2. Stellar Properties and the Making of Planets: Theories and Observations

2.1 The Starry Realm

Stars, just like human beings, come in all varieties. They display a multitude of colors, and they are found in densely packed groups or in solitary isolation. They are born, age and die; some living long, quiet lives, others rushing headlong through a luminous youth to an explosive death. The stars, just like human beings, spin and weave their way through space and time; they exhibit spots or flaws of various sizes, they contract and expand, and on occasion thin down and lose mass. Unlike human beings, however, for whom there is no descriptive calculus, the stars are inherently simple physical objects, which is not to say that we fully understand how they form, operate and/or function. In a prescient poem entitled "Mythopeia," dedicated to C. S. Lewis, J. R. R. Tolkien summed up the stellar situation nicely: "A star's a star, some matter in a ball." Indeed, a star is a giant sphere of very hot, mostly hydrogen and helium, gas, and its size is determined according to its age and the manner in which it generates energy within its interior through nuclear fusion reactions.

In this chapter we shall be concerned with the annotation of the stars within the Milky Way Galaxy – their number, their distribution, their physical structure and their relationships one to another. It will be via this extended discussion that the similarities and differences between the Sun and α Cen A and B will be contrasted and compared. Not only this, but the known unknowns, as well as the astronomical issues associated with the α Centauri system in general will be examined. As we shall see, just because α Centauri is the closest star system to us at the present time does not mean that we fully understand it.

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Let us begin our stellar journey of discovery by first considering the Sun.

2.2 The Sun Is Not a Typical Star

By being such a common, everyday and familiar sight the Sun is often overlooked as a *bone fide* object of astronomical interest. There is perhaps an historical reason for this sentiment, and it should be remembered that it is barely 150 years since it became demonstrably clear, through spectroscopic studies, that the Sun is a star and, up to a point, *visa versa*. Towards the end of the nineteenth century Arthur Searle (Harvard College Observatory) commented in his widely read *Outlines of Astronomy* (published in 1874) that, "Very little, indeed, is known of the stars." He later asserted, however, that, "Observations with the spectroscope have also confirmed the belief previously grounded on the brightness and remoteness of the stars, that they are bodies resembling the Sun." Charles Young further writes, in his 1899 *A Text-Book of General Astronomy*, that "the Sun is simply a star; a hot, self luminous globe of enormous magnitude …. although probably of medium size among its stellar compeers."

With this description, Young confirms the star-like nature of the Sun but has introduced yet another characteristic, stating that the Sun is "probably only of medium size." Accordingly, not only are other stars like the Sun, but there is also a range of stellar sizes, and by implication temperatures, and masses as well. The fact that stars have varying degrees of energy output (that is, luminosity) had already been established[1] about 60 years before Young wrote his text.

Hector Macpherson, in his wonderfully named *The Romance of Modern Astronomy* (published in 1923), picks up on Young's statements by writing that, "The stars are Suns. This is a very good truth which we must bear in mind." Macpherson continues

[1] This fact was evident as soon as the first (believable) stellar parallax measurements were published in 1838/9. Indeed, since the star Vega (as observed by Friedrich Struve) was found to be some 2.2 times further away than 61 Cygni (as observed by Friedrich Bessel) and yet is six magnitudes brighter, it must accordingly have a greater intrinsic luminosity.

to explain, however, that the Sun is a yellow dwarf star. William Benton, in his 1921 *Encyclopedia Britannica* entry concerning the Sun, additionally comments upon its size and notes that, "The Sun is apparently the largest and brightest of the stars visible to the naked eye, but it is actually among the smallest and faintest." The comments by Macpherson and Benton, while in contrast to those of Young, actually build upon the monumentally important results of Ejnar Hertzsprung and Henry Norris Russell, who circa 1910 independently introduced the idea of dwarf and giant stars existing within what is now known as the HR diagram (see Appendix 1 in this book) – a plot of stellar temperature versus luminosity.[2] In terms of stars being blackbody radiators (again a theory not actually established in its modern form until the appearance of the pioneering quantum mechanical model of Max Planck in 1900), the size (radius, R), temperature (T) and luminosity (L) are related according to the famous Stefan-Boltzmann law: $L = \text{constant } R^2 T^4$. That the luminosity is further related to the mass of a star was established by Arthur Eddington in 1924.

By arranging the stars in the HR diagram it is possible to begin comparing the Sun's physical characteristics against those of stars in general. Accordingly, Simon Newcomb, in his *Astronomy for Everybody* (published 1932), explains, albeit rather tentatively, "What we have learned about the Sun presumably applies in a general way to the stars," and that with respect to the HR diagram he notes, "The dot for the Sun, class[3] G0, is in the middle of the diagram."

With Newcomb's latter comment we begin to see a new and quite specific picture of the Sun emerge; it is an average, middle-of-the-road sort of star. Indeed, this comparative point was specifically emphasized by Arthur Eddington in his book *The Nature of the Physical World* (published in 1935). Eddington writes, "Amid this great population [the galaxy] the Sun is a humble unit. It is a very ordinary star about midway in the scale of brilliance…. In mass, in surface temperature, in bulk the Sun belongs to a very common class of stars." To this he later adds (in classic

[2] Here we betray a theoretical bias, since observationally the diagram is a plot of absolute (or apparent) magnitude versus spectral type. The various quantities are, of course, equivalent, but not in any straightforward fashion.

[3] The Sun's spectral type is now described as being G2.

Eddingtonian language), "in the community of stars the Sun corresponds to a respectable middle-class citizen."

With the continued acquisition of data and the development of astrophysical theories, it is reasonably clear that from circa 1930 onwards that the Sun's relative characteristics are generally interpreted as being ordinary or just average. That this notion still prevails within the general astronomical literature is an absolutely remarkable state of affairs since it is patently clear that the Sun is both special, and far from being anything that resembles a typical or ordinary star – it is indeed, extraordinarily special.

The Sun is often described in terms of being typical, average, run-of-the-mill, ordinary, mediocre, and even normal. All such expressions are usually employed in the sense that if a star was picked at random within the galaxy then it would be like the Sun, and/or if one measured a range of values for stellar mass, radius, temperature, and luminosity, then the averages would all somehow reduce to intrinsic solar quantities: 1 $M_\odot$, 1 $R_\odot$, T ~ 5,800 K, and 1 $L_\odot$, respectively.

There are clearly a number of problems with such expectations – not least the fact that this is entirely wrong. When the Sun is described as being an "average" or a "typical" star it is rarely, if ever, stated with respect to what specific distribution of stars. There are, for example, some very obvious comparisons where the Sun would be an extreme and highly untypical object. To the stars in a globular cluster, for example, the Sun would, in comparison, be an extremely young star with a very odd chemical composition (that is, having an extremely high metal abundance). And yet, to the stars in a newly formed OB association, the Sun would by comparison be a low mass, low luminosity, rather old star, with a relatively low metal abundance. Even if we make a more sensible comparison, however, between the Sun's properties and those stars that reside in the solar neighborhood, the Sun in no manner has typical stellar characteristics.

The most complete catalog[4] of stars located close to the Sun with well-measured physical characteristics is that provided by the *Research Consortium On Nearby Stars* (RECONS). Table 2.1 is a summary of the RECONS dataset for the stars located

[4] See the extensive details provided at the Research Consortium On Nearby Stars (RECONS) website: www.recons.org.

TABLE 2.1 Summary of the RECONS data as published for January 1, 2011[a]. The first column indicates the total number of known objects (stars as well as white and brown dwarfs) within 10 pc of the Sun, while the second column indicates the number of stellar systems (single, binary, triple, etc.). Columns three through nine indicate the number of stars of a given spectral type (the Sun, included in the dataset, is a G spectral-type star). Columns 10 and 11 indicate the number of white dwarf (WD) and sub-stellar brown dwarf (BD) objects. The last column indicates the number of planets that have been detected to the present day

Objects	Systems	O	B	A	F	G	K	M	WD	BD	Planets
369	256	0	0	4	6	20	44	247	20	28	16

[a]See the extensive details provided at the Research Consortium On Nearby Stars (RECONS) website: www.recons.org

within 10 pc of the Sun. It is generally true that the vast majority of stellar objects within 10 pc of the Solar System are identified within the RECONS catalog. (This result is probably not true, however, for the brown dwarfs (recall Fig. 1.15), but they do not concern us here.). It is also generally true that the solar neighborhood dataset is representative of that which might be found in any region of the galaxy's disk at the Sun's galactocentric distance of 8,000 pc. A quick glance at the entries in Table 2.1 immediately indicates a predominance of low mass, low temperature, small radii, K and M spectral-type stars. Indeed, the O and B stars are sufficiently rare that the nearest such objects are over 100 pc away from the Sun.

The number of stars of mass M, within the RECONS 10 pc catalog, is described by the mass function $N(M) = 4.6/M^{1.20}$. If there were equal numbers of objects at any given stellar mass then the exponent in the mass function would be zero, but as it stands, of the 320 stars in the 10 pc survey the Sun is among the top 25 most massive. The most massive star within 10 pc of the Sun is Vega, weighing in at just over two times the Sun's mass. The modal, that is, most common, mass value in the 10 pc survey falls in the range between 0.1 and 0.15 $M_{\odot}$, and the median value, for which half of the systems have a greater mass and half have a smaller mass, is 0.35 $M_{\odot}$. That the latter results are more typical for the rest of the Milky Way's disk is revealed by the available data relating to the so-called initial mass function (IMF), which describes the number of stars formed in a specified mass range. Although the slope of the IMF varies in a complex manner according to the mass range being considered, the peak number of stars formed is invariably (even universally) found to fall in the 0.1–0.5 $M_{\odot}$ range.

Sun-like stars having, by definition, a mass near 1 $M_{\odot}$ and thereby a G spectral type are found to make up just 6 % of the stars within the RECONS dataset out to 10 pc. In contrast, the M spectral-type stars constitute 77 % of the total number. Furthermore, the modal absolute magnitude for the stars in the 10 pc dataset is found to be $M_V \approx +13.5$ – a value some 8.5 magnitudes fainter than that of the Sun. Compared to the most typical (that is, ordinary, common, run-of-the-mill, pedestrian, etc.) stars in the solar neighborhood the Sun is nearly 10 times more massive, 10 times larger, 2 times hotter and 10,000 times more luminous. The Sun is not a typical star even within its own precinct.

2.3 How Special Is the Sun?

Given that the Sun is not an average, ordinary or even typical star within the galaxy or the solar neighborhood, is it special in any other way? This question is not intended to focus on humanity's existence – in which sense the Sun is extremely special and we would not exist without it. Rather, the question refers to its defining characteristics such as being a single star, and then a single star with an attendant planetary system, and so on. Again, one can turn to reasonably well known and reasonably well understood datasets to answer this question. Following an approach adopted by astronomer Fred Adams (University of Michigan) the answer to our question can be expressed as a probability.[5] Accordingly, the probability P_{Sun} of finding a star within the galaxy having similar characteristics to the Sun can be written in the form of a Drake-like equation[6]:

$$P_{Sun} = 100 \, \mathrm{x} F_1 F_{SB} F_Z F_P F_H \tag{2.1}$$

[5] Adams, F. "The Birth Environment of the Solar System" (*Annual Review of Astronomy and Astrophysics*, **48**, 47, 2010).

[6] The parallel here is to Frank Drake's famous equation for estimating the number of extraterrestrial civilizations within the Milky Way Galaxy. (Frank Drake introduced his now-famous formula for estimating the number of possible extraterrestrial civilizations in 1961, and it has been greatly abused and misunderstood almost ever since.)

The terms entering Eq. 2.1 relate to F_1, the fraction of stars with a mass of order 1 $M_\odot$; F_{SB} the fraction of solar mass stars that are single as opposed to being members of a binary or multiple system; F_Z, the fraction of stars with a metal abundance corresponding to that of the Sun at the Sun's location within the galactic disk; F_P, the fraction of solar mass stars harboring planets; and F_H, the fraction of planet-harboring Sun-like stars in which one (or more) might reside within the habitability zone. All of the terms in Eq. 2.1, in contrast to those in Frank Drake's more famous equation, are reasonably well known.

Looking at each quantity in turn, it is evident that $F_1 = 0.06$, corresponding to the fraction of spectral-type G stars within the annotated spectral sequence distribution. To a good approximation $F_{SB} = 1/3$, with the majority of Sun-like stars being found in binary systems (such as in the case of our nearest neighboring system α Centauri AB). F_Z is again reasonably well constrained, and the Sun, in fact, has a relatively high metal abundance, with the survey data indicating that within the solar neighborhood $F_Z = 0.25$ for $Z \geq Z_\odot$. Indeed, it should be noted that the composition exhibited by the Sun is not that corresponding to just any radial location within the Milky Way Galaxy, a condition that in fact negates the statements that imply the Sun is somehow situated in an "ordinary" or "nondescript" region of the galaxy. The fraction of Sun-like stars supporting large planets is known to vary with the composition (recall Fig. 1.21) and hence galactic location, and the observations presently suggest that the fraction of Sun-like stars with Jovian planets varies as $F_P = 0.03 \times 10^{\,Z/Z\odot}$, which is to suggest that $F_P = 0.3$.

And finally, the least well-known quantity in Eq. 2.1 is that relating to the fraction of stars harboring planets within their habitability zone.[7] At present this number may only be constrained via theoretical modeling, but generally it is thought that the fraction of planet-hosting systems harboring habitable planets is something like $F_H = 0.05$.

[7] This term will be defined later on, but its meaning is reasonably clear in that it relates to the zone around a star in which an Earth-like planet might support liquid water (and possibly life) upon its surface.

With our various quantities now in place, the following evaluation is found: $P_{Sun} \approx 0.01$ %. In other words, if one picked a star at random within the disk of our galaxy then there is a 99.99 % chance that it will *not* have the same intrinsic characteristics as our Sun. With such odds against it, clearly, the Sun is not an ordinary star. In addition, the special characteristics associated with the Sun and Solar System apply irrespective of the origins of life on the habitable planet. If we wish to include our own existence in the calculation then P_{Sun} will (according perhaps to one's bias) be many orders of magnitude smaller. Irrespective of this latter addition, by any reasonable standards, the Sun and its attendant planets constitute a rare and uncommon type of system within our galaxy.

If the Sun is a special, decidedly non-typical kind of star within the Milky Way Galaxy, then what is the most typical type of star? The general survey data is, in fact, absolutely clear on this point, and the most typical or most ordinary kind of star that one is most likely to encounter at random within the solar neighborhood (and the greater Milky Way Galaxy) is an object just like Proxima Centauri – a low mass, low temperature, faint, M spectral-type dwarf star.

2.4 There Goes the Neighborhood: By the Numbers

The RECONS data, as summarized in Table 2.1, indicates that the typical spacing between stars within 10 pc of the Sun is about 2.8 pc.[8] That the α Centauri system is located just 1.35 pc away from us, therefore, indicates an unusually close encounter (recall Fig. 1.17).

[8] The typical number of systems (single stars, binary stars and so on) per unit volume of space is 0.09 per cubic parsec. The number of systems in a volume V^* will then be $N^* = 0.09 \times V^*$. If we divide the volume V^* equally between all the stars within its compass, then the volume for each star will be $V_S = V^*/N^* = 1/0.09 = 11.1$ pc^3. The radius r of the sphere having a volume V_S can now determined, and we find $r = 1.4$ pc. Given a typical separation will be of order $S = 2r$, we have a typical system separation in the solar neighborhood of 2.8 pc.

This close proximity is, in fact, even more remarkable if we just concentrate on Sun-like stars. In this case, the survey data reveals a total of 454 Sun-like stars within 25 pc of the Sun, which suggests a typical spacing of 6.5 pc between such stars. Furthermore, the survey data also reveals that only 33 % of Sun-like stars reside within binary systems, which suggests that the nearest twin Sun-like star system to the Sun should, on average, be about 13 pc away. By this standard α Centauri is undergoing an incredibly close flyby of the Solar System.[9] As we shall see later on, Proxima Centauri is an M dwarf flare star,[10] and the spatial density of such stars in the solar neighborhood is 0.056 per cubic parsec, indicating that one might typically expect to find one such star within a sphere of radius 1.6 pc centered on the Sun. On this basis, it can be argued that Proxima is not unusually close to the Solar System. If these same statistics are applied towards α Cen AB, however, then Proxima is remarkably close. Indeed, the odds that Proxima should be located just 15,000 au from α Cen AB purely by random chance are about 1 in 57,000.

Although small probabilities can always be realized the issue of Proxima's close companionship to α Cen AB will be addressed

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[9] The twin Sun-like binary star system ζ Retuculi, located just over 12 pc away, is quite possibly the most notorious star system known. In terms of sheer science-fiction horror, it was upon the (imagined) moon Acheron (formally LV-426) orbiting the (imagined) planet Calpamos orbiting ζ^2 Reticuli, that the hapless crew of the mining ship Nostromo first encountered the entirely ruthless, parasitic, jaw-snapping, tail-stabbing, acid-blood-dripping *Alien* (as created by the Swiss artist Hans Giger). Directed by Ridley Scott the movie *Alien* was released to critical acclaim in 1979 and has since spawned a whole number of equally horrifying sequels. The movie prequel *Prometheus* (released in 2012 and once again directed by Ridley Scott) takes the story to another moon (LV-233), and it is revealed that this moon was essentially an abandoned bioweapons installation. On a seemingly more benign front, ζ Reticuli is also associated with the bizarre 1961 abduction case of Betty and Barney Hill. This couple from New Hampshire claims that they were abducted and medically examined by "gray aliens" aboard a landed UFO. Subsequent questioning under hypnosis resulted in Betty Hill recalling a star map that she had been shown. This map apparently revealed 'trade routes" between local star systems, and subsequent analysis by other researchers has linked the home planet of the aliens to ζ Reticuli. Intriguingly, a 100-au radius Kuiper-Belt analog debris disk, possibly hinting at the existence of associated planets, was detected around ζ^2 Reticuli with the Herschel infrared telescope in 2010. The discovery of a Jupiter-mass planet in orbit about around ζ^1 Reticuli was reported in late 1996, but the detection was later retracted and the data explained in terms of stellar pulsations.

[10] Such stars undergo irregular and unpredictable increases in brightness on timescales of minutes to hours.

later on in this chapter. Suffice to say now, however, that it is not entirely clear if it is simply an unlikely random pairing, or a *bona fide* triple star companion.

