This extract shows the first two (non-paginated) pages of each chapter together with a sample of the mathematical section (chapter 7)

Preface

My intention in writing this book was to serve a specific audience: the science aware and interested; advanced amateur astronomers; and those studying astronomy, or planning to, at undergraduate level.

There are some excellent photograph-rich and descriptive introductory level books on astronomy which I would put into the ‘awe and wonder’ category; inspirational works which show the scale and beauty of astronomy.

At the ‘other-end’ of the spectrum are graduate and research level treatises which require high levels of mathematical education and competence to be able to read. These are challenging and leading edge works aimed at professionals and researchers and not specifically written with readability in mind!

My aim is to provide a transitional step between these two genres.

I believe that in order to understand the science of astronomy, and hence to put the awe-and-wonder in context, and serve as the basis for being able to take on some of the higher level works, an appreciation and understanding of the underlying mathematics and physics is essential.

However, my approach here has focused on four tenets:

1. Not to assume too much background knowledge. If you have read through any of the awe-and-wonder genre books, or can recall some school level science, this book is appropriate for you.

2. In order to keep readability, I have sought to avoid too much mathematics within the main body of the text. I have shown the descriptive equations and how they are used, but their genesis and derivation is provided within the specific mathematical chapter.

3. I have provided full expansions. I have not used ‘it can be shown that’ as I think this is not appropriate in an educational focused book. Where the scope of this book means that I have *had* to ‘import’ an equation, I have provided a reference (an audit trail!) for where the reader can research more into how the equations have been derived and where they come from.

4. The mathematics used is no more complex than would be found at first year undergraduate level, and only within the mathematical chapter at this level.

Astronomy is a very dynamic and active science. Space probes are sending data to Earth literally on a daily basis and theoretical papers are being issued every month. Many areas of the science are still not understood and this provides challenges and opportunities for real advances to be made.

Although this book is about the Sun, there are a number of references to other areas of astronomy and I have used the Sun as the ‘shining-light’ on the science as a whole.

My aspiration is that this book can serve as the primer for the reader to delve deeper into this most fundamental of sciences and to inspire learning and researches. I wish you years of enjoyment.

Acknowledgements

In writing this book I am indebted to the scientists throughout history up to the present day who through their hard work, inspirational genius and frequent sacrifices have made such great inroads and insights into our science. Astronomy, as all sciences, builds upon astute and accurate observations, experimental successes and ‘failures’, and theoretical interpretation using mathematical descriptions. This book uses the results and works from innumerable astronomers and mathematicians. Specific texts which I have used most often as works of reference have been included in the Bibliography and Additional Works sections, which together with the References and Online resources cited, I gratefully acknowledge the authors of these works.

I also acknowledge my more personal gratitude to the following few scientists and non-scientists who have supported me in my endeavours here.

First and foremost, I wish to both recognise and thank my teachers. I refer specifically to my tutors at Teesside Polytechnic and in particular John R Dormand, Peter J Prince and Alan W Bush; and my lecturers at Queen Mary University London, and in particular Iwan P Williams and John C B Papaloizou. Together with the inspirational physics teacher I had at Whitby school, Mr Wallace, they have given me a lifelong passion for astrophysics and mathematics. On a more practical note I have used their learning and the notes I took from their lecturers freely.

My passion however would have stayed just that, and unwritten had it not been for the support and encouragement of Elaina Taylor, Amanda Taylor, John Malaney, Adam Poundall and Svetlana Zigel. I acknowledge Maria Hyde for her support and help with the illustrations, and my proof-readers Janet Hyde, and Adam McMurchie of the SSIG (Scottish Space Interest Group). To each of these I owe an un-redeemable debt to which I can merely offer my heart-held appreciation towards. However, I am without saying, solely responsible for any omissions or errors which have found their way to the final print.

The Sun’s basic characteristics

Solar parameter	Value	Reference section
Mean distance from/to Earth	149,597,871 km	1.3.3
Distance from/to nearest neighbour star	4.2 light years (Proxima Centauri)	-
Distance from/to milky way galactic centre	8.2kpc	5.1.1
Radius	695,508 km	1.4.1
Volume	1.41×10^{18} km^3	1.4.1
Mass	1.9885×10^{30} kg	1.4.2
Mass loss rate (solar wind)	4.7×10^{16} kg yr^{-1}	3.8.3 & Ref [1]
Mass loss rate (energy production)	1.37×10^{17} kg yr^{-1}	Ref [1]
Luminosity	3.845×10^{26} W	2.4 & 7.6
Apparent magnitude	-26.75	2.3.2
Absolute magnitude	+4.83	2.3.3
Average density	1408 kg m^{-3}	1.4.2
Central density	1.51×10^5 kg m^{-3}	3.4.2
Central pressure	2.33×10^{16} N m^{-2}	3.4.2
Photosphere temperature (effective)	5770 Kelvin	3.6
Central temperature	15.7×10^6 Kelvin	3.4.1
Coronal temperature	10^5 to 3.5×10^6 Kelvin	3.8.2
Rotational period (polar regions)	~35 days	3.6.1
Rotational period (equatorial)	24.47 days	3.6.1
Photospheric level escape velocity	617.7 km s^{-1}	4.9.3
Current age (since ZAMS, fusion started)	4.6×10^9 years	2.5.8
Estimated time before white dwarf phase	5.9×10^9 years	2.5.9

1. <u>OUR STAR - THE SUN</u>

The Sun is *just* another star. One of one hundred million stars in our galaxy, the Milky Way which is just one of at least another one hundred million other galaxies. But to us, it's rather important. Without it, neither you nor I would exist, or any other life on Earth. There would be no planet Earth.

In this book we explore how the Sun was formed; its structure; how it generates power; its observable features and why they come about; and how the Sun will evolve and eventually 'die'. But to begin with, in this chapter we will take a look at some of the Sun's characteristics and qualities and how over the past 500 years, scientists have developed the study of solar astronomy.

1.1 The Sun's basic characteristics

The Sun is huge. It has a diameter of 1.39 million km (865,000 miles). That's vast compared to the Earth's diameter of just over 12,700 km (7900 miles), but compared to other stars, it is nothing special and is defined as a dwarf star. The Sun doesn't actually have a solid surface (you couldn't stand on the Sun for quite a number of reasons) but what we 'see' as the surface has a temperature of about 6000° Celsius. At the middle of the Sun however, it's a bit warmer at around 16 million° Celsius.

