depicting. The words come by way of explanation and it is those words that may throw the eager viewer for a loop for the language of astronomy is strange.

My scientific interest has been the study of stars, young, extremely hot stars mostly, but also I've been interested in stars that are born in pairs (**binary stars**) or as triples. Sometimes, when binary stars evolve, they grow old in their way without interacting with their companion, but most often they interact dramatically with each other. Under these circumstances one star may get **cannibalised**, that is the companion consumes part of it, but perhaps it gets its material back; maybe it gets heated and evaporated to a central core. Sometimes binary stars appear in a form like dumbbells we cannot explain. The possibilities are endless. It is a strange, mostly unknown world out there. From a study of these stars and single stars using theoretical models, once generated laboriously by hand but now in an instant by a computer, we have gotten a good grasp of the way stars are born, live and die. Sometimes they end like embers, gently snuffing out, or explosively leaving in their wake bizarre remnants. Binary stars often die by convoluted pathways making them an even more interesting topic for the discussion that follows on the way stars evolve.

But, as one reads in the newspapers, astronomy is much more than the study of stars. The European and American space programs are uniting at times to explore our solar neighbourhood as well as out to the boundaries of our universe. A new space telescope—**Gaia**—has been launched and is currently observing at a **critical point**, called **L2**, 1.5 million km from the Earth, beyond the Moon, where gravity from Moon, Earth and Sun are balanced by the spacecraft's orbital centrifugal force (see Figure 1-4). It is a good place to park a telescope because you are well away from the Earth which takes up a fair bit of the sky when you are in an Earth-based orbit. At L2 you are further away but still, with some gentle orbital changes, able to affect the direct connection needed to download data while the Sun, needed to charge the solar panels, is visible.

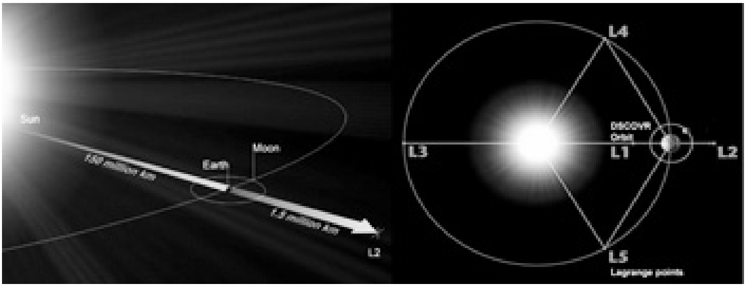

Figure 1-4. L2, the favourite location for orbiting observatories is shown on both panels. Other points of zero gravity are shown in the right-hand panel. They are located at the points where the orbital centrifugal force balances the joint attraction of the Sun and the Earth. Credit: **European Space Agency (ESA).**

The search for **extrasolar planets**, or planets going around other stars, is going at full throttle as well as cosmological research aimed at understanding the first moments of creation. "Why the universe looks like it does, and its long-term fate?" **Stellar astronomy** finds itself between the