2.5 That Matter in a Ball

A star's a star, some matter in a ball
compelled to courses mathematical
amid the regimented, cold, Inane,
where destined atoms are each moment slain

– J. R. R. Tolkien, "Mythopoeia" (1931)

So far we have described stars as being Sun-like, or dwarfs or giants, or of one spectral type or another. Such distinctions are based upon observed characteristics, such as their temperature, their luminosity and their physical size. Indeed, these three parameters describe the position of a star in the HR diagram (see Appendix 1 in this book). Now, however, the question is not so much *what* are the intrinsic characteristics of a specific star but rather, *why* does a star have such and such properties?

By unraveling the orbital characteristics of the two stars within a binary system it is possible to determine their individual masses – literally how much matter they contain. The observations indicate that the smallest stars have a mass of about 0.08 $M_{\odot}$, while the most massive stars contain about 100 times more matter than the Sun. As we have seen, however, nature tends to favor the formation of low mass stars over massive ones, and the reason for this is entirely due to physics. There is nothing to stop an interstellar cloud collapsing through gravity into an object less massive than 0.08 $M_{\odot}$, but such an object won't be a star. It will either be a brown dwarf or a massive Jupiter-like object. The reason there is a lower mass limit to *bona fide* stardom relates to the run of internal temperature and density. Below 0.08 $M_{\odot}$ the central temperature and density of a collapsing gas cloud do not allow for the initiation of internal energy generation through hydrogen fusion reactions (but more on this latter topic in a moment).

Although the lower limit for stardom is set according to the attainment of a minimum central temperature, the upper mass limit is set according to the luminosity (the energy output per second) being too high. In this latter case the problem is not so much that stars more massive than a hundred times that of Sun transgress some forbidden physical limit; it is rather that the in-falling material from the collapsing interstellar cloud can't get to the star's surface to increase its mass. This is an effect related to the radiation pressure built up by the newly forming star becoming so high that it begins to drive any in-falling material outwards again, working against gravity to stop the accretion (and thereby the mass growth) process. Accordingly, the physics of stardom is closely related to energy generation. If the central temperature is too low, then energy generation via nuclear fusion reactions is not sustainable; if the energy release rate is too high, then material accretion is ultimately choked off.

Not only can the masses of the stars within a binary system be determined through the analysis of their orbits, but, with a good distance measurement, so too can their luminosities. If a diagram is constructed in which the logarithm of the luminosity of a star is plotted against the logarithm of its mass, then a remarkable result unfolds. The various data points make up a near perfect straight line. This result indicates that the luminosity of a star is determined by its mass; the more massive a star the greater its luminosity, with the general relationship for low to intermediate mass stars being that $L \sim M^{\eta}$, with $\eta \approx 3.5$.

When this luminosity-mass relationship was first made clear, in the first quarter of the twentieth century, it was realized that, when combined with the HR diagram, it was the mass of a star that dictated its entire appearance. The mass at the end of the star formation process (the moment at which nuclear fusion reactions begin – see below) determines the luminosity of a star. The fact that the star must also first reside on the main sequence (as described in the HR diagram) further dictates that the star must have a very specific temperature (spectral type) and radius. The remarkable mass-luminosity-temperature-radius relationship is illustrated in Fig. 2.1.

The mass-luminosity-temperature-radius diagram for main-sequence stars does not produce a perfect straight line; rather, it shows a small spread in temperatures and luminosities for stars of equal mass. These variations, it turns out, relate to the age of the star (a topic we shall return to later) and its composition – that is, what the star is made of and how much of each specific chemical element it contains. This situation is described according to the

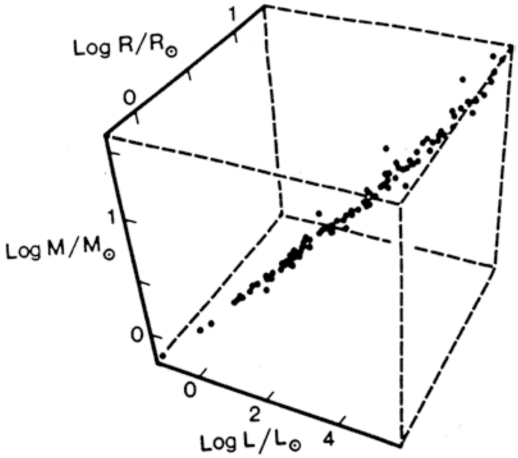

FIG. 2.1 The luminosity – mass – radius relationship for main sequence stars. The data points fall on a diagonal line through the axis cube, rather than being scattered at random (Data from J. Andersen, "Accurate masses and radii of normal stars" (*Astronomy and Astrophysics Review,* **3**, 91, 1991); R. W. Hilditch and A. A. Bell, "On OB-type close binary stars" (*Monthly Notices of the Royal Astronomical Society,* 229, 529, 1987))

so-called Vogt-Russell theorem, which reasons that once the mass and chemical composition of a star are specified, then its internal structure is uniquely determined.[11]

[11] In his classic text, *An Introduction to Stellar Structure* (University of Chicago Press, Chicago, 1939), Chandrasekhar presents a formal definition of the Vogt-Russell theorem: "if the pressure, *P*, the opacity, k, and the rate of generation of energy, e, are functions of the local values of *r* [density], *T* [temperature], and the chemical composition only, then the structure of a star is uniquely determined by the mass and the chemical composition". In many ways the Vogt-Russell theorem isn't a theorem at all. It is essentially a statement about the boundary conditions required to obtain a solution to the collected equations of stellar structure. The theorem has never been mathematically proven, and numerical studies have additionally shown that it is not true under some restrictive circumstances. For newly formed and main sequence stars the theorem is more than likely true and accordingly once the boundary conditions are specified (mass and chemical composition) then a unique solution to the equations of stellar structure will exist. This being said, astrophysicist Richard Stothers (late of the Institute for Space Studies at the Goddard Space Flight Center) found violations of the Vogt-Russell theorem for constant composition, massive stars under certain conditions (see "Violation of the Vogt-Russell theorem for homogeneous nondegenerate stars", *The Astrophysical Journal*, **194**, 699, 1974). Specifically, Stothers found that in the restricted mass range between 170 and 200 solar masses, three envelope solutions, each having different radii, could be 'attached' to a single stellar 'core' solution. Since very few stars form with such high masses, it is probably safe to assume that the non-uniqueness issue is not observationally important. Additionally, present-day numerical models of stars, based upon improved opacity tables and revised in-put physics, do not reproduce Stothers findings.

Without going into details here, stars like the Sun are composed of about 70 % hydrogen, 28 % helium and 2 % all other elements (such as oxygen, carbon, nitrogen, zirconium, and even uranium). What the Vogt-Russell theorem now tells us is that if you change the compositional makeup of a star, then it will take on a slightly different luminosity, temperature and radius; its internal structure will also be somewhat different. The Vogt-Russell theorem also tells us that stars change their observable characteristics (luminosity, temperature and radius) as they age. This result comes about since stars generate their internal energy by transforming one atomic element into another, via nuclear fusion reactions, and this must inevitably change their internal composition. We shall continue the story and implications of stellar evolution in the next section.

Of course, the physics of the situation is a little more complicated than simply describing the mass of a star along with the variation of its internal composition, temperature and energy generation rate. A star, a *bona fide* object, is also an object that continuously hovers on the boundary between collapse, due to gravity, and dispersion, due to the thermal pressure of its hot interior. This condition is known as dynamical equilibrium, and it comes about through a remarkable set of natural feedback mechanisms. The great, if not founding, astrophysicist Arthur Eddington provided a very helpful two-component picture of stellar structure in his famous (but now a little dated) book *The Internal Constitution of the Stars* (first published in 1927). A star, Eddington realized, may be thought of as a material component superimposed upon and continuously interacting with a radiative component. Figure 2.2 illustrates Eddington's basic idea.

The material component in Eddington's picture, as the name suggests, refers to the material out of which the star is made. This is the physical component (the molecules, atoms, ions, electrons and protons) that *feels* the gravitational force, and it is gravity that is trying to make the star as small as possible. The second, radiative component refers to the photons that transport energy in the form of electromagnetic radiation. At the center of the star, where temperatures are at their highest, the photons are in the form of X-ray radiation, but as they progressively move outwards, towards the surface of the star, down the outwardly decreasing temperature

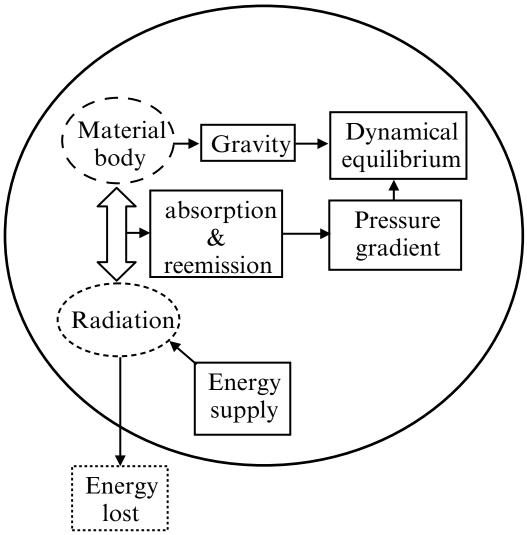

Fig. 2.2 Eddington's two-component star picture. By being hot inside, a star can set up an inwardly increasing pressure gradient that holds the inwardly acting pull of gravity. A dynamical equilibrium is established once the inward and outward forces at each level within a star are in balance

gradient, they continuously interact with the material component, being ceaselessly absorbed, re-emitted and deflected.

Indeed, while the photons travel at the speed of light, and could in theory exit the entire star in a matter of just a few seconds, their journey outwards is slowed dramatically to occupy a timespan of hundreds of thousands of years. Indeed, a photon typically moves just a few millimeters before it interacts with a material particle. By the time that the photons emerge at the surface of the star (from a region appropriately called the photosphere), they are no longer X-rays but light rays, with a characteristic wavelength corresponding to a yellow-orange color.

It is the continuous interaction between their material and radiative components that allows stars to exist. If there was no interaction, the radiation would leak out from the star in a just few seconds, the star would cool dramatically and with insufficient pressure the material component would collapse inward under gravity. In reality a dynamical balance is achieved. By dramatically slowing down the outward journey of the photons the interior of a star can remain hot, and thereby establish an appropriate temperature and pressure gradient at each and every point, to support the weight of overlying material layers. In this manner a star can come into an equilibrium configuration maintaining a constant radius.

The point not so far addressed in this picture is, how does a star remain hot? Clearly stars are losing energy into space at their surface (this is how and why we see them), but if there was no replenishment of that energy then their interiors would eventually cool-off – just as a hot cup of coffee cools off if left standing on a desk. All of this inevitable cooling is encapsulated within the inescapable bite of the second law of thermodynamics. So, to stay hot within their interiors and in balance against gravitational collapse, the stars need an internal energy source, and this is where nuclear fusion comes into play. By converting four protons into a helium nucleus a star can tap a massive internal energy source (literally the hydrogen out of which it is mostly composed), and thereby remain stable for many eons on end. Indeed, we know from the geological record and the study of meteorites that the Sun has been shining (that is, it has clearly not collapsed[12]) for at least 4.56 billion years.

With Eddington's picture in place we can now proceed to describe, albeit briefly, the formation of a Sun-like star. In this description we shall follow a classical approach and consider the pure gravitational collapse of a large, low density, low temperature and spherical interstellar cloud. This picture of collapse will be modified later on when planet formation is discussed.

The starting point of star formation begins with a diffuse cloud of interstellar gas, and we write this symbolically as *Cloud* (R_{cl}, ρ_{cl}, T_{cl}) with R_{cl} being the initial radius, ρ_{cl} being the density and T_{cl} being the temperature. The next step is to add in the effect of gravity – and this, of course, will result in the cloud becoming smaller, denser and hotter. The cloud becomes denser since it is envisioned that as time proceeds the same amount of material is contained in a progressively smaller and smaller volume of space.

[12] The dynamical collapse time for the Sun is about 50 minutes.

The temperature of the shrinking cloud increases because as it becomes smaller gravitational energy is released.[13]

As the collapse proceeds the interstellar cloud decreases in size by about a factor of one million, shrinking from an initial cloud radius $R_{cl} \sim 0.1$ pc $\approx 4.4 \times 10^6$ $R_\odot$, to a proto-star size of $R_\star \sim 2$–3 $R_\odot$. Likewise the temperature and density inside of the shrinking cloud steadily increase. The end of the gravitational collapse phase is determined by the condition that $T_\star > T_{nuc}$ at its center, where T_{nuc} is the temperature at which nuclear fusion reactions can begin. As we shall discuss further below, for hydrogen fusion reactions to begin, T_{nuc} must be of order 5–10 million degrees. Symbolically, the cloud-to-star collapse sequence can be expressed as:

$$Cloud\left(R_{cl}, \rho_{cl}, T_{cl}\right) + gravity \rightarrow Star\left(R_*, \rho^*, T_* = T_{nuc}\right)$$

where it is explicitly taken that $R_* \ll R_{cl}$, $\rho_\star \gg \rho_{cl}$, and $T_* = T_{nuc} \gg T_{cl}$.

Why should the gravitational collapse stop simply because nuclear fusion starts? Loosely speaking we can say that the gravitational imperative for continued collapse doesn't go away once nuclear fusion begins; rather it is simply held in check. This is the condition of dynamic equilibrium as described earlier with respect to Eddington's two-component star picture. Turn off the fusion reactions within a star's central core, and gravitational collapse will set in. Indeed, if nothing stops the gravitational collapse, then a black hole will eventually form. At this stage, therefore, the questions we need to ask are, how do fusion reactions work, and how long can they keep gravity in check?

Nuclear fusion reactions, from a star's perspective, are all about the transmutation of one of its internal atomic elements into another. More importantly, however, the stellar alchemy must also proceed exothermically – that is, the process of atomic

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[13] The reason that a collapsing gas cloud becomes hotter is encapsulated within the so-called Virial theorem. This theorem relates the total kinetic energy K of a self-gravitating gas cloud to its gravitation potential energy U and provides the result that at all times $2K + U = 0$. Since the temperature T of a gas cloud is directly related to the kinetic energy, and the gravitational potential energy is proportional to $-M/R$, where M is the mass of the cloud and R is the radius, so $T \sim 1/R$ since the mass of the cloud is taken to be constant. From this result we see that as the cloud collapses and becomes smaller, so the temperature must become higher. See R. J. Taylor (Note 17 below) for a detailed derivation of the Virial theorem.

alchemy must also liberate energy. It is the energy liberated by the fusion reactions, recall, that keeps the interior of a star hot, thereby enabling dynamical equilibrium to come about.

The essential workings of the energy generation process were first outlined by Eddington in the mid-1920s. It was a wonderful piece of reasoning. Eddington began with the results obtained by chemist Francis Aston, who found that the mass of the helium nucleus, composed of two protons and two neutrons, was smaller by about 0.7 % than the mass of four protons. Here lies the secret of the stellar energy source. Schematically, we have $4P \Rightarrow He - \Delta m$, where 4P indicates the idea of bringing together four protons (hydrogen atom nuclei), He is the helium atom nucleus and Δm is the mass difference indicated by Francis Ashton's laboratory-based measurements.

At this stage the exact details of the fusion reaction process do not concern us. All we need to know is that nature has found a way of taking four protons, converting two of them into neutrons, and then combining the lot in a helium nucleus. The point, as Eddington fully realized, is that if the conversion can be done, then the mass difference Δm is not just vanished away. Rather, using Einstein's famous formula, it is converted into energy, with $E_{4P} = \Delta m\ c^2$, where c is the speed of light. Eddington reasoned, therefore, that while Δm is extremely small per set of 4P conversions the c^2 term is very large, and accordingly only a small fraction of the total quotient of protons within a star need be converted into helium nuclei per second for it to easily replenish the energy lost into space at its surface. To order of magnitude the amount of matter that must be converted into energy per second to power the Sun is simply: (mass → energy per sec.) $c^2 = (E_{4P}/\text{per sec}) = L_\odot$, where $L_\odot = 3.85 \times 10^{26}$ Watts is the Sun's luminosity. This relationship indicates that for the Sun the (mass → energy per sec.) term is about 4×10^9 kg/s – that is, the Sun must convert, through nuclear fusion reactions, about four billion kilogram of matter into energy per second in order for it to shine at its observed luminosity. By human standards four billion kilogram is a lot of matter,[14] but compared to the Sun's total mass of $M_\odot = 1.9891 \times 10^{30}$ kg, the mass lost is

[14] The world production of brown coal and lignite in 2006 amounted to some 1 billion tons, which translates to about 30,000 kg being extracted (on average) per second.

entirely insignificant. Indeed, over the age of the Solar System, a time of some 4.56 billion years, the amount of matter that the Sun has converted into energy is of order 6×10^{26} kg, which is just under 104 Earth masses. This is certainly a large amount of matter, yes, but it is still an insignificant amount compared to $M_{\odot}$. Indeed, it is just 0.03 % of its mass.

Continuing our order of magnitude calculations, given that the energy liberated per 4P conversion to helium is $\Delta m\ c^2 = (0.007)\ 4m_P\ c^2 \approx 4.2 \times 10^{-14}$ J (where $m_P = 1.6726 \times 10^{-27}$ kg is the mass of the proton), so of order 10^{38} such conversions must be taking place per second in order to power the Sun. That is, the number of protons involved in keeping the Sun shining at any one instance is about 4×10^{38}. Eddington, much to the disdain of book printers, used to like writing out large numbers with all their zeros in place.[15] This certainly emphasizes the sheer scale of the quantities involved. So here goes: $4 \times 10^{38} \equiv$ 400,000,000,000,000,000,000,000,000,000,000,000,000. This number can be contrasted against the total number of free protons N_P available to undergo 4P fusion reactions within the Sun, and incredibly, it dwindles thereby into insignificance. We can estimate N_P via the Sun's hydrogen mass fraction, since, indeed, it is the nuclei of the hydrogen atoms that are undergoing the 4P reaction.

Accordingly, $N_P = (0.7)\ M_{\odot}/m_P \approx 8 \times 10^{56}$. So, once again, only a very small fraction (about 0.0000000000000000005 in fact) of the Sun's total number of available protons are involved in generating energy within its interior at any one instant. All in all, it would appear that the Sun can easily power itself by 4P fusion reactions. The question now is, for how long can such fusion reactions proceed?