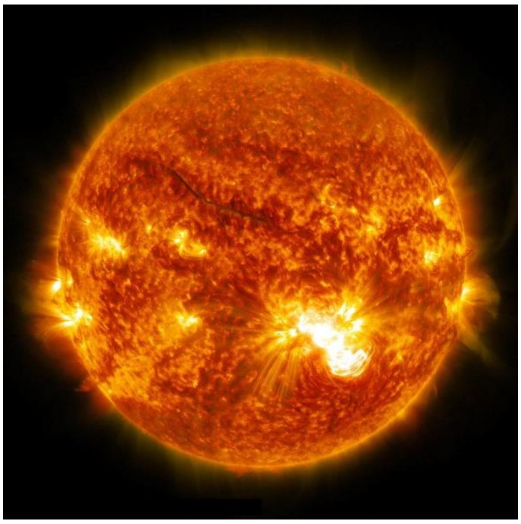

Figure 1 The Sun

The Sun generates its heat (energy) by nuclear reactions in and near the centre. Here, nuclear fusion reactions convert hydrogen to helium, and in doing so release some energy every time a conversion (a fusion) happens. This is very different to the nuclear *fission* in the power stations we use to generate electricity on Earth; these work by breaking atoms such as Plutonium and Uranium into other atoms and release energy during the breaking apart.

The Sun has been around for nearly 4,600,000,000 (4.6 billion, 4.6×10^9) years and is in a very stable state. It will stay like this for another 6 billion years or so, after which time it will change into a giant red star, swallowing-up the Earth. It will stay as a red giant for a few million years and then collapse to a 'white dwarf', a fraction of its current size, and slowly radiate away all its remaining energy. But there is no need to worry, we have plenty of time to have developed space travel for when we need to find another planet to live on!

The Earth, like all the other planets, comets and asteroids, orbits around the Sun. Our orbit is very nearly circular so the average distance from the Earth to the Sun is fairly constant at 149,600,000km. At this distance, it takes light just over eight minutes to reach us once it 'leaves' the Sun, so it's quite a long way. The average distance from the Earth to the Sun is an important distance in astronomy; it is called the '*Astronomical Unit*' or 1AU for short.

We will explore how these, and many other facts came to our general knowledge in the following chapters, but for the rest of this first one, let us look at how we know two of these things:

- How far away is the Sun? and
- How big is the Sun?

1.2 How far away is the Sun?

This is a simple question, but the answer is not as straightforward as one might expect. Astronomy books rarely show how an answer was reached to this fundamental question. It's a very old question and although a very good answer was found almost 500 years ago, it's only in the last 50 years that we have obtained an accurate measure for the real value of the Astronomical Unit. There are three ways of measuring the Astronomical Unit which we will look at here. The method used by astronomers in the pre-telescope era; the use in the 18th Century of *Parallax* and transits of Venus; and the modern method of radar measurements. All three methods inherently use a knowledge of planetary orbits, so we'll start our review here.

1.2.2 Planetary orbits

The Sun is the most massive object in the solar system and therefore the gravity it exerts dominates the movement of the planets. All the planets move around the Sun in elliptical orbits. To be precise, the Sun and the planet(s) move around their common centre of gravity but as the Sun is more than 1000 times as massive as Jupiter (which itself is more than 300 times more massive that the Earth), this is a nuance that we can safely ignore for now. An ellipse is a closed shape a bit like a flattened circle (in fact, a circle is a special sort of ellipse).

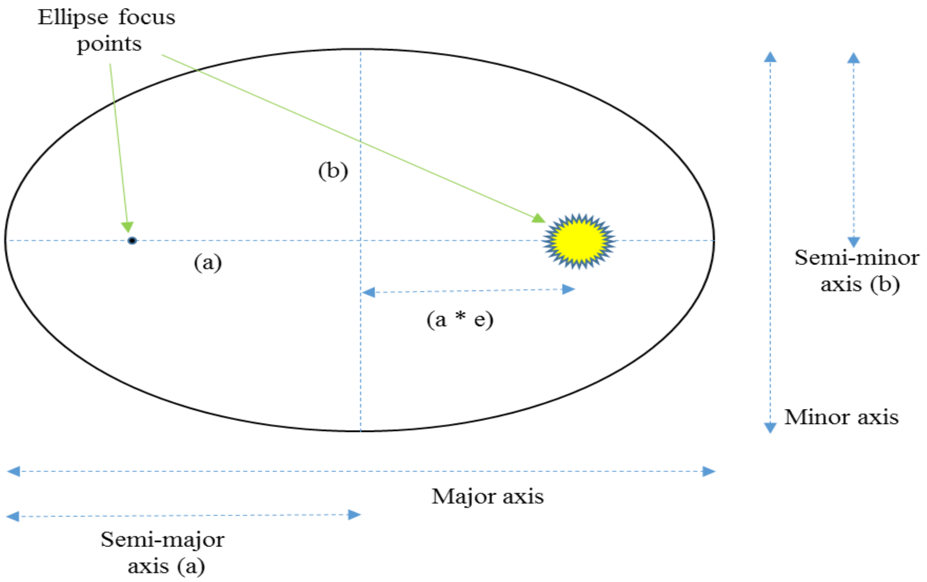

Figure 2 Elliptical orbits

The ellipse is defined by a number of elements, the key ones being:

Semi-major axis (a)

This can be thought of as the average distance of the planet from the Sun

Eccentricity (e)

This is the degree to which the ellipse is flattened. An ellipse has two focuses. In our solar system planetary orbits, the Sun is at one focus and the other focus is empty. A circle is a special case of an ellipse where the eccentricity is 0. Other special cases of ellipses are where the eccentricity is equal to 1; this is called a parabola or parabolic orbit and is an open orbit, ie it stretches out forever. The case where the eccentricity is more than 1 is called a hyperbola. This sort of 'orbit' again is an open orbit

<……Subsequent pages omitted from extract….>

2. POWER GENERATION IN THE SUN - The Physics of the Sun

In this chapter we'll look at how the Sun generates its energy; the physical processes which take place at the very high temperature deep within the core; and the different types of radiation the Sun emits. By looking at the Sun's energy, we see how its emissions can be used to deduce what is happening deep inside the Sun; we will also discover how we know the temperature of the Sun; and how we know what the Sun is made of. It is now known that the Sun produces its energy through nuclear reactions, but *how* do we know this? And how long will the Sun last?

Many sciences converge and overlap. Astronomy and physics are very much interrelated, and never so close as when looking at the topics of this chapter. Having seen in chapter 1 the huge scale of the Sun in terms of mass and size, we now need to use atomic and quantum physics to find answers, so our investigations will start with atomic structure. But first let's define what we mean by energy.