The nuclear timescale T_{nuc} over which a star can generate internal energy via 4P fusion reactions is estimated by considering how much hydrogen fuel energy it has to begin with divided by the rate at which the hydrogen fuel is used up (or more correctly, converted into helium). Symbolically we have: $T_{nuc} = (0.7)\ 0.007 M^*\ c^2/L^*$, where M^* and L^* are the mass and luminosity of the star,

[15] The classic example is the Eddington number $N_{Edd} = 136 \times 2^{256}$, which when written out in full is a number 80 digits long. Eddington once commented that he worked out the number long-hand while on a ship crossing the Atlantic.

and the 0.7 accounts for the initial hydrogen mass fraction. For the Sun we find T_{nuc} $(\odot) \approx 2.3 \times 10^{18}$ s (or about 7×10^{10} years).

Detailed numerical calculations indicate that only about 10 % of a star's hydrogen is converted into helium before it is forced to find a new energy source (this topic will be discussed more fully later), and accordingly we have, for the Sun, a nuclear timescale of about ten billion years. Given that the Solar System is already about 4.5 billion years old, the Sun, apparently, is middle-aged, with perhaps another five billion years to go before it evolves into a bilious red giant.

The nuclear timescale formula can be re-cast purely in terms of the mass of a star. To do this we need to recall the luminosity-mass relationship described earlier. Accordingly, we generalize our timescale formula to read: $T_{nuc} = T_{nuc}$ $(\odot)/(M^*/M_{\odot})^{2.5}$. This provides us with what at first appears to be a contradictory result. The more massive a star is, so the shorter is its nuclear timescale. This seems odd, at first, since a star more massive than the Sun must surely have more hydrogen fuel. This is true, but the luminosity-mass relationship tells us that as the mass of a star increases so too does its luminosity, and accordingly it uses up its fuel supply much more rapidly. Massive stars live short, but brilliant, lives. In contrast, stars less massive than the Sun lead long, tenebrous lives.

Since α Cen A and B are Sun-like stars, their nuclear timescales will be about the same as that for the Sun – some ten billion years. Proxima Centauri, however, has a mass about 1/10 that of the Sun, and accordingly, it will spend a tremendous amount of time slowly converting its hydrogen fuel supply into energy: T_{nuc} (Proxima) $\approx 2 \times 10^{12}$ years. Incredibly, the nuclear timescale for Proxima is some 169 times longer than the present age of the universe.[16] We shall explore the consequences of the various nuclear timescales relating to the stars in α Centauri in detail in the next section.

The minimum temperature below which the 4P fusion reaction will no longer run efficiently is about ten million Kelvin. Given that the Sun has a central temperature of some 15 million

[16] The universe is estimated to be about 13.7 billion years old.

Kelvin,[17] we can estimate the size of the core region undergoing fusion reactions. First, however, we need an estimate of the temperature gradient within the Sun. This is the measure of how much the temperature drops per meter in moving from the core to the surface. Approximately, the temperature gradient will be $\Delta T/\Delta R = (15 \times 10^6 – 5{,}800)/R_\odot$, where the Sun's surface temperature is taken to be 5,800 K.

With this approximation in place, we find that the temperature decreases only slowly, by some 0.02 K per meter, as we move from its center outwards. The size of the region over which the temperature exceeds ten million Kelvin is therefore $(15 \times 10^6 – 10 \times 10^6)/0.02 = 2.5 \times 10^8$ m $\approx 0.36\ R_\odot$. In other words, the nuclear fusion reactions take place within the inner third of the Sun.

Up to this point we have skirted around the actual physics of the 4P transmutation. Indeed, as Eddington and others were able to do in the 1920s, we can say an awful lot about the inner workings of the stars without knowing the full details of the nuclear fusion process. Eddington once famously quipped of those critical to the idea that stars were not hot enough for the 4P fusion process to take place, that they should, "go and find a hotter place." Indeed, there are no hotter places than the centers of stars in the entire universe.[18]

It turns out, however, that although many fusion reactions are possible, in terms of generating energy from the conversion of four protons into a helium nucleus, stars employ either (or both) the so-called PP chain and the CN cycle. These mechanisms describe the step-by-step interactions needed to complete the transmutation, with each step having its own specific timescale and nuance. The various interaction steps in the proton-proton chain are illustrated in Fig. 2.3, while those in the CN cycle are illustrated in Fig. 2.4.

[17] The author has previously provided a series of solutions and approximations to the equations of stellar structure in the book, *Rejuvenating the Sun and Avoiding Other Global Catastrophes* (Springer New York, 2008). See also the highly recommended introductory text by R. J. Taylor, *The stars: Their Structure and Evolution* (CUP, Cambridge, 1994).

[18] Technically the entire universe was hotter than the centers of the stars for a few brief minutes after the Big Bang. But then, at that time, no stars actually existed.

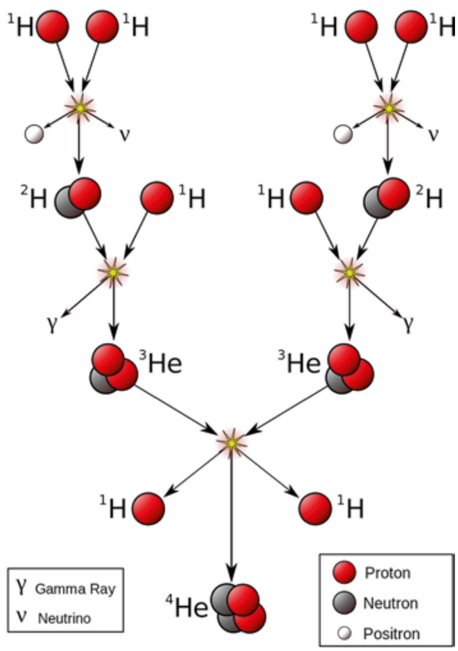

Fig. 2.3 The steps involved in the PP chain. The first step requires the generation of deuterium by the interaction of two protons. This is the slowest step in the entire sequence, since it requires that at the time of interaction one of the protons undergoes an inverse beta decay (to produce a neutron along with a positron and a neutrino). The final step is the interaction of two ^{3}He nuclei to produce a ^{4}He nucleus. A total of six protons are required to produce the two ^{3}He nuclei, but two protons are 'returned' when the ^{4}He nucleus is produced (Image courtesy of Wikipedia commons. FusionintheSun.svg)

Irrespective of which fusion reaction is followed, the PP chain or the CN cycle, the end result is that four protons have been converted into one helium nucleus, and 0.7 % of the mass of the four protons has been released as energy (in the form of gamma rays, neutrinos[19] and positrons[20]) to power the star. The physical conditions under which the two processes can run, however, vary

[19] The neutrinos do not actually interact with the material body of the star and are lost, within a few seconds, into space. In the case of the Sun this neutrino loss turns out to be useful, since by measuring their flux on Earth an experimental test of solar models can be made.

[20] The positrons are an energy source since they will rapidly annihilate with an electron to produce two gamma rays.

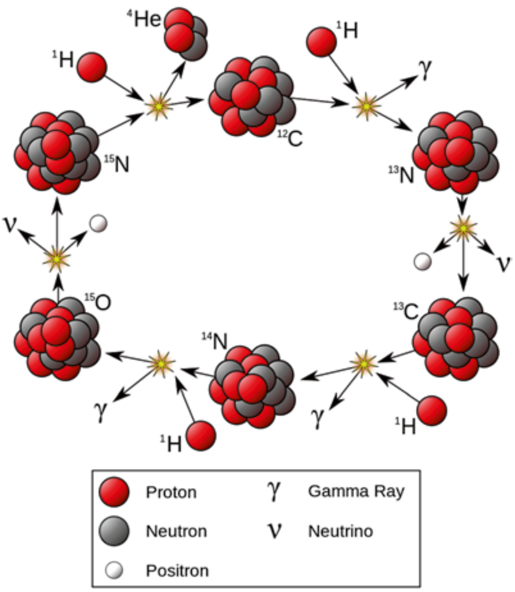

FIG. 2.4 The steps involved in the CN cycle. In this reaction network, the carbon and nitrogen nuclei act purely as catalysts, and the cycle begins with the interaction between a proton and a ^{12}C nucleus. As the cycle precedes nuclei of ^{13}N, ^{13}C, ^{14}N, ^{15}O and ^{15}N are successively produced through beta decays and proton captures (Image courtesy of Wikipedia commons. CNO_Cycle.svg)

and are highly sensitive to both the temperature and density. In general, the detailed numerical models show that the CN cycle operates at higher temperatures and densities than those required for the PP chain. Interestingly, the turnover point at which the total amount of energy generated via the CN cycle begins to dominate over that generated by the PP chain is for those stars just a little bit more massive than the Sun. In fact, with a mass 1.1 times larger than that of the Sun, α Cen A is right on the threshold at which the energy generation mechanism, PP chain versus CN cycle, transition takes place – and this has important consequences for its inner core structure.

So far it has been assumed that the energy generated within the core of a star is transported outwards by the radiative component – the photons. It turns out, however, that energy can also be transported within a star by its material component

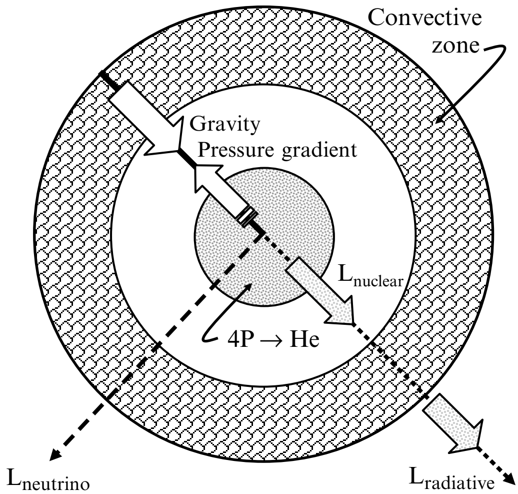

FIG. 2.5 A schematic diagram of the Sun's interior

through convective turnover. In this case a fluid instability literally results in the bulk motion of the material component – just like the bubbling motion seen in a boiling pan of hot water. The mode of energy transport within a star is determined by how much energy there is to be transported outward, the value of the temperature gradient and the ionization state of its constituent material. Detailed calculations indicate that for the Sun, the outer third, by radius, is undergoing convective turnover motion. For α Cen A and stars more massive than about 1.1 $M_{\odot}$, for which the CN cycle begins to dominate the central energy generation process, convective cores begin to develop. For stars less massive than about 0.3 $M_{\odot}$, the entire interior undergoes convective turnover. As we shall discuss shortly, it is the existence of extensive outer convective zones within Sun-like stars that determines their magnetic activity cycles.

Bringing all our results together, we can now construct a schematic diagram of the Sun's inner structure and workings (Fig. 2.5). At each point within the interior there is a dynamical balance between the inward force of gravity and the outward pressure due to the hot interior. The conversion of hydrogen into helium via the PP chain takes place inside the inner third of the Sun's interior, and these fusion reactions generate an outward flow of energy $L_{nucelar}$. The outer third of the Sun's interior undergoes convective motion.

At the photosphere the energy radiated per second into space corresponds to $L_{radiative}$. There is additionally a stream of neutrinos, with a total luminosity of $L_{neutrinos}$, that directly exits from the Sun's core, without any interaction, and streams into space. Given their observed characteristics (see below), the internal structure of both α Cen A and α Cen B will be essentially identical to that derived for the Sun and as illustrated in Fig. 2.5. Humanity may still be many centuries away from directly visiting α Centauri, but we already know, with a high degree of confidence, what the internal structure and workings of the principal stars are like. Hernán Cortés, from that lonely peak in Darien, may well have seen the far-off Pacific horizon and thirsted for adventure (and fortune), but the deeper-penetrating gaze of mathematics and physics has revealed to us the inner workings of the Sun and the far-flung stars. What an incredible result this surely is.

2.6 An Outsider's View

Angel, king of streaming morn, Cherub call'd by Heav'n to shine.

So wrote British poet Reverend Henry Rowe in 1796. Indeed, the Sun, to humanity, is more than just a star; it is our life blood and inspiration. It is also a star that we can see in detail. Indeed, the Sun is one of just a handful of stars that can be resolved beyond a point source into a disk, directly showing thereby a whole host of atmospheric features and phenomena.

It was across the projected disk of the Sun that early telescope-using astronomers, including Galileo Galilei, John Harriot and Christoph Scheiner among others, first observed and traced the motion of sunspots. Against the wisdom of the ancients, the sunspots revealed that the Sun was not a perfect featureless sphere, and moreover, it was not a static sphere. The Sun is spinning, and what is more, later observations by British astronomer Richard Carrington in the 1850s revealed that it was spinning differentially. The time for the Sun to complete one rotation around its equator is some 25 days, while one rotation in the high polar regions takes about 35 days.

The first teasing out of the story encoded within sunspots was begun in the early nineteenth century, and it was started in the hope of finding a new planet. German astronomer Heinrich Schwabe started observing the Sun in 1826, and his intent was to detect the small, dark disk of planet Vulcan while in transit across the Sun. He observed the Sun for over 40 years but never found Vulcan. Indeed, we now know, of course, that there is no such inter-mercurial planet to be found.[21] What Schwabe did find, however, was that the number of sunspots varied in a regular fashion over a period of about 11 years.[22] Schwabe presented his initial observational results in 1843, but the mechanisms underpinning the properties of the sunspot cycle have been challenging astronomers and physicists ever since. The manner in which sunspots are counted and recorded was standardized by Rudolf Wolf in 1848, and it is the time variation of the Wolf number that has been studied ever since.

Working independently of each other Richard Carrington in England and German astronomer Gustave Spörer began studying not only sunspot numbers but also sunspot locations. Although Carrington published first in 1858, the rule describing the variation in sunspot latitude is most commonly called Spörer's law.[23]

Somewhat confusingly, when the data on sunspot latitudes is plotted in diagrammatic form the result is usually called Maunder's butterfly diagram.[24] Moving beyond pure numbers and location, American astronomer George Ellery Hale (MIT) first determined the magnetic nature of sunspots in 1908. Hale's discovery

[21] The planet Vulcan was a supposed inter-Mercurial planet. It was estimated to be similar in size to Mercury, but with an orbital radius of about 0.2 au. Many systematic searches for Vulcan were conducted during the later half of nineteenth century – and several observers actually reported finding it! See also Note 44 below.

[22] Schwabe was awarded the Gold Medal of the Royal Astronomical Society in 1857 for his discovery of "the periodicity of the solar spots."

[23] The basics of Spörer's law are this: At the start of each new solar cycle, the sunspots initial appear at mid-latitudes, between 30° and 45°. As the cycle proceeds, however, the sunspots begin to appear at successively lower latitudes. At solar minimum, when the sunspot number is at its lowest count, the sunspots are characteristically found at latitudes ranging between 10° and 25°. At solar maximum, when the sunspot number is at its maximum count, the sunspots characteristically appear within just a few degrees of the Sun's equator. After the time of maximum the cycle begins over again, with the sunspots preferentially appearing at mid-latitudes.

[24] This diagram was first constructed by the husband and wife team of Annie and Edward Maunder in 1904.

followed in the wake of his invention of the spectroheliograph, an instrument that can take an image of the Sun at one specific wavelength of light. With his new instrument Hale found that the spectral lines in regions surrounding sunspots showed the Zeemann splitting effect,[25] and this clearly implicated the presence of strong magnetic fields. Not only were sunspots associated with localized regions of strong magnetic fields in the Sun's photosphere, Hale also found that when sunspots appeared in pairs, they had opposite polarities. Indeed, the magnetic polarity of sunspot pairs shows a 22-year cycle (being twice that of the Wolf number variation and the butterfly diagram).[26] The motion of sunspots not only reveals the differential rotation characteristics of the Sun; it turns out that their very existence also depends upon it. The Sun's magnetic field is generated within its outer third or so by radius through a dynamo process. As shown in

Figure 2.5 the energy transport mechanism in this same outer region is that of convection – literally, the broiling motion of its constituent plasma gas. It is this combination of rotation and convection that combines to produce the Sun's magnetic field and controls the properties of the sunspot cycle. Schematically we have:

$$\begin{gathered} plasma + rotation + convection \\ + meridional\,circulation \rightarrow solar\,dynamo \end{gathered}$$

Figure 2.6 illustrates the characteristics and operation of the magnetic dynamo. Although the whole process is hugely

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[25] The so-called Zeeman splitting was first described by Dutch physicist Pieter Zeeman in 1896. Apparently, the story goes, Zeeman disobeyed the direct instructions of his research supervisor and set about studying the effects of magnetic fields on atomic spectral lines. He found that in the presence of a strong magnetic field additional spectral lines could be produced. The first excited state of hydrogen, for example, is split into three energy levels in the presence of a magnetic field; this is opposed to having just one energy level when no magnetic field is present. Though Zeeman was fired for his supervisor-defying efforts, he obtained vindication in 1902 when he received the Nobel Prize in Physics for his discovery.

[26] For the first half of the cycle, for example, the sunspot pairs in the Northern Hemisphere are such that the polarity is *north* for the leading sunspot and *south* for the trailing sunspot (leading and trailing, that is, in the sense of solar rotation). The sunspot pairs in the Southern Hemisphere show the reverse polarity, with *south* leading *north*. This polarity pairing switches during the second half of the cycle, with sunspots in the Northern Hemisphere now having *south* leading *north* polarities, and sunspots in the Southern Hemisphere having *north* leading *south*.

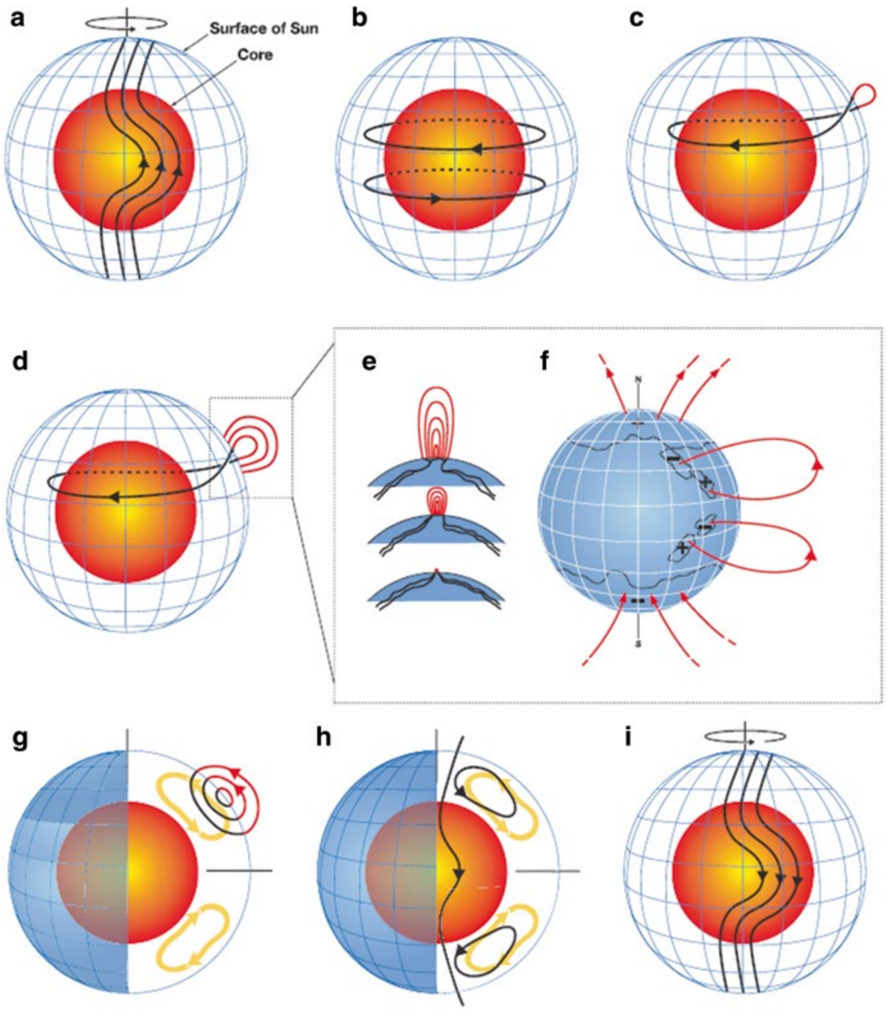

FIG. 2.6 The solar dynamo model. (**a**) The shearing of the poloidal (north–south) magnetic field by differential rotation near the base of the convection zone. (**b**) End result of stage (**a**) and the generation of a toroidal magnetic field. (**c**) Buoyant loops of the toroidal magnetic field rise to the surface, twisting as they do so. Where the loop cuts through the photosphere a pair of sunspots are produced. Further sunspot developmental details are shown in figure (**d**) through to (**f**). Meridional flow (**g**) carries the surface magnetic field poleward, causing polar fields to reverse. Transport of magnetic flux tubes downward to the base of the convection zone at the poles (**h**), resulting in the formation of a new poloidal magnetic field. The newly established poloidal magnetic field (**i**), with the reverse polarity to that in (**a**), begins to be sheared by differential rotation, eventually producing a toroidal magnetic field with the reverse polarity to that shown at stage (**b**) (Image courtesy of Mausumi Dikpate NCAR, Boulder. Used with permission)

complicated, the key principles that are invoked in the operation of the solar dynamo and its accompanying explanation of the sunspot cycle are differential rotation – called the Ω effect – which produces a strong toroidal magnetic field at the base of the convection zone, and then a rising and twisting process – called the α effect – that results in the production of sunspot pairs in the photosphere. It is the meridonal circulation that then stretches and carries the surface magnetic field poleward, establishing the conditions for a poloidal magnetic field and the beginnings of a new magnetic cycle. The basic workings of the αΩ model and its description of the sunspot cycle were first developed by Horace Babcock in the early 1960s, but the details of the theory are still under active investigation.

The first observation of a solar flare was made by Richard Carrington in 1859, and it was subsequently found that flares are typically associated with active sunspot regions. Indeed, the flares represent the explosive release of magnetic energy, resulting in the generation of a stream of high velocity charged particles and electromagnetic radiation that moves away from the Sun and on into the Solar System.

Although the energy released during a flare is variable, in the more extreme cases it can be a sizable fraction of the Sun's luminosity. The number of solar flares observed is variable and changes according to the sunspot cycle, with perhaps several being observed per day at solar maximum, and maybe one per week being seen at solar minimum.

Although sunspots and flares can be observed directly on the Sun, the overall activity is often gauged according to the so-called S-index related to the strengths of the H and K absorption lines associated with the single ionized calcium atom. This index is high at the times of intense sunspot activity and low at the times when few sunspots are present. The utility of the S-index comes into its own, not so much with the Sun but in the observation of other stars for which the disk cannot be directly resolved. It is a proxy measure therefore for determining magnetic cycle chromospheric activity in other stars.

This method of measuring stellar activity was pioneered by astronomer Olin Wilson at Mount Wilson Observatory in the 1960s. More recently, however, Sally Baliunas and co-workers have reviewed the Mount Wilson S-index survey data and found that 60 % of the stars in the H-K Project survey showed periodic variations, 25 % showed irregular variations and 15 % showed no discernible variation at all (see Fig. 2.7 – Ref.[27]). The magnetic activity cycle of Sun-like stars is apparently variable, and it would appear that such stars can move rapidly from a periodic active phase into one of long-term inactivity and/or high variability. Indeed, it is now clear that the Sun has passed through at least one inactivity phase when the sunspot cycle shut down. Known as the Maunder minimum, after solar researcher Edward Maunder (who first traced its history), it appears that in the time interval between 1645 and 1715 not only were no sunspots or solar flares observed, but the effervescent waves of aurora in Earth's upper atmosphere mysteriously vanished as well.[28]

Although the latter disappearance reveals a link between solar flare activity and upper atmosphere phenomena on Earth, the Maunder minimum, more importantly, coincided with a distinct drop in Earth's global average temperature. When the sunspot cycle stopped, northern Europe lapsed into what is known as the Little Ice Age. It was a time when the river Thames in London would freeze solid each winter and ice fairs could be held across its frozen surface. As the sunspot cycle re-established itself in the 1720s so Earth's global average temperature increased and aurorae were once again seen in the night sky.

The specific mechanisms that produced the Little Ice Age are not fully understood, but the message is clear enough: if the sunspot cycle stops again, and the Mount Wilson Observatory data says that it will, then Earth will face another climate changing challenge.[29] Indeed, the data obtained through the H-K Project at Mount Wilson suggests that on timescales of perhaps thousands of years the Sun should spend of order 20 % of the time in a Maunder minimum-like state. At the present time we have no certain way

[27] The history, current research and rational of the H-K Project at Mount Wilson Observatory is described in detail at: www.mtwilson.edu/hk.

[28] The aurorae are controlled by the solar wind and modulated by solar flare activity. The possibility of a wind of charged particles streaming away from the Sun was first suggested by Ludwig Bermann in 1951.

[29] By saying another we mean in contrast and in addition to the global warming trend, now clearly related to human activity, which is presently forcing Earth's climate towards a rapid and possible devastating change.

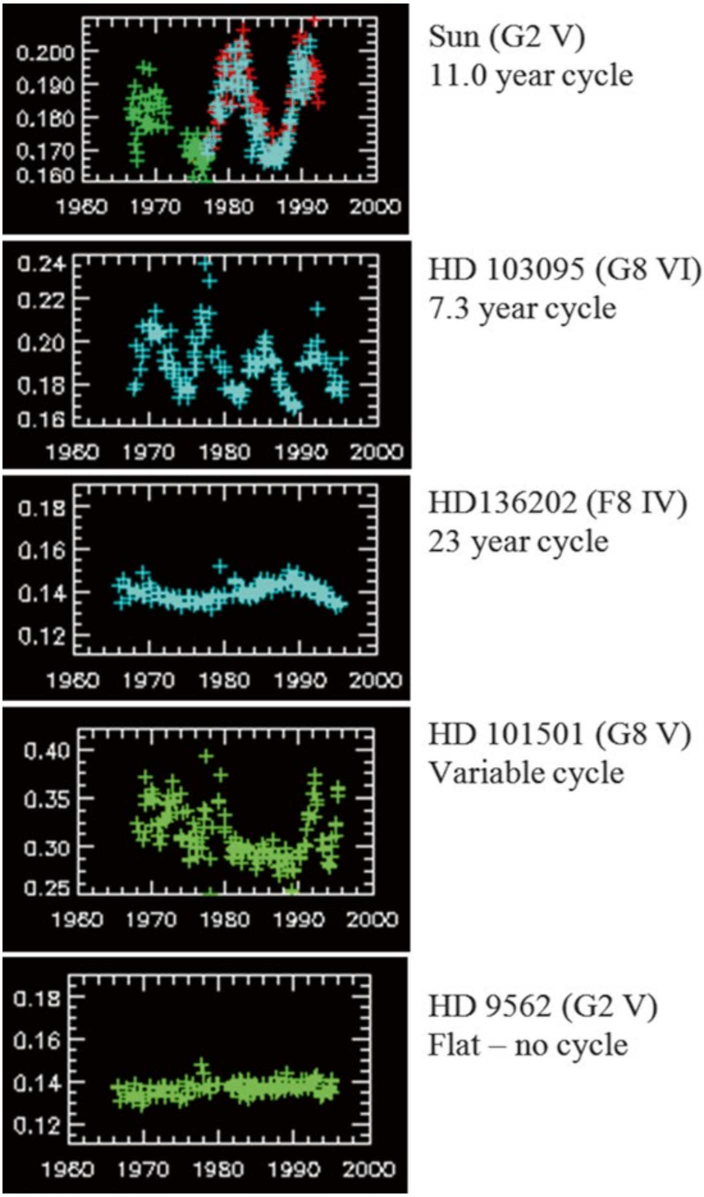

FIG. 2.7 Chromospheric activity of several stars studied in the H-K Project at Mount Wilson Observatory in California. The images show (from *top* to *bottom*) the activity cycle for the Sun, HD 103095 (Argelander's Star), HD 136202, HD 101501 and HD 9562. The activity cycles for the first three stars indicate periods of 10.0, 7.3, and 23 years, respectively. The last two stars show a variable cycle and a flat cycle, respectively (Images courtesy of Mount Wilson Observatory. Used with permission) (The history, current research and rational of the H-K Project at Mount Wilson Observatory is described in detail at: www.mtwilson.edu/hk)

of predicting when the Sun's magnetic activity cycle might switch off again.

Where do α Cen A and B fall with respect to their chromospheric activity? The data appears to be reasonably clear and reveals that α Cen A is in a Maunder minimum-like phase, its activity index having been essentially constant over the past 10 years. This being said, however, Thomas Ayres (University of Colorado) has recently argued that the historical run of data obtained with the ROSAT, XMM-Newton and Chandra X-ray telescopes supports the possibility that α Cen A is either in the process of waking up from a Maunder minimum slumber, or that it exhibits a very long period activity cycle of order 20 years. In contrast α Cen B shows a clear 9-year variation in its chromospheric activity, indicating that its magnetic cycle is a few years shorter than that of the Sun at the present time. Consistent with the study of other Sun-like stars α Cen A and B show a range in their observed magnetic cycle variability. Interestingly, however, as pointed out by Thomas Ayres, near-term future observations of α Cen A may well reveal how the variability cycle picks up again after switching into a deep quiescent mode, and this, of course, may reveal important lessons for us when the Sun once again slides into another Maunder minimum-like phase.

As soon as the means of projecting an image of the Sun's disk onto a screen became available, the blemish of sunspots, along with their variability, was easily noticed. The Sun, however, shows variability in much more subtle ways than the appearance of dark splotches, and indeed, if one looks close enough and in the correct manner its *surface* is found to be pulsing and writhing, with large swaths of the photosphere shifting upwards when other regions are moving down. The Sun is literally ringing, and although there are dominant frequencies the summed effect is a discordant harmony – "like sweet bells jangled, out of tune and harsh."

More than just the circulation of plasma flows within the rising and falling channels of convection cells. This vertical oscillation proceeds through the propagation of acoustic waves. In essence the Sun acts as a resonant cavity for the pressure (that is sound) waves that move through its interior. The existence of these pulsation zones in the Sun's photosphere was first revealed by Robert Leighton (CalTech) and co-workers in 1962. Indeed, by

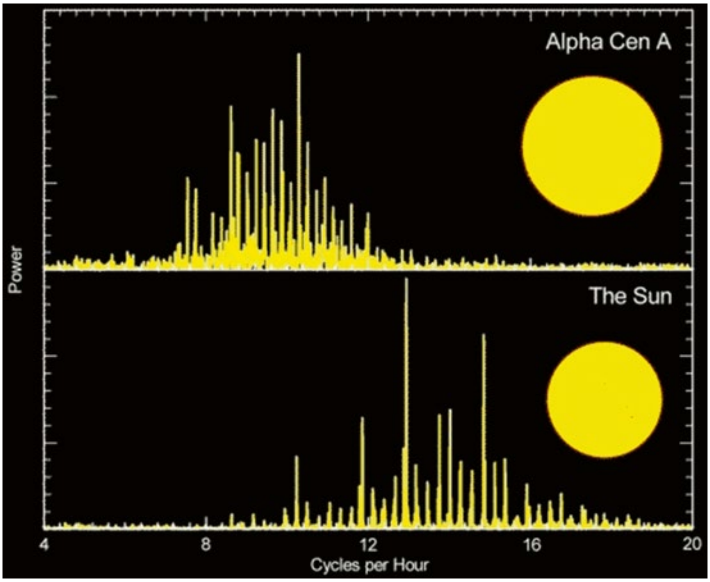

FIG. 2.8 Power spectra for the Sun and α Centauri A. This data reveals the dominant frequencies (where the power is large) of the recorded oscillations. Although many modes of oscillation are present the Sun shows a distinct power spectrum peak close to 12 cycles per h (this is the 5-min oscillation mode). Although α Cen A also shows many oscillation modes, a distinct peak in the power spectrum is revealed at about 10 cycles per h (this corresponds to a 7-min oscillation mode) (Image courtesy of the National Center for Atmospheric Research in Colorado. Used with permission)

studying the Doppler shifts of selected absorption lines Leighton et al. found that localized regions of the Sun's disk showed coherent 5-min oscillations (Fig. 2.8), with the various zones moving either up or down with speeds of order 0.5–1 km/s. From the seeds of helioseismology, literally, the study of Sun-shaking, grew asteroseismology, the study of non-radial star pulsations, and this field of observation now provides some of the strongest constraints upon which to test models of stellar structure.

Asteroseismic studies provide detailed information about stellar interiors, since the observed frequencies of oscillation are directly related to the sound travel time across a star. The speed of sound c in an ideal (perfect) gas is related to the pressure P and density ρ via the relationship $c^2 = \Gamma_1 \, P/\rho$, where Γ_1 is a constant. By measuring the dominant oscillation frequencies, therefore, a measure of the average ratio of the internal pressure and density can be found, and this can then be compared against the computer model predictions. An additional key point about such studies is that different frequencies of oscillations probe differing depths of a star's interior. Longer wavelength oscillations probe deeper stellar depths than smaller wavelength waves. Not only do the oscillations provide information about the pressure and density of a star's interior, they also provide information about the rotation state of its interior. Such studies, for example, have probed the variation of rotation speed within the Sun's outer convective zone, showing that while the outer regions show differential rotation, the rotation speeds being slower in the polar regions than that at the equator, at the core-envelope boundary (recall Fig. 2.5), the speed becomes uniform. This shows that the core spins like a solid ball. It is in the boundary region of high rotational sheer, the so-called tachocline region, which characterizes the solar dynamo (recall Fig. 2.6, and see below).

Asteroseismic studies of α Cen A and B have been conducted since the early 1980s, with various research groups reporting strong oscillation modes at 7 and 4 min, respectively. Detailed comparisons between theory and oscillation observation have, again, been made by various groups, and these studies have been used to gauge the age of the Centaurian system. Patrick Eggenberger (Observatoire de Geneva, Suisse) and co-workers, for example, used the asteroseismic data to deduce a system age of 6.52 ± 0.3 billion years. Other studies, using differing techniques, have found ages in the range between 5 and 7 billion years for α Centauri, and in general we take the system age of be 6 ± 1 billion years. Compared to the Sun, the stars in the Centauri system are at least 0.5 billion, to perhaps as much as 2.5 billion years older. Not only can the age of the α Centauri system be constrained by asteroseismology but so, too, can their deep interiors.

In this latter respect Michaël Bazot (Universidade do Porto, Portugal) and co-workers have recently reviewed the data relating to α Cen A, and specifically looked to see if there is any evidence that it might have a convective core. As described above one of the conditions under which a convective core might develop in a star is that when energy via the CN-cycle begins to dominate over that of the PP chain – the CN cycle requiring a higher temperatures and core density in order to operate efficiently. The development of such convective cores is important, since they have an effect upon the entire structure and future evolution of a star. Additionally, since there is no fully agreed upon theory to describe convective energy transport within stars, the approximation theory that is used[30] needs careful calibration. It is generally believed that a convective core should develop in main sequence stars more massive than about 1.1 $M_{\odot}$, and accordingly α Cen A sits right at this boundary.

The study conducted by Bazot et al. used a statistical approach to investigate the possible internal makeup of α Cen A. In this manner they constructed nearly 45,000 stellar models, each having slightly different values of the mass, age, composition and mixing length parameter. Comparing this extensive grid of stellar models against the available observations the study revealed an age estimate of about five billion years for α Cen A (this is towards the younger end of the variously published results). The study further revealed a best-fit mixing length parameter of $\alpha = 1.6$, slightly smaller than the value of 1.8 deduced for the Sun.

With respect to the possibility that α Cen A has a convective core Bazot et al. find that the probability is less than 40 %. Indeed, they constrain the core mass and radius to be no larger than 1.5 % and 4 % of the total mass and radius of α Cen A. The situation, at present, remains unclear as to whether α Cen A has a convective core. The odds are not unfavorable, but they are still less than 50–50. Future, higher resolution asteroseismic studies will be required before we can clearly tell what is going on in the core of α Cen A and before we can conduct any similar such parameter study of α Cen B. There are still many secrets that have yet to be unraveled.

2.7 α Cen A and B As Alternate Suns

The stars of α Cen AB are alternate Suns – both literally and physically. The Sun is the prototype, therefore, for understanding their behavior and appearance. Alternatively, the physical properties of

[30] The standard method for describing convective energy transport within a star is the so-called mixing length theory. Here the idea is that a convective *blob* of plasma moves through a specific distance l before dissipating into the surroundings. Generally, the mixing length is specified as being $l = \alpha H_P$, where α is a constant (parameter to be specified) of order one, and H_P is the pressure scale height – the height over which the pressure changes by a factor of $e = 2.71828\ldots$.