2.1 Energy

This is a very complicated subject where the laws of thermodynamics and quantum mechanics are all appropriate. We will take an outline approach here! You will see many different distinctive 'forms' of energy but essentially they all reduce to one of two types; *Kinetic* energy which is associated with a particle's motion; and *Potential* energy which is associated with a particle's position within a *force field*, where the force could be either a gravitational, electromagnetic, strong or weak nuclear force. Energy is the effect of transferring forces between objects or particles, and in the System Internationale (SI) standard of measurement it is measured in joules. One joule is the energy transferred when applying a force of one Newton (which is the force needed to accelerate 1kg at the rate of 1 metre per second^2) for one metre. Or in more familiar terms:

$$1 \text{ joule(J)} = 1 \frac{\text{kg m}^2}{\text{s}^2}$$

There are many equivalent measures of energy e.g. Watts (1 joule per second) and ergs (1 erg = 10^{-7} J) One which we will use is the electron-volt (eV). The energy equivalent is 1eV = 1.6 x 10^{-19} J

One of the fundamental principles of physics is the principle of conservation. This comes in several guises, including conservation of mass; conservation of angular momentum; and conservation of energy. The principle of conservation of energy states that within any 'closed' system, energy is conserved; it cannot be created or destroyed. It can be converted into different forms but the total amount of energy in the system will always remain the same.

The key here is to recognise the essential need to define the 'closed' nature of the system. If there are any inputs to the system (for example heating from an external source, or say an interaction with a nearby star) or outputs from the system (for example if an object were to be perturbed, i.e. gravitationally disrupted, from its orbit onto a hyperbolic escape path) then the definition of the 'system' would need to be extended. The conservation principle is sound, but needs to include the mass equivalence when nuclear fusion processes take place. Einstein's famous equation:

$$E = mc^2$$

where E is energy (in joules), m is mass (in kg) and c is the speed of light (in m/s) showed that there is a mass equivalence to energy. So any conversion of mass into energy affects both the conservation of mass and conservation of energy within the star. We'll look at these complications later.

2.1.1 Kinetic energy (E_k)

The kinetic energy of a particle is related to its velocity (v) and its mass (m) and is given by the equation:

$$E_k = \frac{1}{2}mv^2$$

2.1.2 Potential energy (E_p)

The potential energy of a particle of mass (m) is related to its position within a force field. We will consider here the force field to be gravity, and the force due to that exerted by a large object of mass M. In this case, the gravitational potential energy between the two objects is given by:

$$E_p = -G\frac{Mm}{r}$$

where r is the distance between the objects and G is the universal constant of gravitation. The minus sign indicates that the potential is measured from the massive object (or the centre of mass in the case of a single object or say condensing nebula).

How these two energy equations are derived is shown in section 7.3.

2.1.3 Virial theorem

The Virial theorem is a wide ranging theorem that relates the total kinetic and potential energies within a gravitationally bound and stable system. It is used in many areas of mathematical physics, and in astronomy in areas such as orbital mechanics, dynamics of stellar systems (star clusters and galaxies), and the identification of dark matter (mass undetected by direct observation or emissions). It is also used in the modelling of stars. It states that for a system of particles in stable equilibrium within a closed gravitational field:

$$2\sum E_k + \sum E_p = 0$$

An elegant derivation of this formula is given within the suggested further reading [4] to which the mathematically interested reader is referred. We will use the definitions of these energies and the Virial theorem later.

2.2 Atomic structure

All matter is composed of atomic particles; and the structure of the basic building block of matter, the atom, has a rich history of research. This is ongoing and continues to be at the forefront of modern physics research. The ancient Greek philosophers considered that matter was composed of minute particles, called atoms. The 'modern era' has included work by all the great names in physics such as Geiger, Rutherford, Einstein, Pauli, Bose, Dirac, Fermi and Schrödinger; and more recently Feynman, Schwinger, Englert and Higgs, up to today's researchers at CERN (Conseil Européen pour la Recherche Nucléaire, the European organisation for nuclear research based on the Swiss / French border near Geneva).

The model most conceptually understandable is the particle model developed and proposed in 1913 by the Danish physicist Niels Bohr (b.1885 d.1962). However, this model is not quite right and atoms often behave as if they were a wave-form. In 1926 Erwin Schrodinger (b.1886 d.1961) defined a mathematical model for the wave theory of matter, based on the ideas proposed in 1924 by Louis de Broglie (b.1892 d.1987). The problem with atoms behaving as both particles and waveforms means that atomic particles' position and mass (or momentum) cannot be known at the same time - the so called uncertainty principle defined by Werner Heisenberg (b.1901 d.1976) in 1926. However, for our needs, the concepts of the Bohr model will generally suffice so we will use that until we need to say where other amplification is needed.

2.2.1 Elements and atoms

The Sun is predominately composed of hydrogen, the simplest of elements. The elements are all composed of atoms and all elements have the same basic structure. Atoms comprise a nucleus (a core) which contains protons ('electrically' positively charged particles with a mass of 1.6726 x 10^{-27} kg) and neutrons (particles of about the same mass as a proton – just 0.14% higher – but without any electrical charge).

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3. SOLAR FORM AND STRUCTURE

In chapter 2 we saw how the Sun produces its energy, and how by looking at its spectrum we can deduce the visible layers of the Sun's composition. We will build on these ideas and develop a model of the Sun based on the way in which the energy generated within the core is transported outwards to provide the luminosity we see. We will see how the force of the fusion reactions is balanced by gravitational forces, and how we can be reasonably sure that the Sun will not violently explode - at least for the next 6 billion years!

During our investigations, we will review the temperature, pressure and density conditions within the Sun and show how we can estimate these fundamental properties. We will take a brief look at the emerging science of helioseismology and how this can and has been used to inform us of the Sun's interior. The nature and source of the Sun's magnetic field(s) will be considered and the effects these have on observational features and the solar atmosphere will be reviewed.

3.1 Solar structure

We begin by presenting an overview of the current model of the structure for the Sun. See figure 26 below. In this picture, which is based upon a photograph of the sun taken at the Hα wavelength, the key components are marked numerically and refer to:

1. **The Core**; where fusion reactions are taking place and powering the energy of the Sun's emissions. The core extends approximately 25% of the Sun's radius outwards, has a central temperature of around 16 million Kelvin, and a density around twenty times that of iron.

   As we saw in chapter 2, hydrogen is fused to create helium and, in doing so, vast quantities of energy are produced by mass conversion. Some energy is also produced by early stages of the Carbon-Nitrogen-Oxygen fusion process.

2. **The Radiative zone** of the Sun. Here energy from the core flows outwards and is transported by radiative processes; no convection takes place within this region. No fusion or energy generation process takes place within this zone. The radiative zone, which is almost completely ionised, accounts approximately for the region from 25 to 70% of the Sun's radius. Temperature reduces in this zone from 7 million at the extent of the core to about 2 million Kelvin at the start of the convection zone. Density similarly reduces from three times that of iron to about one fifth that of water over the same space.

3. **The Convection zone**; this as the name suggests is the region where energy transport is dominated by convection energy transport processes, and as per the radiative zone, no energy is created in this area. The transition region between the radiative and convective zones is called the *Tachocline*; this is most likely to be the source of the Sun's powerful magnetic field.