TABLE 2.2 Physical properties deduced for α Cen A and B compared to those for the Sun

	α Cen A	α Cen B	Sun
Mass ($M_\odot$)	1.105	0.934	1.000
Luminosity ($L_\odot$)	1.519	0.500	1.000
Radius ($R_\odot$)	1.224	0.863	1.000
Temperature (K)	5,790	5,260	5,778
Rotation rate (days)	22.5	36.2	24.5
Composition	$1.5 \times Z_\odot$	$1.6 \times Z_\odot$	$Z_\odot$
Age (Gyr)	6 ± 1	6 ± 1	4.5
Magnetic field	Yes	Yes	Yes
Magnetic cycle (years)	None (?)	~ 9	11
Oscillations	Yes (7 min)	Yes (4 min)	Yes (5 min)
Planets	??	Yes (?)	Yes

α Cen A and B enable the construction of alternate models for our own Solar System. They provide us with "what might have been" scenarios. Table 2.2 provides a summary of the observationally deduced characteristics of α Cen A and α Cen B and contrasts their data against that derived for the Sun.

The data set displayed in Table 2.2 shows that α Cen A and B bracket the Sun with respect to their mass. They illustrate the dramatic effects that just a 1 % change, plus or minus, in the mass our Sun would have had on the Solar System. For indeed, this small 1 % change in mass, when multiplied through the luminosity-mass relationship, would indicate a 50 % change in the Sun's energy output, and life on Earth would never have evolved. At 1 au from α Cen A the temperature of a Doppelganger Earth would be too hot for liquid water to exist; there would be no oceans, which are the cradle of all life.

Indeed, for the planets as they are in our Solar System, with a central star having the mass and energy output of α Cen A, there would be no habitable planet at all. Mars would certainly be warmer, and it would sit within a region in which liquid water on an Earth mass planet might exist, but its mass at 1/10 that of Earth would still be too small for it to maintain an atmosphere – vital for the safekeeping of oceans – for very long. Exchanging our Sun for α Cen A would result in a lifeless planetary system.[31]

At 1 au from α Cen B the temperature on a Doppelganger Earth would be too low for liquid water to exist; it would be a frozen world sheathed in deep ice. Alternatively, however, Venus (Earth's twin in terms of mass) would now be located within the zone in which liquid water might potentially exist upon an Earth-mass planet's surface. Life, not necessarily as we know it upon Earth, would apparently be possible if the Sun and α Cen B were switched. Once again we learn the important lesson. Earth is a very special place within the universe. The topic of habitability zones, where life on an Earth-like planet might evolve, will be discussed in more detail shortly.

In terms of physical size α Cen A and B are not dramatically different from that of the Sun, being of order 20 % larger and smaller respectively. Their surface temperatures differ only slightly, with α Cen A being just a fraction hotter than the Sun and α Cen B being 500 K cooler. In terms of rotation rates α Cen A appears to be spinning just a little bit slower than the Sun, while α Cen B rotates about 50 % faster.

Detailed spectral analysis of α Cen A and B indicates that for the most part as far as their composition goes they have a similar makeup to the Sun but are definitely richer with respect to many of the heavy elements. Iron, for example, is some two times more abundant in α Cen A than in the Sun. Carbon is only enhanced by a factor of about 1.15, however, and calcium is under abundant by a factor of 0.95. Furthermore, the observations indicate that α Cen B has a slightly higher iron abundance than that determined for α Cen A. Usefully, the generally greater than solar heavy element abundances deduced for both stars in the Centauri system provides us with some insight as to where they might have formed, and it also provides us with the hope that multiple numbers of planets yet await to be found within the system.

[31] The caveat here is that life may still chance to evolve within sub-surface ocean locations such as that found in the interior of Jupiter's moon Europa. In this case the internal heating is provided for by gravitational tidal stretching and as exemplified by the black-smoker ecosystems found in Earth's deepest oceans. Life can find ways to thrive in conditions of complete darkness without the aid of photosynthesis.

That the enhanced heavy element abundances deduced for α Cen A and B is encouraging with respect to the system possibly harboring multiple numbers of planets is based upon exoplanet survey work carried out over the past decade. The data on exoplanet systems and specifically the data on their host stars, indicates that in general planets are more likely to be found the higher the heavy element abundance (Z). Indeed, it appears that the probability increases as approximately the square of the heavy element abundance. Although this probability ostensibly applies to the detection of Jovian, or gas-giant, planets (the actual detection methods will be described later), it is generally believed that the same result will apply to smaller, terrestrial worlds.

The first terrestrial planet in the α Centauri system has already been detected (in orbit about α Cen B – the component with the slightly higher heavy element abundance), and it is probably only a matter of time before more are found not only in α Cen B, but in α Cen A and quite possibly in Proxima as well. We shall pick up this discussion in more detail later.

The idea that the chemical history and evolution of the Milky Way Galaxy is written in the abundances, dynamics and distribution of the stars was first expounded by American astronomer Olin J. Eggen, along with Donald Lynden-Bell (Cambridge University) and Allan Sandage (Carnegie Observatories), in the early 1960s. Accordingly, the stars most depleted in heavy elements are found in the galaxy's outermost halo, moving along highly elliptical orbits with an isotropic distribution around the galactic center. Moving inwards and towards the disk of the galaxy, the stars are richer in heavier elements, and they move in circular orbits around the Sun.

The Sun and α Centauri belong to what is called the thin-disk population of objects, which means that they are relatively young stars moving along circular orbits that carry them no higher than a few parsecs above and below the galactic plane. Not only does the chemical abundance of the stars vary according to the halo and disk structure, the heavy element abundance also increases upon moving closer in towards the galactic center. Specifically, it appears that the history of star formation within our galaxy has favored the inner few thousand parsecs of the disk and core. Since more stars, and importantly, more massive stars, have formed in the inner regions of the galactic disk, so the interstellar medium there is enhanced by heavy elements.[32] Towards the outer boundary of the galactic disk, star formation has been less prolific, and the interstellar medium is accordingly less heavy element-enhanced. That α Cen A and B have heavy element abundances that are somewhat greater than that of the Sun suggests that they probably formed in a region slightly closer-in towards the galactic center – but not by much. Indeed, while it is not possible to say exactly where either the Sun or α Cen A and B (and Proxima) formed (other than within the thin disk component at a radial distance of about 8,000 pc from the galactic center), it is reasonably clear that while they are not common siblings, born of the same natal cloud as the Sun, they are rather distant cousins sired only within the same basic region of the galactic disk.

By comparing detailed numerical models of stellar structure against observed properties it is possible to estimate how old a star might be. In this manner, for the observed mass, temperature and luminosity of star, the compositional abundance terms of a stellar model are adjusted until a good agreement is achieved. Since the internal composition of a star changes systematically with age (as a result of the fusion reactions within its core) so an age can be fixed. The situation is a little better for our Sun, since the laboratory analysis of meteorite fragments enables a formation age to be accurately determined – with the result (as seen before) that the Sun is 4.5 billion years old. When numerical models representing α Cen A and B are adjusted to come into agreement with their observed temperature and luminosity, for their known masses, then ages of order five to seven billion years are derived.

Typically it is taken that the stars of α Centauri are at least some 6 billion years old, making them something like 1.5 billion years older than the Sun. By comparison, therefore, it appears that the Sun is the younger, distant cousin to α Cen A and B. Indeed, a general assessment of star ages in the solar neighborhood finds that the average age is about one billion years older than that of the Sun. It would appear, therefore, that the Sun, the Solar System and humanity are the new(er) kids on the galactic block.

[32] It is through supernovae explosions that all of the chemical elements beyond hydrogen and helium are generated and dispersed into the interstellar medium.

Although α Cen A and B are most definitely Sun-like stars, they are not solar twins. Indeed, this latter category of objects is a decidedly select group of objects that not only have the same mass as the Sun but also the same age and composition. At the present time not quite half a dozen stars are known members, or are at least adjunct members, of the solar-twin club.

More solar Doppelgangers are likely to be found in the future, but it turns out that they are relatively few and far between. The closest known member of the solar twin club is the star 18 Scorpii, and it is located at a distance of some 14 pc. Its mass is estimated to be 1.04 ± 0.03 times that of the Sun, and its deduced iron to hydrogen abundance ratio is just 1.1 times higher than that of the Sun.[33] The age estimates for 18 Sco places it between 4 and 5 billion years old – bracketing thereby the 4.5 billion year age deduced for the Sun.

Another solar twin is the star HD 102152, located some 78 pc away. Interestingly for this star, however, is that although it has a near identical mass and composition to the Sun it is estimated to be nearly four billion years older. In essence HD 102152 offers a glimpse of the future Sun.

Although it might seem that 18 Scorpii and HD 102152, given their near perfect solar twin characteristics, are ideal objects to study for possible planetary companions, no new worlds have been located in orbit around them. This, of course, is not to say that none is there, but rather that they haven't been detected yet. Indeed, in the case of these two stars, and for that matter any other solar twin, the most interesting result would be that they are genuinely devoid of planets.

The details of planet formation will be described shortly below, but it is generally taken to be the case that virtually all Sun-like stars should have an associated planetary system. The present paradigm is that low mass stars and planets form in tandem, one with the other and only very rarely separately. Planet-hunting pioneer Geoffrey Marcy (University of California, Berkeley) along with Erik Petigura and co-workers presently interpret the observational situation as indicating that some 26 % of

[33] It additionally has a regular sunspot activity cycle of 7 years duration – similar, indeed, to that of the Sun.

Sun-like stars have associated planets with sizes of between 1 and 2 times that of Earth, with orbital periods between 5 and 100 days.[34] The current observations also indicate that about 11 % of Sun-like stars should have an Earth-like planet located within their habitably zones, with orbital radii between about 0.8 and 1.2 au. Furthermore, Courtney Dressing and David Charbonneau (both of the Harvard-Smithsonian Center for Astrophysics) have also looked at the statistics relating to the low mass, low temperature K and M spectral-type stars, and they find that the occurrence rate of planets with sizes of between 0.5 and 4 times that of Earth, with orbital periods shorter than 50 days, is 0.9 planets per star.[35] In other words, essentially all K and M spectral type stars should have at least one associated planet. To this result can be added the conclusions from another statistical study, of just M dwarf stars, conducted by Mikko Tuomi (University of Hertfordshire, England) and co-workers who find that the occurrence rate of planets less massive than 10 times that of Earth is of order one planet per star.[36]

Given that the present observations imply that all Sun-like and lower mass stars should form with at least one planet, the finding of a genuine planet-less system suggests that some catastrophic processes may occasionally be at play. Indeed, *before*, *during* and *after* planet formation disrupting mechanisms can be identified. The close packing of stars in their natal cloud, for example, leads to a *before* mechanism in the sense that close

[34] See, E. A. Petigura et al., "Prevalence of Earth-sized planets orbiting Sun-like stars." This paper can be downloaded at arxiv.org/abs/1311.6806.

[35] See, C. D. Dressing and D. Charbonneau, "The occurrence rate of small planets around small stars" – arxiv.org/abs/1302.1647v2. In addition to estimating the number of planets expected per star, the authors also find that at a 95 % confidence level, the closest transiting, Earth-sized planet located within the habitability zone of its parent star (see Sect. 2.16) should be located within 21 pc of the Sun. Additionally, the nearest non-transiting planet located within its parent star's habitability zone should be closer than 5 pc (16 light years) away (again, at a 95 % confidence level).

[36] See, M. Tuomi et al., "Baysean search for low-mass planets around M dwarfs – Estimates for occurrence rate based on global detectability statistics" – arxiv.org/abs/1403.0430. The results from this study are remarkable since of order 75 % of all stars are red dwarfs. Indeed, the researchers also conclude that perhaps of order 25 % of all M spectral type stars within the solar neighborhood could have super-Earth planets located within their habitability zones (see Sect. 2.16). The data gathered for the study was obtained with the HARPS detector (see Fig. 2.15) and the Ultraviolet and Visual Echelle Spectrograph (UVES) operated by the European Southern Observatory.

encounters between protostars might conceivably destroy their planet-forming disks. The system is then essentially stillborn. A *during* mechanism for planet loss is that of planet migration, where a large Jupiter-mass planet moves inwards and gravitationally scatters any interior planetary bodies prior to interacting with the parent star itself and being consumed via direct accretion. An *after* mechanism would correspond to that of planet stripping via a very close random encounter with another star long after the planets have formed. (See Appendix 2 in this book for the characteristic timescale of such encounter events and also see Fig. 1.17.)

2.8 Proxima Centauri: As Small As They Grow

Nature, for so it would appear, likes to make low mass stars, and Proxima Centauri has about as small a mass that a star can possibly have. Observed as M spectral-type, red dwarfs with low surface temperatures, low luminosities and small sizes, stars like Proxima are located in the very basement of the main sequence. Remove just a shaving of mass from a red dwarf, and it would no longer be a star – rather, it would become a brown dwarf.

Although astronomers are not universally agreed upon an exact definition, it is generally felt that a star is an object that is hot and dense enough within its central regions to initiate hydrogen fusion reactions (recall Fig. 2.3). To achieve these conditions a star, as it forms, must have access to a minimum amount of matter that it can accrete. As before, we can symbolically describe the initial state of a star forming cloud, prior to gravitational collapse, as *Cloud* (R_{cl}, ρ_{cl}, T_{cl}), where R_{cl} is the radius, ρ_{cl} the density and T_{cl} the temperature.

Previously, our argument was that cloud collapse will stop once $T_{cl} = T_{nuc} \approx 10^7$ K, that is, collapse stops once the central temperature is high enough for fusion reactions to begin. With Fig. 2.2 as our guide, it is through the onset of nuclear reactions that a star is able to tap into an internal energy source. The energy generated by the hydrogen fusion reactions then exactly balances the energy lost into space at a star's surface (its observed luminosity). By having a hot interior, a star sets up a pressure gradient, with high pressure at the center and low pressure towards the surface, so that the weight of overlying layers is supported at each point within its interior. The star is then able to find a dynamically stable configuration in which the internal pressure supports the star against continued gravitational collapse.

It is in this manner that at each point within a star the thermal pressure of the interior gas $P_{thermal}$ is exactly balanced by the gravitational pressure $P_{gravity}$ due to the weight of the overlying layers. The thermal pressure is directly related to the density of the gas, assumed at this stage to be a perfect gas in which the individual components do not interact with each other, and the temperature. Working purely in terms of dependent quantities (and ignoring constant terms) we can express the thermal pressure due to the hot interior as $P_{thermal} \sim \rho T$, where ρ is the density of the gas and T is the temperature. The gravitational pressure at the center of a star will be of order $P_{gravity} \sim M^2/R^4$,[37] and when $P_{thermal} = P_{gravity}$ we obtain an approximate expression for the central temperature of $T_C \sim M/R$.[38]

The question we have to address now is, are we sure that the pressure inside of a star can always be described as a perfect gas? And the answer to this is no. Under certain high density low temperature circumstances we may not assume that the gas particles (the atoms, electrons and ions) do not interact with each other. Specifically, the gas within a star can become degenerate, and this dramatically changes the way in which a collapsing gas cloud behaves.

[37] The simplest heuristic way to envisage the equilibrium condition is to imagine the star split into two halves, each of mass $M/2$, around its equator. The centers of mass of these two halves, when brought together, will be about a distance R apart, and the area of interaction between the two halves will be πR^2. Using the definition that pressure is the force divided by the area of interaction, and given that our two halves are held together by their mutual gravitational interaction, we obtain $P_{\text{gravity}} \approx G(M/2)(M/2)/R^2/\pi R^2$, which gives our result: $P_{\text{gravity}} \sim M^2/R^4$.

[38] When $P_{\text{thermal}} = P_{\text{gravity}}$, we additionally have $\rho T_C \sim M^2/R^4$, and with density varying as M/R^3, we obtain the result that $T_C \sim M/R$. Technically it is the temperature averaged over the entire star mass, T_{av}, that we have just derived, rather than the central temperature T_C. A more detailed derivation gives $T_{av} = 4 \times 10^6 (M/R)$ Kelvin, where now the mass and radius are expressed in solar units. Comparing these results against detailed numerical models we find that for the Sun, $T_C \sim 2.5\, T_{av}$. Additionally, at the Sun's photosphere, $T_{\text{surface}} = 5{,}778$ K ~ 10–3 T_{av}.

Degeneracy is a quantum mechanical effect that is related to the Heisenberg uncertainty principle (HUP). This key quantum mechanical principle sets a limit on how well the position Δx and momentum Δp of particle can be known at any one instant. Accordingly, Werner Heisenberg showed in 1927 that $\Delta x\ \Delta p > \hbar/2$, where $\hbar$ is the so-called reduced Planck constant equal to $h/2\pi$. In a degenerate gas, because of the intense crowding, Δx becomes very small, and accordingly the moment Δp must become very large in order to satisfy the HUP. The various particles in a degenerate gas, therefore, must be moving with much higher speeds than would otherwise be expected for a given temperature. Indeed, it turns out that the pressure exerted by a degenerate gas $P_{degenerate}$ is independent of the temperature and only varies according to the density, with $P_{degenerate} \sim \rho^{5/3} \sim M^{5/3}/R^5$.

In the case of the minimum mass for a star to form, the situation is related to which pressure term $P_{thermal}$ or $P_{degenerate}$ comes into equilibrium with $P_{gravity}$ first and thereby halts the collapse. By equating our expressions for $P_{thermal}$ and $P_{degenerate}$ a critical radius $R_{crit} \sim M^{-1/3}$ is revealed, and this provides us (from our earlier expression for the temperature) with a critical temperature $T_{crit} \sim M^{4/3}$. So, in the balance situation where $P_{thermal} \sim P_{degenerate} \sim P_{gravity}$ we have two possible outcomes, depending on the value of T_{crit}. If $T_{crit} > 10^7$ K, then the body can initiate hydrogen fusion reactions before full degeneracy sets in and the body becomes a *bona fide* star with $P_{thermal} = P_{gravity}$. If, on the other hand, $T_{crit} < 10^7$ K then $P_{degenerate} = P_{gravity}$, and it is the degeneracy pressure that stops the gravitational contraction before nuclear reactions can be initiated. Since the degeneracy pressure is independent of the temperature, no matter how much energy the subsequent body radiates into space it will remain stable. A sub-stellar brown dwarf object has accordingly formed. Schematically we now have:

$$
\begin{aligned}
&Cloud\left(R_{cl}, \rho_{cl}, T_{cl}\right) + gravity \rightarrow \\
&Brown\,Dwarf\left(R_*, \rho_* = \rho_{degenerate,} T_{crit} < 10^7\,\mathrm{K}\right)
\end{aligned}
$$

Being neither a star nor a Jovian planet, the brown dwarfs form a distinct class of galactic objects. Detailed calculations indicate that the maximum mass for a brown dwarf, which is also the

Table 2.3 Physical properties deduced for Proxima Centauri

	Mass ($M_\odot$)	Luminosity ($L_\odot$)	Radius ($R_\odot$)	Temp. (K)	Rotation rate (days)	Magnetic field	Planets
Proxima	0.123	0.0017	0.145	3,042	25–85	Yes	??

minimum mass for a star, is $M_{limit} = 0.08\ M_\odot$, or about 80 times the mass of Jupiter. Of the ten stars nearest to the Solar System, Wolf 359 has the lowest known mass, weighing in at just 0.09 times the mass of the Sun. The star EZ Aquarri C (the 12th closest system to the Sun at a distance of 3.45 pc), has an estimated mass right on the 0.08 $M_\odot$ star/brown dwarf divide.