   The convection zone is (relatively) cooler and less dense than the radiative zone and as such is not completely ionised; elements such as Carbon, Nitrogen and Oxygen can retain some electrons. This, and the effect it has on the Sun's opacity, is the trigger for convection to take place. This region takes us from the radiative zone 'up' to the visible photosphere where the density has now reduced to 2×10^{-7} that of water.

4. **The Photosphere** is the visible 'surface' from our perspective and observations. As we have seen, it is not a solid surface but the region of the Sun where the density becomes sufficiently opaque (moving inwards; or transparent if moving outwards) for us to see a visible surface. It extends for a thickness of about 500km – tiny compared to the scale of the Sun. It is the region upon which we see features such as sun-spots: slightly cooler areas where areas of magnetic flux

and forces disrupt the convection process; and the solar granulation, the seething convection cells bubbling up from the solar depths.

5. **The Chromosphere**; an area where the temperature again starts to rise; from 6000 Kelvin in the photosphere to now around 20,000 Kelvin in this irregular 'lower-atmosphere'. The higher temperature generates atomic emission lines; especially in hydrogen and the region is most frequently, but definitely not solely, observed at H**α** wavelength. The chromosphere ('colour-sphere') is the region within which *prominences* and *flares* are seen.

6. **Corona**; best observed at solar eclipse times (or using equivalent instrumentation called a Coronagraph), the corona is the outer atmosphere of the Sun. At an unexpectedly high temperature, circa 1 to 3 million Kelvin, the atmosphere is almost completely ionised.

   This low density (10^{-12} times that of the photosphere) high temperature plasma most likely gains its thermal energy from interactions with the solar magnetic field. Outer regions of the corona become dominated by thermal and radiation pressure and, overcoming the gravitational potential, high energy particles (electrons, protons and helium nuclei) flow outward from the sun at up to 900km/second. This flow is called the solar wind and can have a significant effect upon the Earth.

   The solar wind, 'powered' by the Sun's magnetic field, extends the Sun's atmosphere into what is named the *Heliosphere*. The heliosphere takes us outward up to the edge of the Sun's 'sphere of influence' the boundary of the Sun's magnetic field called the *Heliopause*.

   At the heliopause, the solar wind particles lose the effect of the Sun's magnetic field and reduce in velocity to subsonic speeds as they enter inter-stellar space. The Voyager 1 spacecraft (a multi-planet probe launched in September 1977) was placed on a hyperbolic orbit with respect to the Sun and crossed the heliopause in August 2012, at around 121 AUs from the Sun.

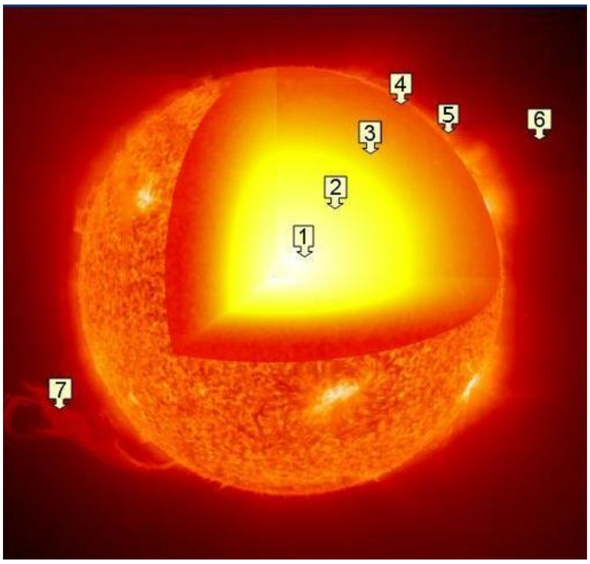

Figure 26 Solar structure overview

We will look at each of these regions (except prominences and *coronal loops* & *mass ejections*, labelled number 7 in figure 26 above, which we will examine in chapter 4 during our review of observational features). However, we will begin by looking at how we know this model is appropriate and the physics governing the Sun as a whole. And to start with we will answer what appears to be a rather basic question. If the Sun is generating huge amounts of power through nuclear fusion, why doesn't it explode?

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4. <u>OBSERVATION AND FEATURES OF THE SUN</u>

In chapter 3 we considered the structure of the Sun and how mathematics and physics can be used to construct theories and models of the Sun. These models are tested against observations and measurements taken across the breadth of the electromagnetic spectrum. Their predictive characteristics and abilities are compared against the observed behaviour and events seen on the Sun and its atmosphere. In this chapter we will look in more detail at the observational features of the Sun and how they vary over the *solar cycle*.

4.1 Introduction and observation of the Sun

In chapter 3 we considered how the magnetic fields of the Sun were exhibited in photospheric and solar atmospheric features. In this chapter we will take a more descriptive look at each of these and other features. We will begin however by taking a very brief look at the history of solar observation. We will look at the methods and techniques which have been used, both historically and today; some of the Earth based observatories; and the results and images from just a few of the more recent satellite/spacecraft probes.

First and foremost, **<u>please do not ever, under any circumstance, look at the Sun directly</u>** through any normal telescope or binoculars. The intensity of the light will cause blindness instantly. Indeed, looking at the Sun with just our eyes for more than a fraction of a second will cause pain and at the very least temporary blindness. At sunset and sunrise, the intensity of the light is, reduced – but the same advice and plea remains. Other than falling over in the dark, serious eye damage through careless or accidental solar observation is one of the thankfully few occupational hazards of the traditional astronomical observer.

4.2 Early historical records

The Sun has been observed of course by all sentient creatures since time immemorial, and the diurnal (daily) and seasonal changing pattern of its position has been known to humankind since prehistoric times. Megalithic and Neolithic era (4000 to 3000BC) standing stones and stone circles, such as the famous sites at Carnac in France and Stonehenge in England have such distinct celestial and solar alignments that their positioning must have been in part, if not in full, for astronomical purposes.

Observations of apparent features on the Sun have a more recent history, yet still a remarkably long pedigree. During sunrise and sunset, and at times when veiled in thin cloud, the disc of the Sun can be seen without the blinding glare. Under suitable conditions, it is feasible for large sunspot groups to be discerned by the naked eye. The earliest written records alluding to sunspots are from the Zhou dynasty era in China, when in circa 800BC court astrologers reported observations of markings on the Sun. More definitive records remain from 28BC, again from Chinese astronomers, of the Han dynasty. Not to be left out, the ancient Greeks make an appearance in early observational records; the Greek philosopher Anaxagoras (b.~500BC d.~428BC) recorded observations of circa 467BC. The earliest known drawing of a sunspot group was produced by an English chronicler, John of Worcester (d.1140). He was a monk at Worcester Priory and drew a sunspot/group on the 8th December 1128.

The immense radiation intensity and glare of the Sun severely restricted pre-telescopic observers and it befell, to Johannes Kepler (section 1.2.3) to use the concept and technology of the *camera obscura*. This uses a pinhole to 'project' the image of the Sun onto a small darkened room/area. In 1607, as part of his work on understanding planetary motions, Kepler had been taking observations of the planet Mercury as it approached its inferior conjunction. Using a camera obscura, on the 28th May of 1607, Kepler believed that he had witnessed part of a transit of the planet Mercury. Several years later however, and after other observers had announced their telescopic observations of sunspots, Kepler realised that what he had observed was in fact a large sunspot group rather than Mercury.

The invention of the telescope brought about the obvious danger of blindness, but also the opportunity to observe the Sun in detail and in safety by using the technique of 'eyepiece projection'. Similar to the concept of the camera obscura, a card or other plain surface (such as a wall) is positioned behind the telescope and, without ever looking through the telescope, the observer points the telescope towards the Sun. The image of the Sun is focused on the card through the telescopes' objective and eyepiece. This revolutionised solar observations and enabled astronomers to take observations, and see magnified images, whenever the Sun was visible.

The identity of the first person to use a telescope to take solar observations in this way is lost in the mists of time, and whilst several 17th century scientists claimed to be first, no one will ever know. Both Galilei Galileo (b.1564 d.1642) in Italy and Thomas Harriot (b.1560 d.1621) in England were taking solar observations by this means in December of 1610. Other notable early solar astronomers include Christoph Scheiner (b.1573 d.1650), and father and son David (b.1564 d.1617) and Johannes (b.1587 d.1616) Fabricius, all of whom were recording sunspot numbers from March 1611 onwards.

The nature and location of sunspots was subject to some considerable debate. Their solar nature was challenged by the idea that they could be objects transiting, orbiting, between the Earth and the Sun. The discovery of the moons of Jupiter had leant considerable support to the latter argument. In 1642 the Bohemian optician and astronomer Anton Rheita, best known for his developments of the terrestrial telescope; his map of the moon; and observations of the cloud bands of Jupiter; observed a large sunspot group for eight days during June of that year. Rheita, an advocate of the Tycho model of the solar system, promoted the view that sunspots were planets superimposed above the solar disc.

The Aristotelian perfection of the heavens was widely held and supported by the established Church. Any unproven 'scientific results' indicating the contrary and which could be explained by other means were difficult to accept. These challenges in reality are the nature of all scientific advances. Science and theories must be robust and resilient to strenuous examination. Many fundamental developments – for example: gravitation, nuclear physics, quantum mechanics and relativity, all seemed unbelievable when first proposed. The sunspot nature dispute was resolved to its solar nature by Galileo who demonstrated observational evidence for the spots originating, evolving and disintegrating on the solar 'surface'.

The latter half of the 17th century saw the establishment of the great national observatories of Europe. Sponsored by King Louis XIV (the 'Sun King') the Paris Observatory was founded in 1642 and led by its first director, Giovanni Cassini. In England, the Royal Observatory at Greenwich was commissioned in 1675 by King Charles II and John Flamsteed (b.1646 d.1719) was appointed as the first Astronomer Royal. His title was originally 'Our Astronomical Observator'. The Astronomer Royal title was first formally bestowed upon was George Airy in 1838, the 7th holder of the position, although the term was in common usage from the 1770s. These observatories were primarily founded for geodetic purposes and to solve the problem of longitude navigation at sea.

The Berlin Observatory – latter to become famous for the discovery of the planet Neptune in 1846 by Johann Galle (b.1812 d.1910) – was established in 1700 by the mathematician Gottfried Leibniz (b.1646 d.1716) and, under the petitions of the astronomer Johann Encke (b.1791 d.1865) and geophysicist Alexander von Humboldt (b.1769 d.1859) subsequently expanded greatly under the patronage of King Friedrich Wilhelm III.

During the early 18th century many astronomers took solar observations and recorded sunspots. These included Ignatius Koegler (b.1680 d.1746), Andre Pereira (b.1689 d.1743) and Johann Weidler (b.1691 d.1755) in Germany; Pierre Le Monnier (b.1675 d.1757), Nicolas Delisle (b.1688 d.1768), the Italian born Giovanni Cassini (b.1625 d.1712) and his son Jacques Cassini (b.1677 d.1756) in France, and James Bradley (b.1693 d.1762) in England to name just a very few.

Perhaps one of the most prolific solar observers ever was the German astronomer Heinrich Schwabe (b.1789 d.1875). During his almost continuous 17-year daily recording of sunspot activity started in 1826, Schwabe took 12185 observations and made 8486 drawings. In 1844 he published his

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5. NEBULAE AND THE FORMATION OF THE SUN

In chapter 4 we looked at the features and dynamics of the Sun; how the forces of magnetism as well as nuclear fusion and gravity shape our Sun and produce the ever-changing detail visible in telescopic observations. In this chapter we turn our 'clocks-back' about 4.5 billion years and consider how the Sun came into being. We begin with a general view of where the Sun is within our galaxy, the Milky-Way, and the building materials available within the galaxy for star formation i.e. huge 'clouds' of gas and dust which are generically called *nebulae*. We will look at the varieties of the nebulae and examine models of how they may condense into stars. And we will see why our Sun is unusual in that it doesn't have a close companion.

5.1 Galactic morphologies and the Milky Way

We begin our studies into the Sun's formation by considering where the Sun is in our home galaxy and by looking at the type of galaxy we live in. We call our own galaxy the Milky Way because on a clear dark night, looking along the plane of our galaxy towards the galactic centre we see a band of apparent milkiness. Binocular and telescopic observations resolve this milkiness into individual stars, but the milky-background persists. This effect is caused by the immense number of stars within our galaxy, and their blurring together as our eyes and telescopes are unable to resolve the myriad of individual, fainter and more remote stars.

Galaxies are vast 'islands' of stars containing from 10^9 to 10^{14} individual stars, though the 'average' galaxy contains around $10^{10 \text{ to } 11}$ stars. There are three main types of galaxy: elliptical, spiral and irregular, based on a classification proposed by Edwin Hubble in 1926. Galaxies themselves are not usually isolated but occur in clusters. And galaxy clusters also occur in groups, or super-clusters.