Although brown dwarfs do not initiate hydrogen fusion reactions via the proton-proton chain within their interiors, they can, in their young phases, briefly fuse deuterium via the reaction $D + H \Rightarrow {}^3He + \text{energy}$. There is again a temperature limit to the onset of these fusion reactions, and detailed calculations indicate a lower mass limit to the brown dwarfs at about 13 times the mass of Jupiter. Objects with masses smaller than the brown dwarf limit are planets. Although the radii of brown dwarfs vary as $R \sim M^{-1/3}$, the radii of planets, which once below the mass of Jupiter tend to have a near constant density, vary as $R \sim M^{1/3}$. An additional distinction between brown dwarfs and planets is planets are thought only to form within the accretion disk surrounding a newly forming star. Planets, in effect, need a parent star to come into existence, while brown dwarfs can undergo a virgin birth through the direct collapse of a small interstellar gas cloud.[39]

Having a mass of 0.123 $M_\odot$ Proxima Centauri is about 50 % more massive than the brown dwarf limit of $M_{limit} = 0.08\ M_\odot$. So, while Proxima is a low mass stellar object it is nonetheless very much a star, and its variously observed characteristics are summarized in Table 2.3.

[39] Where the population of free-floating Jupiters fits into this scenario has not, as yet, been fully resolved. Although the standard origin scenario for these objects invokes gravitational scattering and ejection after formation within a star's surrounding accretion disk, a recent study by Gösta Gahm (Stockholm University) and co-workers has found evidence to suggest that some may, in fact, be born free through the direct collapse of small "globulettes."

Even though Proxima is already some six billion years old (i.e., the same age as α Cen AB, as described earlier), it has barely started what will be its multi-trillion year stellar journey. For the next many tens of billions of years Proxima's energy output, size and temperature are hardly going to change; it is the quintessential stable star – well, nearly. Though Proxima is in a very stable internal energy generation phase, its outer layers are in erratic turmoil. Proxima is a flare star.

Flare stars were first recognized as a distinct stellar class in the early to mid-1900s. Dutch astronomer Ejnar Hertzsprung serendipitously photographed the very first flare star on the night of January 29, 1924. The unidentified star underwent a sudden and rapid change in brightness for about 1.5 h. Hertzsprung thought that he might have found a new kind of nova. Indeed, it was a nova outburst triggered, he suggested, by the destruction of a small planet in the outer atmosphere of a star. Other stars were soon discovered, however, that showed similar sudden and short-duration outbursts to Hertzsprung's star. Additionally, it was quickly realized that the outbursts were irregular both in their intensity and their duration, and that the time interval between outbursts was entirely random. Not only this, there were just too many repeat outbursts to be the result of planetary in-fall and destruction alone. An internal, rather than an external, mechanism to explain the sudden brightness enhancements was apparently required.

Low mass, red dwarf flare stars are typically classified as being UV Ceti stars – this solar neighbor (just 2.68 pc away – see also Fig. 1.18) being the prototypical star showing irregular flare activity.[40] It is estimated that about 75 % of all red dwarf stars show some form of flare activity, with the outbursts being seen as brightness enhancements across the entire electromagnetic spectrum, from X-rays to radio waves. The flares show a whole range of profile characteristics, but typically there is a rapid rise to maximum brightness followed by a slower decline back to normal. The flares can last from seconds to minutes, and shorter, less energetic flares are more common in occurrence than longer, large energy ones.

[40] First described by Dutch astronomer William Jacob Luyten in 1948, UV Ceti is actually a member of a high proper motion binary system (the flare star component is technically identified as Luyten-726-8A).

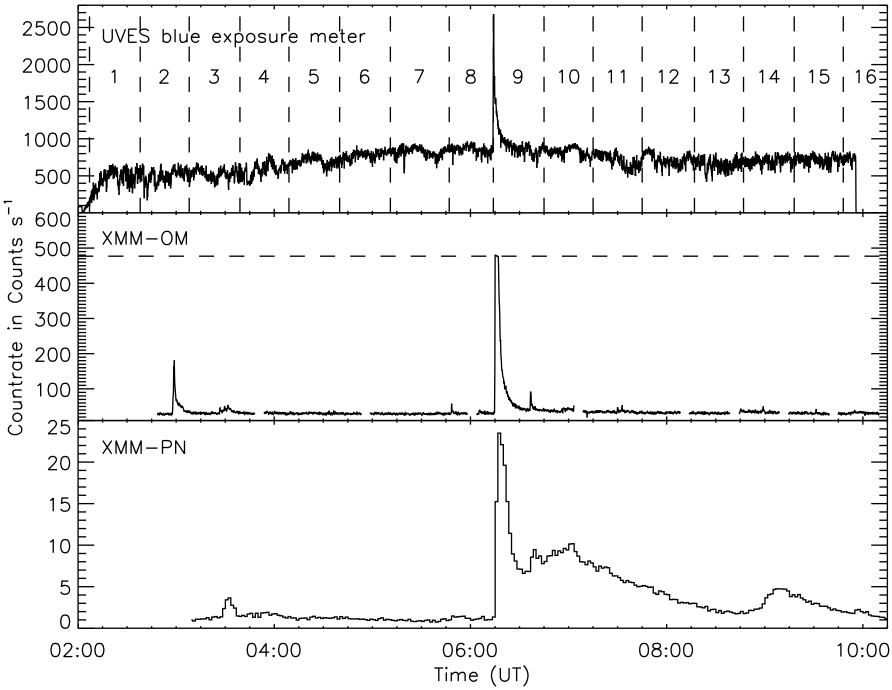

FIG. 2.9 Light curves for Proxima Centauri over a 3.5-h time interval on the night of March 14, 2009. The *top* panel shows optical brightness variations as recorded by the Ultraviolet-Visual Echelle Spectrograph (UVES) attached to the 8.2-m VLT-Kueyen telescope in Chile. The *middle* panel shows the output from the optical monitoring camera of the XMM-Newton spacecraft. The *lower* panel indicates the variation in the X-ray flux as recorded by the XMM-Newton spacecraft. A distinct flare is evident at about 06:15 UT. In the optical part of the spectrum the flare lasts for about 15 min; at X-ray wavelengths the flux is enhanced for nearly 3 h and shows several secondary flare events (Image courtesy of Birgit Fuhrmeister, University of Hamburg. Used with permission)

American astronomer Harlow Shapley, at the time director of Harvard College Observatory, first noticed that Proxima was a flare star in 1951. At that time he commented that, "Dwarf red flare stars may become of considerable importance in considerations of stellar evolution," and in this he was entirely correct. Flares from Proxima have been detected at optical as well as UV and X-ray wavelengths, and Fig. 2.9 shows a number of short duration flares (spikes in the light curves) observed simultaneously from the ground, at the Cerro Paranal Observatory in Chile, and from space with the XMM-Newton X-ray satellite.[41]

Ever since they were first observed the possible mechanisms responsible for producing stellar flares have been a topic of some considerable debate. Although the basic flare mechanism is now understood to be due to the violent release of magnetic field energy, other modulating mechanisms may still be important. These latter processes usually rely upon accretion effects, such as the impact of a comet, asteroid or Kuiper Belt-like object into a star's outer envelope. Indeed, as we shall see later, it is possible that some of Proxima's flare activity is related to its passage through an Oort Cloud structure of cometary nuclei formed around α Cen AB.

Solar flares were first observed on the Sun by Richard Carrington and Richard Hodgson in 1859. From the outset, these localized brightenings were found to be associated with sunspot groups, and accordingly it eventually became clear that they were associated with magnetic field loops. In particular the flares are the result of a process known as magnetic reconnection, in which the magnetic field rapidly rearranges itself, causing thereby a dramatic release of energy. Some of the energy extracted from the magnetic field in a reconnection event heats the surrounding atmospheric plasma, while some additionally goes into accelerating charged particles away from the Sun. In some cases so much energy is released by the Sun's magnetic field that a coronal mass ejection occurs, accelerating massive amounts of material into the greater Solar System.

Such events, if they chance to intercept Earth, result in solar storms and dramatic displays of the aurora. In the case of the Sun, as discussed earlier (Fig. 2.6), the solar magnetic cycle is driven by the αΩ dynamo mechanism. One of the essential components of this magnetic field-generating mechanism is the existence of an inner radiative zone – or more specifically, the tachocline region at the core-envelope boundary. This boundary, located about two-thirds of the way out from the center, is characterized by the presence of a large velocity sheer region. Indeed, it is at this boundary that the rotation changes over from being like that of a solid body to the latitude dependent, differential rotation regime exhibited in

[41] B. Fuhrmeister et al., "Multi-wavelength observations of Proxima Centauri" (*Astronomy and Astrophysics*, **534**, id. A133, 2011).

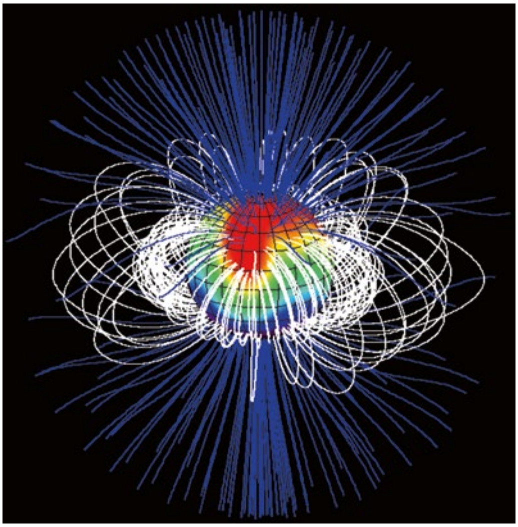

Fig. 2.10 Reconstruction of the magnetic field lines of V374 Pegasi as they extend into space above the star's surface. The topology of the magnetic field is clearly well organized into loops about the equator and polar field lines extending into the surrounding interstellar medium (Image courtesy of M. M. Jardine and J-F Donati. www2.cnrs.fr/en/412.htm. Used with permission)

the convective envelope. It is the characteristics of the tachocline region that determines, in a far from clearly understood manner, the overall properties of the magnetic activity cycle. For Sun-like stars, such as α Cen A and B, there is no specific reason to suppose that the αΩ dynamo mechanism is not at play, and that accordingly it is the mechanism responsible for their observed chromospheric behaviors.

For Proxima, however, we encounter a problem with the αΩ dynamo – the key point being that for Proxima, and indeed all stars less massive than about 0.4 $M_{\odot}$, there is no radiative core. Since such stars are convective throughout their interiors they have no tachocline region within which to anchor a magnetic dynamo, and the question becomes, how can such stars maintain long-lived magnetic fields? For indeed, not only do red dwarf stars have magnetic fields, they also appear to have well-ordered magnetic fields. This latter situation is illustrated by a remarkable study of the M dwarf star V374 Pegasi published in the journal *Science* by Jean-François Donati (Laboratoire d'astrophyhsique de Toulouse et Tarbes) and co-workers in February of 2006 (Fig. 2.10).

Located some 6 pc away V374 Pegasi is about a third the size of the Sun, and detailed modeling of the field line structure suggests that it rotates more like a solid body; this is in direct contrast to the Sun, in which differential rotation dominates in the outer convective zone.

That Proxima, and similar such M-dwarf stars, show magnetic activity is a modern-day mystery and the focus of much detailed research. Indeed, a new mechanism, beyond that of the αΩ dynamo for generating an organized, self-generating magnetic field, is required to explain why Proxima has a magnetic field and undergoes flare activity.

So, what are the current options? Clearly rotation and convective motion are still going to be important, and the answer to our conundrum has to lie within the physics of these phenomena. One measure that is often used to gauge the extent to which convective motion might be dominated by rotation is that of the Rossby number $\mathrm{Ro} = P/t_{convective}$, where P is the rotation period and $t_{convective} \approx R/\langle Vc \rangle$ is the convective turnover time. R is the star's radius and $\langle Vc \rangle$ is the average velocity of the convective motion. It is known that the Rossby number correlates with chromospheric activity – as described, for example, by the S-index related to the strengths of the H and K absorption lines associated with the single ionized calcium atom. As already indicated the αΩ dynamo will not operate when the interior of a star is fully convective, but it turns out another mechanism, called the α^2 dynamo, can operate under such conditions, and indeed it becomes efficient once the Rossby number is smaller than about 10. In the α^2 dynamo, the rising and twisting α-effect is the source of both poloidal and toroidal magnetic components. Again, detailed computer simulations indicate that for fully convective stars, in which the α^2 dynamo is at work, a well ordered surface magnetic field can develop (such as observed for V374 Pegasi – Fig. 2.10) even though the magnetic field in the star's interior varies dramatically on many different size scales.

Does the α^2 dynamo work in Proxima? To order of magnitude the convective turnover time is reasonably well known, and with a characteristic convective velocity of $\langle Vc \rangle \approx 5$ m/s we have $t_{convective} \approx R/\langle Vc \rangle \approx 200$ days – which indicates a relatively rapid mixing throughout its interior. The rotation period P for Proxima is not well known, with the variously published measurements suggesting values anywhere from ~25 to ~85 days. Irrespective of the actual rotation period, however, provided it is actually between the currently published estimates, the Rossby number $\mathrm{Ro} = P/t_{convective}$ will be much smaller than 10, and this suggests that the α^2 dynamo should be in operation. This result clearly bodes well with respect to explaining why and how it is that Proxima shows relatively strong flare activity.

There is another problem, however, that has as yet to be resolved. One of the outcomes from the numerical simulation of magnetic field generation within fully convective stars is that the surface magnetic field should be constant – that is, there is no modulation mechanism to drive a magnetic activity cycle. And yet, there is every appearance that the flare rate from Proxima is not only variable but cyclic. Using data gathered with the fine guidance sensor on the Hubble Space Telescope, Fritz Benedict (University of Texas at Austin) and co-workers have estimated that Proxima shows an activity cycle of about 1,100 days (~3 years). This variation in activity is further reported by Carolina Cincunegui (Instituto de Astronomía y Física del Espacio, Argentina) and co-workers, but they suggest the period of variation is somewhat smaller and more like 1.5 years. The full situation is still unclear, and exactly what is going on with respect to the observed X-ray emission and chromospheric flare activity of Proxima (and other M dwarf stars) is a challenging and open research question.

2.9 Making Planets

The recipe for making a planet is fairly straightforward and may be easily written down. Understanding the subtle alchemy behind the workings of the recipe, however, continues to be a modern-day research challenge. Using the symbolic formula introduced above to describe the basic star formation process, we need only add one more "ingredient" to begin making planets. Our new recipe proceeds according to the mixing of gravity and rotation:

$$Cloud\left(R_{cl}, \rho_{cl}, T_{cl}\right) + gravity + rotation \rightarrow Star\left(R_{*}, \rho_{*}, T_{nuc}\right) + accretion\,disk$$

By introducing rotation the way in which the interstellar cloud collapses changes from that of a large spherical cloud collapsing radially into a small spherical star to that of a large spherical cloud collapsing into a pancake-like, rotating disk structure. To perhaps overly push our cooking analogy, it is within the pancake that the planets eventually coagulate. The material in the collapsing gas cloud is now envisioned to fall onto the accretion disk and then gradually spiral inward to eventually be accreted by the centrally growing proto-star. The first accretion disk structure to be imaged at optical wavelengths was that associated with the star β Pictoris (Fig. 2.11), and in this case we see the disk edge-on.

Having produced an accretion disk around a newly forming star, a sub-recipe for planet formation must now be introduced. This new mixing procedure operates in such a way that matter clumps begin to form within in the disk – symbolically we have

$$\begin{gathered}\textit{Accretion disk} \rightarrow \textit{planetesimals} \rightarrow \textit{planets} \\ + \textit{dwarf planets} + \textit{comets} + \textit{asteroids}\end{gathered}$$

The key idea of the planet-forming sub-recipe is to turn the gas and dust of the collapsing gas cloud into solid structures of gradually increasing size. Essentially, from the chemistry of the gas and dust grain interactions, molecular structures begin to form. From the molecules new dust-sized grains are produced. From the dust-sized grains, sand grain-sized structures form, and from the sand grain-sized structures, pebble-sized structures accumulate – and so on.

To build a planet, our cooking mantra is, start small and build ever bigger. Not only does solid matter begin to form in the accretion disk, but this recipe in essence cooks itself. Close to the center of the disk, where the proto-star is located, the temperature is high and accordingly only high melting point matter, such as iron and corundum, can exist in the solid phase. Further out the temperature in the disk decreases and so silicates and carbon compounds can begin to appear. Deeper still into the disk the temperature eventually drops to the level at which water-ice can form, and then even further outwards CH_4 and CO ices appear, and so on. The outward decrease in disc temperature drives the chemistry and sorts the basic building materials into specific compositional domains. The important dividing line is that where water-ice can form. The dividing properties either side of the ice line are

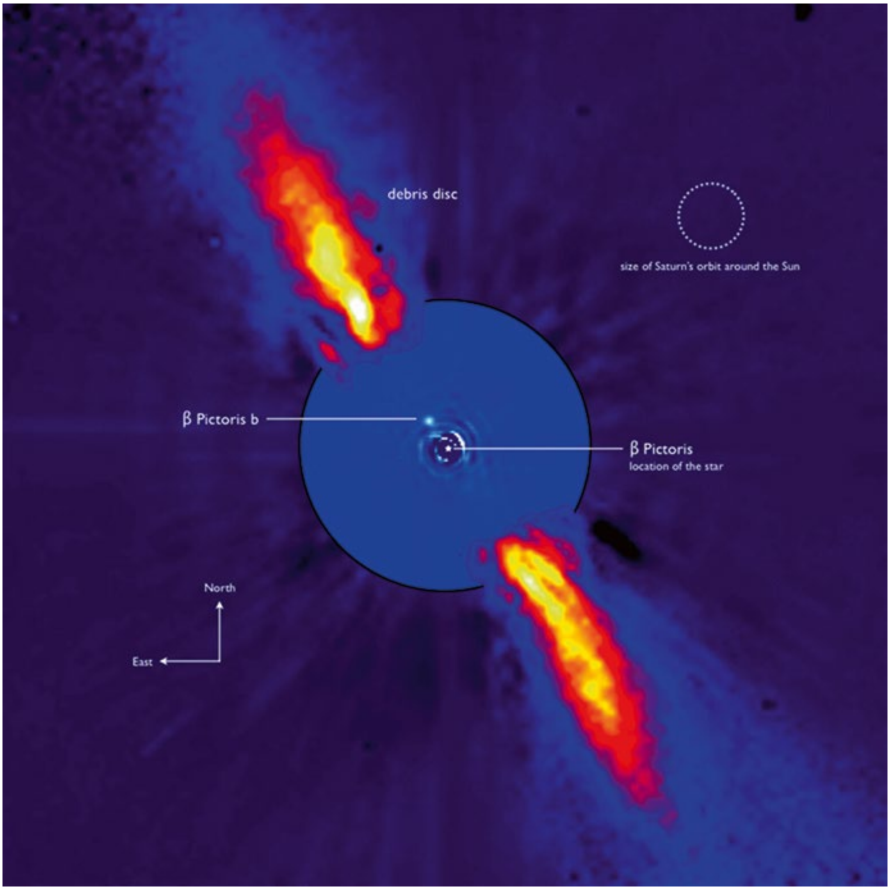

FIG. 2.11 The edge-on disk associated with the star β Pictoris and the planet β Pic b. The star itself has been obscured by an occultation disk, so that the faint light scattered within the disk can be imaged. The disk is about 100 au across, and at least one Jupiter-mass planet has formed within it. The circle to the upper right indicates the scale according to the orbit of Saturn (19 au across) in our Solar System (Image courtesy of HST/NASA)

distinguished in our Solar System according to the characteristics of the terrestrial and Jovian planets. Inside of the ice line, which for Sun-like stars is located some 3 au into the disk, terrestrial planets, made predominantly of silicates and iron, form. Beyond the ice line, the massive Jupiter-like planets grow.

Although the temperature and ice line determine the basic compositional makeup of the disk, the planets themselves are built-up by random collisions – a literal hit and stick process. The first kilometer-sized structures to appear in the disk are called planetesimals, and it is through the collision and accretion of these objects that planets are eventually produced. In the Solar System the leftover planetesimals, not actually accreted into a planet, are observed as cometary nuclei and asteroids.

The processes of collision and accretion, collision and break apart continues within the disk until a few gravitationally dominant structures appear. These will ultimately be the planets. Having formed, however, the process of orbital sorting is far from over, and the observation of exoplanets clearly informs us that migration, especially of massive Jovian planets, is common. Indeed, by migrating inwards, from beyond the ice line where they were formed, the hot Jupiter planets are produced. As part of this migration inward, planet-on-planet gravitational interactions and scattering will additionally take place, and this will result in the ejection and possibly orbit flipping of interior planets (i.e., the terrestrial planets that formed interior to the ice line). The inward migration and gravitational scattering process is also the most likely mechanism for producing cold Jupiters. These are represented by the Jovian exoplanets located at many tens to even hundreds of au from their parent stars.

The formation of planets around stars with binary systems is not greatly different to that for single stars. The only caveat relates to how close the two stars in the system approach one another. Again, it is the mutual gravity and tidal forces between the two stars and their individual disks that will determine the outcome of planet formation. Detailed numerical simulations of the accretion growth process show that a close companion can either enhance the planet formation process or it can totally destroy it. Several research groups have specifically studied the formation of planets in α Cen AB, and the general consensus is that there is no specific reason to suppose that planets cannot form there. The real questions are: where have the planets formed, and how many planets are there?

Although some of the details will be discussed below shortly, it appears unlikely from both the observations and the planet-formation modeling studies that either α Cen A or B has any associated large Jupiter-mass planets. Part of the reasoning behind this conclusion is that the ice line for these stars will be located at about 2–3 au, and this is very close to the limit set for stable orbits (discussed further below). Additionally, it has also been suggested that disk-disk gravitational interactions in the newly forming α Cen AB system might act to suppress giant planet formation and favor the production of close-in terrestrial planets. There is no present consensus on the exact details, indicating of course that we could easily be surprised by what is eventually found, but the numerical simulations suggest that planets in the mass range from sub-Earth to perhaps 1–2 times the mass of Earth may exist about both α Cen A and B with orbital radii between about 0.5 and 2.5 au. Theoretically it would appear that we are good to go. There is no specific physical reason to suppose that planets cannot exist within the α Cen AB binary, and the challenge now is to see if any such objects can be found observationally.

2.10 New Planets and Exoworlds

In a strange way the response of both the media and the public to the discovery of the first planet in the α Centauri system was rather muted. Certainly the discovery and initial announcement made the headlines, but within just a few days the whole show was over and seemingly done with. We have indeed become a jaded society, overwhelmed and inundated by tabloid gossip and trivial pursuits. Perhaps the lackluster response was a Northern Hemisphere effect. After all, α Centauri is not visible from Russia, most of China, Asia, Europe and North America, countries where the greater part of the world's overburdened population lives. Indeed, an informal poll reported in the *Huffington Post* for October 17, 2012 (one day after the planet's discovery was announced) found that only 54 % of the people interviewed in San Francisco had heard of α Centauri, and less than 1 % of those asked knew that it was the nearest star system. Perhaps the stilted public response was because some 850 other exoplanets had been discovered before α Cen Bb was identified – just another distant world in a long (and continuously growing) list of un-seeable external worlds, another planet whose features can, at the present time, only be imagined rather than experienced through direct imaging.

Well, in spite of this subdued response, the discovery of α Cen Bb was a scientific triumph – a triumph of observational technique, hard work and of detailed system analysis. Indeed, the discovery of α Cen Bb was the result of some 20 years' worth of human perseverance, intellectual tenacity and technological development.

There is no clear beginning to the story of planet and exoplanet discovery. Certainly, philosophers have been speculating upon and astronomers actually looking for additional planets within our own Solar System, and around other stars, for a very long time. Perhaps, stretching the point at issue a little, the Greek philosopher Philolaus (c. 470–385 B.C.) might be credited with creating the first new planet within the universe. As a member of the Pythagorean School, Philolaus held the number 10 in great esteem. It was the tetraktys, the holy or mystic number. In applying this numerical reasoning to the universe, however, Philolaus realized that there was a problem. He knew there were eight 'planetary zones' – which corresponded to the regions of Mercury, Venus, the Sun, the Moon,[42] Earth, Mars, Jupiter and Saturn. And he knew there was a zone for the stars (encompassing the celestial sphere), making in total a nine region dichotomy of the heavens. However this division, Philolaus argued, did not resonate with the importance of the tetraktys, and therefore he speculated that another planet, the counter Earth, must exist.

To satisfy the ideal of Pythagorean numerical harmony, Philolaus reasoned a whole new world into existence. With history repeating itself, the same manner of philosophical thinking once again appeared, some 2,000 years after Philolaus, to bring into existence the planet Neptune (discovered in 1846). In this latter case, however, a much greater power of numerical calculus and logic was employed to argue that a planet must exist – specifically it was required to explain the observed residuals in the motion of Uranus.[43] As always, however, nature loves to toy with human hubris, and the same philosophy that resulted in the successful detection of planet Neptune failed in the case of planet

[42] Both the Moon and the Sun, recall, were viewed as planets in the classical era.

[43] It was by working through the prohibitively complicated mathematics describing the mutual gravitational interaction that would result between Uranus and a hypothetical perturbing planet that led Urbain Joseph Le Verrier and John Couch Adams to successfully predict the properties of the perturbing planet's orbit.

Vulcan – an imagined world postulated to explain the observed motion of planet Mercury.[44]

The eventual discovery of Uranus was inevitable; but as luck would have it the person who saw it as something other than a star was William Herschel. Other observers had recorded Uranus's position on star charts long before Herschel made his results known, but they failed to recognize it as a new world. Indeed, Herschel first thought that he had discovered a new comet, and it was only later he realized he had actually discovered a new Jovian-type planet.

Herschel may well have been fortunate in his planetary discovery of 1781, but he greatly enhanced his chances of success through the very act of pursuing a thorough and systematic study of the heavens. When Herschel began his star gauges it was really just a matter of time before Uranus would swim into his view. Furthermore, there was every reason to believe that additional planets might well exist beyond Saturn (located 9.5 au from the Sun) since Edmund Halley had demonstrated that at least one periodic comet, Halley's Comet, moved as far as 35 au away from the Sun during its 75-year-long orbital sojourn. Indeed, when Halley made his famous prediction in 1707, later confirmed in 1758, his comet (when located at aphelion) more than trebled the size of the then known Solar System.

With the discovery of planet Uranus something extraordinary happened. A new, apparent harmony emerged for the description of planetary orbits. The result would probably have pleased Philolaus and his fellow Pythagoreans, but it continues to trouble astronomers to this very day. This controversial new harmony relates to the so-called Titius-Bode law that was written down and willfully copied by various authors during the mid- to latter part of the eighteenth century. It is a simple mathematical rule that says

[44] When Le Verrier tried to explain the anomalous motion of planet Mercury he invoked the same idea that had resulted in the successful finding of planet Neptune. To this end a new inter-Mercurian planet, given the name Vulcan, was postulated. Planet Vulcan, however, was later written out of existence by the equations of general relativity developed by Albert Einstein in 1916. Indeed, Einstein showed that the observed anomalies of Mercury's orbit were entirely due to the Sun's curvature of spacetime. The story of Vulcan is further described in the author's book, *The Pendulum Paradigm – Variations on a Theme and the Measure of Heaven and Earth* (Brown Walker Press, Florida. 2014).

that the orbital radius a of each successive planet within the Solar System is given by the relationship: $a(\mathrm{au}) = 0.4 + 0.3 \times 2^m$, where $m = -\infty$, 0, 1, 2, 3, … and so on. The sequence for m is certainly odd, starting as it does with a negative infinity that suddenly jumps to a value of zero and thereafter increases by a factor of one in each successive step, but for all of this, it does provide a remarkably accurate expression for the observed orbital radii of the planets in the Solar System – up to a point, that is.

For the planets Mercury ($m = -\infty$) through to Saturn ($m = 5$), the comparison between the formula result and the observations is shockingly accurate. Further pushing the boundaries of credulity the law, for $m = 6$, also describes the size of the orbital radius for planet Uranus. Seemingly, this law has great predictive powers, and astronomers soon argued that the apparent gap in the planetary system at $m = 3$, corresponding to $a(\mathrm{au}) = 2.8$, must contain some undiscovered object.

Sure enough, on January 1, 1801, Giuseppe Piazzi swept up the first of the asteroids. Ceres, as this new object was to be named, is the largest object in the main Asteroid Belt between Mars and Jupiter, and it has an observed orbital radius of 2.7654 au. In many ways the results were, or more to the point are, entirely unreasonable. Why should such a simple mathematical expression as encompassed within the Titius-Bode law provide such an accurate description of planetary orbits? As we saw earlier, the formation of planets is a random, dynamic, and chaotic collision- and accretion-dominated process, and there is no underlying reason to suppose that such complex stochastic processes can be explained by a mathematical rule based on one simple variable and three simple constants. And yet, this appears to be what nature has given us – up to a point.

In spite of its remarkable accuracy in describing the orbital radii from Mercury out to Uranus, the Titius-Bode law fails horribly with respect to its predictions for the orbital radii of Neptune ($m = 7$) and Pluto ($m = 8$). Indeed, for Pluto the formula is in error by more than 100 %. Clearly, there is more to the construction of the Solar System than the dictates of the Titius-Bode law. University of Toronto researchers Wayne Hayes and Scott Tremaine demonstrated this latter point in a wonderful 1998 publication in which they showed that Titius-Bode-like laws could be constructed for almost any random configuration of stable planetary orbits. Hayes and Tremaine also found that the best fit Titius-Bode law for the entire Solar System is: $a(\text{au}) = 0.450 + 0.132 \times (2.032)^{n}$, $n = 0, 1, 2, 3, \ldots, 8$. This new law removes the strange (if not highly suspect) $-\infty$ first power for Mercury, but it now no longer shows any satisfying numerical elegance in its form. The new constants jar the eye.

Well, of course, beauty isn't everything, but it would appear that at best Titius-Bode-like laws are nothing more than useful numerical coincidences that come about due to the fact that if a planetary system is going to remain stable over long intervals of time, 4.56 billion years in the case of the Solar System, then planetary spacings had better satisfy some basic physical principles. Indeed a kind of Goldilocks rule is likely to apply, with the planets not being too close together, else gravitational perturbations will ruin the orbital stability, and yet not too far apart either, since it would appear that if the basic building blocks are in place then nature will build a planet if it can – in other words large gaps in planetary systems are unlikely.[45] Additionally, the planets within the Solar System appear to favor orbits in which the orbital periods of each successive pair satisfies a near mean-motion resonance. In this manner, Mercury orbits the Sun (approximately) five times for every two orbits of Venus (this is a 5:2 mean motion resonance[46]); Venus and Earth exhibit a 13:8 mean motion resonance. Likewise,

[45] On purely geometrical grounds, ignoring gravitational interactions, one can argue that in order to avoid collisions any pair of planets must be arranged so that the aphelion distance of the innermost planet must not be further away from the Sun than the perihelion distance of the outermost planet. This condition can be cast in terms of the orbital periods of the two planets such that Pout/Pin > 1, where the out and in subscripts indicate the inner and outermost planets respectively. Using Kepler's third law this result can be case in terms of the semi-major axis of each planet's orbit so that, $P_{out}/P_{in} = (a_{out}/a_{in})3/2$. Excluding the pairing between Jupiter and Mars, the typical value for P_{out}/P_{in} in the solar system is observed to be about 2. Using this result, we obtain for the non-overlapping orbits condition that $a_{out}/a_{in} \sim 1.6$. We can now, in fact, use this condition to 'predict' the existence of the asteroid belt between Mars and Jupiter. For Mars, $a_{in} = 1.5$ au, so in keeping with the other planetary pairings within the solar system, we might predict the presence of a planet at $a_{out} = 1.5 \times 1.6 = 2.4$ au, and this is indeed just about where the asteroid belt begins – it is also comparable to the orbital radius of the dwarf planet Ceres (a = 2.77 au). Yet another 'planet' could be squeezed-in before we reach Jupiter at aout = 2.4 × 1.6 = 3.84 au. A planet interior to Mercury might also be predicted upon the non-overlapping orbits condition, and in this case $a_{in} = 0.246$ au. Of historical interest the orbital semi-major axis of the latter 'planet' corresponds to that predicted by Le Verrier for Vulcan (see Note 44).

[46] Saturn and Jupiter also exhibit a near 5:2 mean motion resonance, while Neptune and Pluto exhibit a strict 3:2 mean motion resonance.

since orbital stability requires the avoidance of very close approaches between successive pairs of planets so the development of near circular orbits with regular spacings is favored, with the spacing being modified according to the various masses of adjacent planets.

We now see the Titius-Bode law not as some profound physical statement but as an underlying shadow framework for describing planetary spacings within a stable planetary system. There is indeed every reason to suppose that all multiple exoplanetary systems that are stable over long intervals of term will obey some form of a Titius-Bode-like law; strangely, however, its universality lies within the fact that it is simply an ordered sequence of numbers and not a fundamental physical law describing the formation of planetary systems. Remarkably, therefore, it does appear that the Titius-Bode law has the power to predict the existence of planets, but its power is analogous to a trick performed by a well-trained magician rather than a result derived by a reasoned astrophysicist.

The next obvious question becomes, therefore, "Do exoplanetary systems obey Titius-Bode-like laws and can we use them to find otherwise unobserved planets?" The answer to this question is, as we shall see below, yes; but before we can further discuss the issues some details on how exoplanets are detected should be put in place.

2.11 Planets Beyond

The idea that planets might orbit other stars is far from being a new one. Indeed, it is an ancient idea. The atomistic philosophy of Epicurus (341–270 B.C.) supposed, in fact, that there were an infinite number of stars and planets, and specifically an infinite number of Earths. Much later in history, the scripturally misguided polymath Giordano Bruno (1548–1600) reasoned that not only did it make philosophical sense that the universe was infinite in extent, but that every star in the universe should also have an attendant planetary system. René Descartes (1596–1650) further argued, half-a-century after Bruno's condemnation and execution, that the universe was filled with circular eddies in which matter could accumulate. Furthermore, at the center of each vortex, Descartes reasoned, a star would eventually form, and each newly birthed star would have an associated set of sibling planets.

Three-hundred and fifty years further on from Descartes, we now know that the universe isn't infinite in extent, although it is certainly large and relatively old (being brought into existence some 13.8 billion years ago), and it certainly contains many stars. There are something like 10^{23} (100,000 billion billion) stars in the observable universe. Remarkably, however, although the physics behind Descartes vortices has been entirely discredited, and while Bruno had no supporting evidence for his other worlds idea, they were both right in asserting that virtually all low mass and Sun-like stars will have attendant planets. Indeed, modern astronomers suggest that finding a Sun-like star without attendant planets is the oddity, rather than the other way around.

Titius-Bode law guidance aside, all the new, that is non-classical, planets within the Solar System have been found telescopically. In this manner the new discoveries timeline has progressed mostly as a result of technological advancements – bigger telescopes and more sensitive detectors enabling astronomers to find smaller, fainter and more distant worlds. There is a limit to this process, however, and after a while the basic point-and-look approach will no longer yield new discoveries. In order to find exoplanets it turns out that a kind of peripheral vision needs to be applied. Astronomers don't actually look for exoplanets directly, but rather they look for the effect of such planets upon their parent stars – either via astrometric measurements, the Doppler effect or through repeated brightness transients.