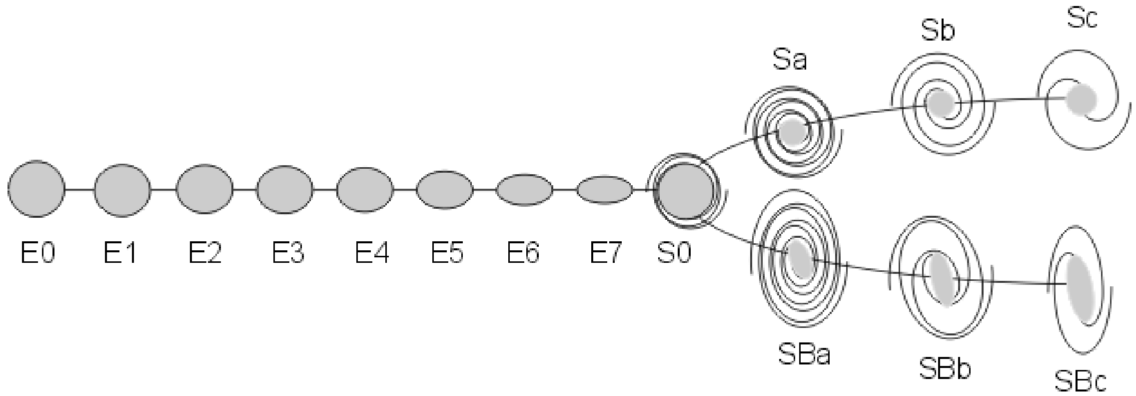

Figure 64 The Hubble classification of galaxies

Hubble's classification defines elliptical galaxies by their degree of oblateness. The eccentricity of the ellipse directly categorises the galaxy, from circular (E0) to highly elliptical (E7, ellipses of eccentricity 0.7). Other than their eccentricity, elliptical galaxies show little other form and are mass accumulations of stars. They are the larger type of galaxy in terms of mass and stellar numbers.

Spiral galaxies have central bulges of stars and are divided into two principal sub-groups: the 'normal' spirals (type S) and the barred spirals (SB). The latter have a distinct central 'line', or 'bar' of stars across their centres and along their planes. The spirals are further sub-categorised by the degree of tightness of their spiral arms, with class 'a' being the most tightly wound and class 'c' the loosest. Spiral galaxies (barred and normal) are the most numerous within the observable universe, with around 75% of all galaxies being of this type.

Apart from their morphologies, key differences between elliptical and spiral galaxies are the type and ages of stars they contain, and most importantly for our discussion on star formation, the amount of dust they contain. Spiral galaxies are 'dust-rich' and when seen edge-ways on, the dust obscures and blocks the light from the more remote stars. The vast majority of dust within spirals is within their spiral arms. Dust within our own galaxy prevents us from seeing the galactic core at optical wavelengths. Fortunately for our observations, interstellar dust is transparent to radio waves. The S0 type of galaxy, often called Lenticular galaxies, are a hybrid between ellipticals and spirals. They have no spiral arms but do have (large) central bulges surrounded by a thin disc of stars.

Irregular galaxies (designated 'Irr') as the name suggests, have no clear or distinct form. They are smaller than the spirals or ellipticals and dust-rich. However, there are two types of irregular galaxies. Type Irr-I are small and occur as single galaxies. The second type, Irr-II are where two galaxies are interacting, disrupting any form of their original progenitors. These types of galaxy are often the most interesting from a dynamical perspective.

All types of galaxies are further designated when relatively small within their category, by a leading 'd' to indicate a dwarf galaxy. So, for example, the designate 'dSBc' refers to a dwarf barred spiral with loosely wound spiral arms.

Whilst it is tempting to consider it as such, it should be emphasised that the Hubble classification, and the pattern of figure 64, is not an evolutionary diagram. Our local cluster contains ~50 individual galaxies of varying size and type. Most galaxies within the group are dwarf spirals, with diameters less than 10^4 light years (ly). The group contains only four (dwarf) ellipticals. The group is dominated by two large galaxies, the Milky Way and the larger, by around 50% in diameter, Andromeda galaxy.

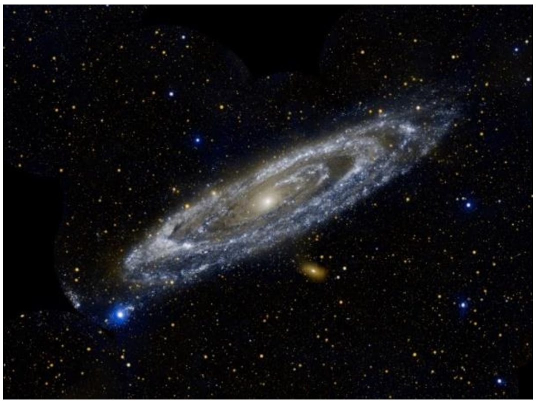

Figure 65 The Andromeda galaxy (NASA/JPL)

The Andromeda galaxy is an Sb category and is similar to the Milky Way, which is an SBc galaxy. Respective 'sizes' are diameters of 140,000ly and 90,000ly each. Notice the spiral arms and the dust lanes within the arms in figure 65. Also visible in this image are two of the galaxy's satellite galaxies.

All galaxies exhibit rotation about their centre of mass but the rotation rate of ellipticals is very much lower than that of spiral galaxies. The rotation rates though have given astronomers a problem. The bars within SB galaxies should not persist, but they do. Equally difficult, the angular momentum of a typical galaxy would mean that gravitationally, the spiral galaxies should disperse, but they don't.

The solution to these conundrums is the presence of 'dark-matter'. By modelling galactic form and observed rotational patterns using the gravitational forces exerted by an unseen, 'dark', matter the problems can be resolved. We do not know the nature of dark matter and we cannot detect it other than by its gravitational effect. Its effects can be detected at galactic-scale and it would appear that dark matter forms the majority (circa 75%) of all matter within galaxies, including the Milky Way.

Whilst considering galaxies, we should mention briefly the 'globular' clusters. Globular clusters are not galaxies, but are smaller, gravitationally tightly bound accumulations of stars, typically containing 10^5 to 10^6 individual stars. They have radii < 30ly and hence have a very high stellar density. They

6. STELLAR EVOLUTION AND DESTINY

In chapter 5 we looked at the position of the Sun within the Milky Way, the stellar population types and the fundamentals of stellar formation from primordial nebulae. In this chapter, we will look forward, to the evolution of the Sun and its destiny. In doing so, we review helium fusion processes and electron degeneracy on the way to the Sun evolving to a white dwarf star and a solar planetary nebula. We will also take a short review of the evolution of more massive stars than the Sun and the genesis of pulsars, neutron stars and black holes.

6.1 Solar evolution and destiny

In section 5.2.3 we described planetary nebula and presented an outline of the evolutionary stages for a star of the Sun's size (and mass). At the current time (astronomers often use the word 'epoch') the Sun is in a stable state, positioned on the main sequence of the Hertzsprung Russell diagram and producing energy predominately by the conversion of hydrogen to helium (via the proton-proton chain reaction) within its core.

In time (about six billion years from now) the core will become depleted of hydrogen and the Sun will start to 'burn' (fuse) helium at its core, converting helium to carbon and oxygen, and hydrogen to helium fusion will migrate outwards into a hydrogen 'burning' shell. When this happens, the Sun will evolve into a red giant star. Its radius will increase to more than one astronomical unit (and so the Earth will be consumed) and it will remain in this state for about 100 million years.

Eventually, the helium fusion processes at the core will cease, (as the helium will all have been converted) and the core will become mostly *degenerate*. Gravitational collapse, against the then reduced radiation pressure from the reduction in hydrogen and helium fusion reactions, will increase the temperature at the core and a cycle of helium fusion 'flashes' will initiate in a shell surrounding the core. At this stage the Sun will eject its outer layers to form a planetary nebula and the core will remain as a single 'star', a white dwarf star. We will expand on this process in section 6.2 but before we go into detail, we will look first at helium fusion processes and electron degeneracy.

6.1.1 Helium fusion – the alpha and triple alpha processes

We saw within section 2.5.3 the proton-proton chain whereby atomic hydrogen fuses to form helium. At higher temperatures, the other fusion processes important for a review of the Sun's evolution are the 'triple-alpha process' and the similarly named 'alpha-process'. The triple alpha process (named as such because an alpha particle in radioactivity studies is a helium nucleus) uses three helium nuclei to produce carbon. It uses beryllium as an intermediate mechanism. The basic fusion process is:

$^{4}\text{He} + {}^{4}\text{He} \leftrightarrow {}^{8}\text{Be} - \gamma(91.8\text{KeV})$

$^{8}\text{Be} + {}^{4}\text{He} \rightarrow {}^{12}\text{C} + \gamma(7.367\text{MeV})$

Notice that in the first part of this reaction an energy requirement is needed (the - 91.8KeV). This is provided by the star's thermal energy and the rate of beryllium production is very sensitive to the star's temperature. This reaction only initiates when the core temperature is around 10^8 Kelvin. The beryllium is unstable (and the first stage of this reaction is reversible) and disintegrates into two helium nuclei in a very short period of time ($\sim 10^{-12}$ seconds). Thus the rate of energy produced is governed by the availability of beryllium (and so highly temperature sensitive) to form carbon by combining with an available helium nucleus.

Another process using helium is the alpha-process. This is where helium nuclei combine with heavier elements to form a 'ladder' of nucleosynthesis of elements. The first stage of the alpha process is the combination of carbon with helium to form oxygen via:

$^{12}\text{C} + {}^{4}\text{He} \rightarrow {}^{16}\text{O} + \gamma(7.16\text{MeV})$

And following this, the other (next two) steps on the ladder are:

$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma(4.73MeV)$;

$^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma(9.32MeV)$;

with each step requiring a higher pressure and temperature for initiation.

6.1.2 Electron degeneracy

We saw in section 2.2.1 the basic form of the atom and the electron shells. These shells (energy levels) can contain a maximum number of electrons as outlined in table 1 of section 2. In a (non-degenerate) gas, electrons are not usually in the lowest energy shells due to the atom's kinetic energy or in other words, because of the temperature of the atom. However, if the gas is at a very low temperature (low kinetic energy), or if the gas is placed under high pressure, the electrons will fill the lower/lowest electron shells.

All fundamental atomic particles within the standard model (except for the Higgs-Boson particle) have an angular momentum, termed the particles 'spin' and this can take a value of 1 or ½; see figure 17 of chapter 2. Electrons (and other ½ spin particles) may have either 'up' or 'down' spin (+ or – ½). The Pauli exclusion-principle, named after Wolfgang Pauli (b.1900 d.1958), states that no more than one fermion (which is an elementary particle having a non-integer spin, and which we will use here to mean an electron) of a given spin can occupy a specific spatial energy level (which is a function of the particles position and spin).

Within the ground level (quantum number N =1) of an atom's electron shells there is only one angular momentum state ('s') and this can be filled by a maximum of two electrons (an up and down spin electron). In the second electron shell (quantum number N=2), there are four angular momentum states (1 x 's' and 3 x 'p') and so this shell can support a maximum of eight electrons. A gas of fermions where all the lowest electron energy shells are full, either due to very low temperature or because of the high pressure the gas is under, is said to be *degenerate*.

In a degenerate gas (or material), as all the lower shells are full, electrons occupy energy states higher than those which they would normally be at for the material 'temperature'. This generates a very high pressure (termed the *degeneracy pressure*) within the gas. The *Fermi momentum* is the outermost / maximum energy level within an atom for a given number of electrons, and is the shell at which the electrons are most energetic. As such, in the degenerate gas the classic ideal gas equation describing the energy distribution, the Maxwell-Boltzmann distribution, no longer applies and the gas does not produce a Planck black-body energy distribution.

In the degenerate gas, the pressure depends predominately on the density, and not significantly upon the temperature. This is because the temperature depends upon the kinetic energy of the electrons and, in the degenerate matter, the electrons are in higher energy shells and are unable to move to lower shells (i.e. to cool by dissipating energy) as the lower levels are full. In the degenerate matter the pressure is proportional to the material density by $P \propto (\rho)^{5/3}$ where P is the pressure and ρ is the density. This is one of the equations of state (EOS) for non-relativistic degeneracy.

In the case of relativistic material, which is appropriate for where the electron velocities within the outer energy shells approach the speed of light (c), i.e. in very high momentum and density cases, the relationship is $P \propto (\rho)^{4/3}$. This is the relativistic EOS.

We can compare these (degenerate) EOS with the EOS for non-degenerate matter. The non-degenerate cases can be modelled using the ideal gas law (see section 7.9) and as such, the relationship between pressure and density is:

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7. SUPPORTING MATHEMATICAL DERIVATIONS AND DESCRIPTIONS

7.0 Nomenclature

Unless otherwise stated within the sections, the following symbols are used for the variables and physical characteristics

Symbol	Variable / characteristic
a	Acceleration
B	Magnetic field strength
E	Energy
E_p	Potential energy
E_k	Kinetic energy
f	Frequency
$\mathcal{F}$	Flux
F	Force
G	Universal constant of gravitation
I	Current
κ	Opacity
l_{ph}	Mean-free-path of photon
$\mathcal{L}$	Luminosity
M	Total mass (of star)
M_r	Mass contained within sphere bounded by radial distance of r
m_u	Atomic mass unit
n	Polytropic index
P	Pressure
P_c	Pressure at centre of star
P_r	Pressure at radial distance r from centre of star
R	Radius of star
r	Radial distance from centre of star
t	Time
T	Temperature
T_c	Temperature at centre of star
T_r	Temperature at radial distance r from centre of star
v	Velocity
V	Volume
X	Proportion by mass of hydrogen
Y	Proportion by mass of helium
Z	Proportion by mass of 'metals' (elements of atomic number >2)
μ	Mean atomic weight of particles
ρ	Density
ρ_r	Density at radial distance r from the centre of the star
ρ_c	Density at the centre of the star
λ	Wavelength
γ	Lorentz factor

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7.6 Kelvin-Helmholtz timescale

Referring section 2.5.1

We will consider an astronomical object, such as a nebula, a proto-star, a star, or a large gaseous type planet, and consider that the object is composed on a large number of particles. For brevity, we will refer to the object as a proto-star in this section.

We have seen (gravitational potential energy section above) that the gravitation potential energy between two particles E_p is:

$$E_p = -G\frac{m_1 m_2}{r}$$

where m_1 and m_2 are the masses of the particles and r is the distance (separation) between them.

Now, consider that the particles are within a sphere of radius *R* and with uniform density ρ and that we define the mass of a thin shell, surrounding and at distance *r* from the centre of mass of the proto-star and of thickness *dr*.

This shell will have a mass of m_{dr}which can be seen to be:

$$m_{dr} = 4\pi r^2 \rho \, dr$$

(mass = volume x density. Here we have $(4\pi r^2 dr)$ as the volume of the shell, the surface area of the shell times its thickness)

We will then summate the total potential energy within the proto-star by looking at all shells around the centre of mass of the proto-star. We do this by integrating over E_p over all dr (m_{dr}) from 0 (zero, ie the centre) to *R*. (the outer reaches of the proto-star). Note that each shell's potentials are being measured against the mass of the proto-star within the sphere defined by the shell (see box below)

Gauss's law can be used to show that the nett effect of many particles is that the gravitational force acts as if the total mass of a (uniform density and perfectly spheroidal) star/proto-star is at the centre of the sphere.

The ancillary to this, and the implied use here, is that the net gravitational force felt by a particle *within* the proto-star's defined radius, is the total of the mass that is closer to the centre from where the specific particle is.

So for example, at the centre of the proto-star, there is no mass within a closer sphere to the centre, so the nett force felt on a particle right at the centre of the proto-star is zero. Similarly, right at the edge of the proto-star, where *r* = *R*, the particle experiences a force due to the entire mass of the proto-star.

Hence, we have the total gravitational potential energy, which we define as U, as:

$$U = -G\int \frac{m(r) m_{dr}}{r}$$

Now integrating over all shells (using limits from 0 to R) we get

$$U = -G\int_0^R \frac{m(r) 4\pi r^2 \rho}{r} . dr$$

But we can also express $m(r)$ in terms of volume and density. The mass of the sphere $m(r)$ is

$$m(r) = \frac{4\pi r^3 \rho}{3}$$

And hence our expression for *U* becomes:

$$U = -G\int_0^R \frac{4\pi r^3 \rho 4\pi r^2 \rho}{3r} . dr$$

$$U = -G\int_0^R \frac{16\pi^2 r^4 \rho^2}{3} . dr$$

And on evaluating the integral we get:

$$U = -G\frac{16\pi^2 R^5 \rho^2}{15}$$

Now, we rewrite this equation to replace the density by a function of mass and volume. Recall that: $M = \rho V$, where *V* is volume, (and thus $\rho = M/V$) and that the volume of the proto-star of radius *R* is:

$$V = \frac{4\pi R^3}{3}$$

and hence

$$\rho = \frac{3M}{4\pi R^3}$$

thus:

$$\rho^2 = \frac{9M^2}{16\pi^2 R^6}$$

And using this expression for ρ^2 in our equation for *U* gives us:

$$U = -\frac{3GM^2}{5R}$$

This is the proto-stars total kinetic energy.

Now, we also know from the Virial theorem, we can relate the kinetic and potential energies by

$$2\sum E_k + \sum E_p = 0$$

And, so, if we define Ω as the total kinetic energy within the proto-star, we have

$$2\Omega + U = 0$$

and rearranging,

$$U = -\frac{\Omega}{2}$$

This tells us that in a gravitational collapse scenario, half the potential energy will be used to increase the thermal (kinetic) energy of the proto-star, and half will be radiated (and from our perspective, will generate the proto-star’s luminosity). Hence the available ‘reservoir’ of energy available for radiation by this mechanism is half the gravitational potential energy.

Relating both expressions we have for *U* and we get:

$$-\frac{\Omega}{2} = -\frac{3GM^2}{5R}$$

This gives us the amount of energy available for radiation to power the observed luminosity. The Kelvin-Helmholtz timescales is then energy available for radiation divided by the observed luminosity, i.e.

$$\tau_{kH} = \frac{\Omega}{\mathcal{L}_{\odot}}$$

Where $\mathcal{L}_{\odot}$ is the Sun's total emitted luminosity (ie emitted energy) and as we have seen above:

$$\Omega = \frac{6GM^2}{5R}$$

and hence:

$$\tau_{kH} = \frac{6GM^2}{5R\mathcal{L}_{\odot}}$$

Now, looking at $\mathcal{L}_{\odot}$

We saw earlier (chapter 2) that an equation for the luminosity of the Sun, $\mathcal{L} = 4\pi R^2 \sigma T^4$ can be constructed based upon the flux of radiation emitted. However, this formula requires that we have knowledge of the temperature of the Sun. In place of using this formula, we will look at how $\mathcal{L}_{\odot}$ can be determined from direct observations.

The luminosity is the measure of the flux of total radiation emitted. We can measure the amount of radiation received at the Earth (this measure is called the solar irradiance) and the solar constant (although that is a misnomer as it is not a constant) is the measure of radiation received at the standard distance of one astronomical unit. The luminosity is the integration of the flux over all radiation wavelengths of the electromagnetic spectrum (see also chapter 2).

We can also define the solar luminosity $\mathcal{L}_{\odot}$ in directly measureable terms by:

$$\mathcal{L}_{\odot} = 4\pi A^2 I_{\odot}$$

where $I_{\odot}$ is the observed solar irradiance at 1 astronomical unit, and A is the distance of the astronomical unit. $I_{\odot}$ has a value of 1.361 kilowatts per square metre (which varies by ~0.2% depending upon the solar cycle); i.e. 1.361 kilojoules/second (and recall 1 joule is $1 \text{kg.m}^2/\text{s}^2$).

The earliest direct measurement of the solar irradiance was made in 1838 by Claude Pouillet (b.1790 d.1868) but we now have the benefits of satellite measurements. So, substituting our known values for M (1.9886×10^{30} kg), R (695.5×10^6 m), G (6.6738×10^{-11} $\text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$ and A (149.6×10^9 m) we arrive at:

$$\tau_{kH} = \frac{6(26.392 \times 10^{49})}{5(2.6621 \times 10^{35})} \text{ seconds}$$

which is ~11.896×10^{14} seconds, or in years, ~37.7×10^6 years. Hence, for the Sun, if nuclear fusion were not taking place, the Sun's current output could only have been sustained for at most 40 million years by this mechanism.

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