We briefly described the astrometric method earlier. Here the presence of a planet is revealed by mapping out the path of the parent star across the sky. Such observations are non-trivial, and highly time consuming. In essence, however, with the astrometric technique one is trying to separate out a sum of motions: the star's proper motion, the star's parallax and the star's reflex motion due to its planetary companion. Ignoring (or more precisely, correcting for) the six monthly parallax variation in position, the reflex motion combines with that of the star's proper motion to produce, over many years, a serpentine path across the sky (recall Fig. 1.20 for Sirius). If there was no planetary companion, and hence no

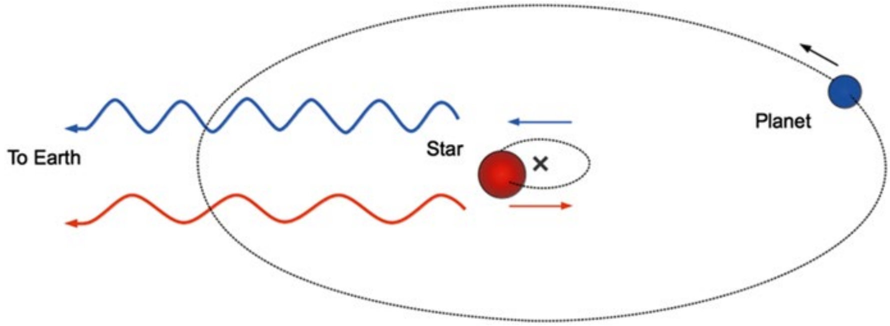

Fig. 2.12 The Doppler method of planetary detection. The unseen planet induces a reflex motion of the star around the system's barycenter (marked *X*), and this motion can be quantified by monitoring the variations in the star's radial velocity, as measured through its photospheric absorption lines, over time. It is the periodic blueshift (motion towards) followed by redshift (motion away) variations in the radial velocity measurements of the star that betray the gravitational presence of the planet (Image courtesy of Wikimedia commons. Radial_Velocity_Exoplanet.png)

reflex motion, then the proper motion path would be a straight line across the sky. The serpentine motion comes about because the star and planet move around a common center of mass (or barycenter) that is displaced away from the center of the star, and because the proper motion actually tracks the straight line motion of the barycenter through space. The star's radius of motion about the center of mass is given by $a_S = a_P(M_{planet}/M_{star})$, where a_P is the planet's radius of motion. The more massive the planet and the larger a_P, so the larger is the reflex displacement of the star. Astrometry, therefore, is all about measuring the displacement a_S. As discussed earlier, the discovery of planets via astrometric techniques has historically proved ineffective, but this is primarily because it comes into its own when looking for large mass (that is brown and/or red dwarf) companions, when a_S is relatively large.

The Doppler method (for details see Appendix 2 of this book) of exoplanet detection also relies upon the measurement of a reflex motion, but in contrast to the astrometric method it operates best when a_S is small (see Fig. 2.12). The reflex motion again comes about because the system's center of motion is displaced away from the center of the parent star. It is a remarkable celestial dance that takes place, with the existence of invisible worlds being betrayed through the barely measurable do-si-do that is stepped out by the apparently single parent star. By directly measuring, over many days, months, years and even decades, the velocity with which the parent star moves about the system's barycenter it is possible to deduce the masses and orbital periods of its associated planets. Indeed, in the ideal case, where the planet has a circular orbit and when we are fortunate enough to see the orbit edge-on (this maximizes the Doppler shift signal), then the system of equations to solve for are:

$$\left.\begin{aligned} V_S &= \frac{2\pi\ a_S}{P} \\ M_{\text{star}} &= \frac{a^3}{P^2} \\ M_{star} a_S &= M_{planet} a_P \end{aligned}\right\} \tag{2.2}$$

where V_S is determined via the Doppler shift variations, P is the orbital period (again measured from the radial velocity variations) and $a = a_S + a_P$. In the second relationship shown in Eq. 2.2, which is actually Kepler's third law of planetary motion, it is assumed that the mass of the star is very much greater than the mass of the planet. To fully determine the orbital radius a_P and mass of the planet M_{planet}, an appropriate value for M_{star} must be specified. By algebraically combining the equations listed in Eq. 2.2 it is possible to show that

$$V_S^2 = 4\pi^2 \left(\frac{M_{planet}^2}{M_{star}} \right) \left(\frac{1}{a_P} \right) \tag{2.3}$$

where the typical case in which $a_S \ll a_P$ is assumed.

From Eq. 2.3 we now discover an important distinction between the astrometric and Doppler techniques for finding planets. Although the astrometric technique works best for companions with large orbital radii (large a_P values), the Doppler technique works best, that is produces a larger and more easily measured velocity signal, when the planet's orbital radius a_P is small – that is, close in towards the parent star. Conversely, Eq. 2.3 indicates that the smaller the planet mass and the greater the distance it is from the parent star, so the smaller is the velocity variation signal.

The idea that planets might be detected in orbit about distant stars through the Doppler monitoring of reflex motions was first discussed in the 1950s, but it was not until the early 1990s that the observational techniques were in place to make such studies feasible. The technical challenge that planet detection presented was that the velocities to be measured were in the range of meters per second, rather than the kilometers per second that astronomical spectroscopes had otherwise worked to. In the case of the Sun, for example, the reflex velocity induced by Jupiter amounts to a 13 m/s variation (Fig. 2.13). The radial velocity induced by Earth is about 0.1 m/s. Not only is the velocity small, but for an extraterrestrial civilization monitoring the Sun, they would have to take measurements over at least 12 years, the orbital period of Jupiter, before it was clear that a planet had actually been detected. Exoplanet hunting, if our Solar System is taken as typical, is not for the hasty or faint of heart. Luckily for astronomers, however, it now appears that our Solar System is not typical, and that the existence of planets around other stars can, on occasion, be the subject of just a few weeks worth of (hard and exacting) work.

The discovery of the very first exoplanet was announced in the august pages of the journal *Nature* for November 23, 1995. The authors of this historical work were Michel Mayor and Didier Queloz, astronomers working at the Geneva Observatory in Switzerland. It was a remarkable piece of work, with a remarkable and entirely unexpected outcome. The two observers had embarked upon a spectroscopic survey of Sun-like stars in early 1994, and after some 18 months of data collection had identified a number of candidate stars that showed the promise of having attendant planets. The system that they specifically chose to concentrate upon, however, was 51 Pegasi, a Sun-like star located some 15.4 pc from the Solar System.

Mayor and Queloz explain in their research paper that the first observations of 51 Peg were obtained in September of 1994, and that by January 1995 the first indications of a short-period planetary companion were evident – a result that was later confirmed during two dedicated observational campaigns in July and September of 1995. The radial velocity variations of 51 Pegasi were undoubtedly periodic, alternately showing redshifts and blueshifts of 60 m/s (see Fig. 2.14). A new world, 51 Peg b, had been

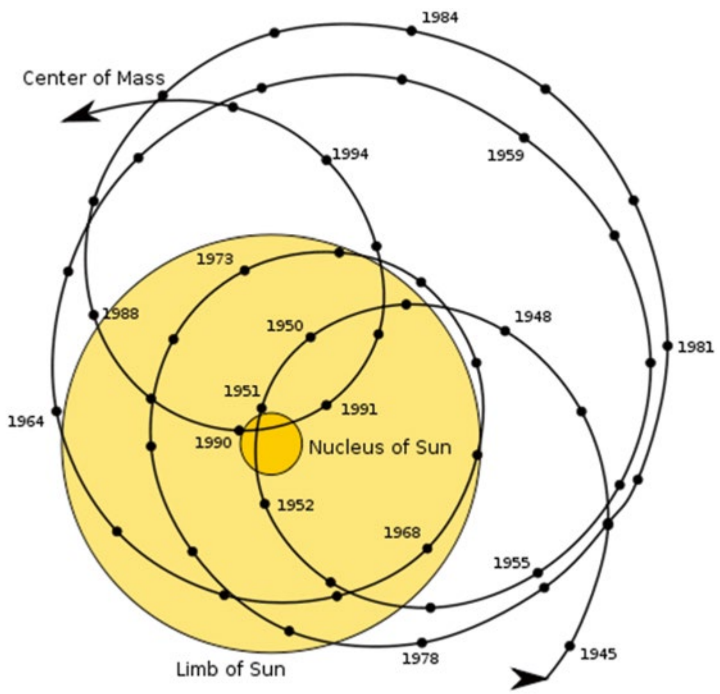

Fig. 2.13 The reflex motion of the Solar System's barycenter due to motion of the planets around the Sun (Image courtesy of Wikimedia Commons. Solar_system_barycenter.svg)

discovered, and the radial velocity data indicated a planet having a mass about half that of Jupiter moving on a close-in orbit with respect to its parent star.

Incredibly, the new planet had an orbital period of just 4.23 days and moved along a near circular orbit with a radius of just 0.0527 au. This result was unprecedented, and a good deal of initial doubt and pessimism had to be overcome before all astronomers agreed that a new planet had, in fact, been detected. The problem, as described earlier, was that no theory in the mid-1990s predicted that gas-giant planets might be found any closer than about 3 au from a Sun-like star. Having an orbital radius nearly 100 times smaller than the expected lower limit at which Jovian planets should form clearly required further investigation, but Mayor and Queloz confidently asserted that the problem of 51 Peg b lay with the theory and not with the observations – and they were, of course, entirely right.

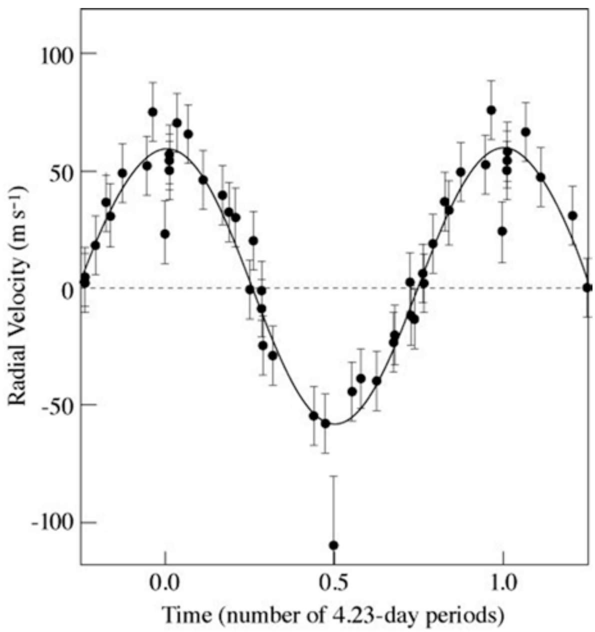

FIG. 2.14 The regular radial velocity variations of the star 51 Pegasus, indicating the presence of an attendant planet – 51 Peg b. The observed 54.9 m/s maximum radial velocity and the 4.23 day period indicate that 51 Peg b has a mass of 0.45 $M_{Jupiter}$ and an orbital radius of 0.0527 au (Diagram courtesy of NASA's Cosmos andTufts University)

Numerous research groups have developed extremely sensitive techniques for measuring exoplanet Dopper shifts, but the state-of-the-art system at the present time is HARPS – High-Accuracy Radial Velocity Planetary Searcher). Developed by the European Southern Observatory (ESO) consortium, with Michel Mayor as principle investigator, HARPS saw first light in 2003 and is attached to the 3.6-m telescope at La Silla Observatory in Chile. The HARPS system (Fig. 2.15) is all about stability and precision. The central component is a ruled grating that splits the incoming starlight into a very high resolution spectrum. The star spectrum is simultaneously compared against a thorium-argon calibration spectra, which not only allows for a very precise evaluation of the stellar absorption line wavelengths (the critical part of the radial velocity measure), but it also allows for extremely precise instrumental drift corrections.

FIG. 2.15 The HARPS spectrograph, shown here with its vacuum chamber casing open. The heart of the spectrograph is the rectangular echelle diffraction grating (seen slightly *above* image center) (Image courtesy of ESO)

Indeed, to help improve instrument stability not only from day to day but from year to year, the whole instrument is housed within a large vacuum vessel in a temperature-controlled environment. Such attention to detail has enabled HARPS to provide long-term radial velocity measurements to an accuracy of 1 m per second, and since operations began it has assisted in the discovery of more than 150 exoplanets. A second instrument, HARPS-N (the N standing for Northern Hemisphere) has recently been commissioned and housed upon the 3.58-m Telescopio Nazionale Galileo Telescope on La Palma; this instrument saw first light in 2012. The HARPS-N instrument has been highly successful in helping to characterize a number of the transiting exoplanets discovered by the Kepler spacecraft (see later).

In the 15 years since the discovery of 51 Peg b, 1,791 additional exoplanets have been discovered around some 1,111 stars (as of May 27, 2014). Planets, indeed, appear to be almost everywhere; they orbit single stars, they orbit binary stars, and they roam freely through space.

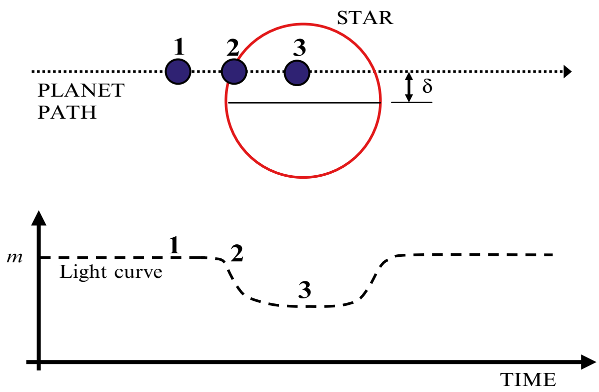

FIG. 2.16 The transit method of planet detection. The light curve, brightness versus time, diagram, for a star hosting a planet will undergo periodic dimming (positions 2 and 3) at intervals corresponding to the orbital period of the planet. Outside of the transit times (position 1) the star's brightness remains constant. The latitude of transit is given by the angle δ, with a perfect central transit corresponding to δ = 0

Although the first exoplanets to be discovered were found through the Doppler technique, additional detection methods exist. Some discoveries have been made by direct imaging techniques, using a small, pinhead-sized occultation disk to block out the light from the parent star to reveal the faint reflected light of the planet (recall Fig. 2.11). Other new worlds have been discovered through gravitational lensing, where the planet induces a distinctive variation in the brightness of a star (as seen from Earth). Yet more, indeed, many more planets have been discovered by the transit method, whereby a planet moving in front of its parent star (in the observer's line of sight) causes distinct and periodic decreases in the stars brightness (Fig. 2.16). This method has produced dramatic results in recent years due to the Convection, Rotation and Transits (CoRoT) and Kepler spacecraft[47] missions conducted by the Centre National d'études Spatiales and NASA, respectively.

[47] Originally developed as the FRESIP (FRequency of Earth-Sized Inner Planets) mission the spacecraft was eventually named Kepler after Johannes Kepler (1571–1630), who not only discovered the basic laws of planetary motion but also pioneered the theory behind the design of modern-day optical telescopes.

If the planet within a transiting system has an orbital period P, a radius R_P and orbital radius a, then the transit time T to cross a star of radius R_S is

$$T = \frac{P}{\pi}\left(\frac{R_S \cos\delta + R_P}{a}\right) \tag{2.4}$$

For an alien observer monitoring the Sun when the transit of latitude is $\delta = 0$, the transit time will be of order 13 h for Earth, but just 5 h for Jupiter. These results bring out one of the advantages of the transit detection method. Although it is true that Jupiter is 11 times larger than Earth, its much greater distance from the Sun results in a much shorter transit time (by a factor of 2.6). For our transit monitoring alien observer, therefore, it is more likely that they will find Earth, which undergoes a 13-h transit once every year, than Jupiter, which undergoes a 5-h transit once ever 11.86 years. In general, the probability of observing a transit for randomly orientated systems is $P_{transit} = (R_S + R_P)/a$, when the longitude of transit is $\delta = 0$. In general, therefore, the probability that some alien observer somewhere within the galaxy might see Earth in transit across the Sun is $P_{transit} \approx 0.47$ %. The probability that Jupiter might be detected is nearly 5 times smaller, being $P_{transit} \approx 0.1$ %. Indeed, Venus has the highest probability of detection, by a random galactic observer, of all the planets within the Solar System, with $P_{transit} \approx 0.65$ %.

If we take the brightness (that is, measured flux f) of a star to be directly related to its cross-section surface area, then the flux ratio outside f_{out} and during a planet transit, f_{in} can be expressed as

$$\left(\frac{f_{out}}{f_{in}}\right) = \frac{R_S^2}{\left(R_S^2 - R_P^2\right)} \tag{2.5}$$

where R_S and R_P are the radii of the star and planet, respectively. Casting this in terms of a magnitude variation Δm (see Appendix 1 in this book), we have

$$\Delta m = m_{in} - m_{out} = -2.5\log\left[1 - \left(\frac{R_P}{\mathrm{R}_S}\right)^2\right] \tag{2.6}$$

With respect to transit detection we see from equation (2.6), as would be expected, the larger the planet is compared to its parent star, the larger will the magnitude variation during a transit be (for a given orbital configuration). In the Solar System Jupiter is about a tenth the size of the Sun, and accordingly for a distant observer recording a transit $\Delta m = -0.01$; for the Earth, which is about a 1/100th the size of the Sun, $\Delta m = -0.0001$.

Although such flux (magnitude) variations are small, they are well within the domain of measurements with present-day technology, and this has allowed for the discovery of literally hundreds of new, small, Earth-sized planets. These planets, many hundreds of times less massive than Jupiter, are invisible to those surveys employing the Doppler technique, since their resultant reflex effect upon the parent star is too small to measure with current techniques.

In spite of a statistics-based failed prediction that Earth Mark II, literally an Earth-mass planet located 1 au away from a Sun-like star, would be discovered in May of 2011, it is no doubt just a matter of time before numerous Earth-mass planets situated 1 au from their parent Sun-like stars are discovered. This discovery, of course, will open up all manner of exciting opportunities to investigate the development of planetary atmospheres and possibly the evolution of life elsewhere in the galaxy.

In terms of possibly detecting planetary transits within the α Cen AB binary, the transit probabilities for us will be similar to those for an alien observer detecting Earth in orbit around the Sun. Formally, using Table 2.2 as our guide, the probabilities for detecting an Earth-sized planet having an orbital radius of 1 au are 0.2 % for α Cen A and 0.4 % for α Cen B. For Proxima the probability that an Earth-sized planet at 1 au will show transits is 0.07 %; an Earth-sized planet located in Proxima's habitability zone (to be discussed later below) with $a = 0.02$ au has a relatively high chance of showing transits, with $P_{transit} \approx 3.6$ %. The probability that α Cen Bb (described in more detail below) might show transits is not unreasonably low, at about 10 %.

Earth Mark II, as of this writing, still awaits discovery, but multiple planetary systems have already been found. The star υ Andromedae was the first such system to be discovered, and it sports four Jupiter-mass planets with orbital radii of 0.06, 0.83, 2.53 and 5.25 au. The star HD 69830 has three Neptune-mass planets. The star 55 Cancri has five planets (and an outer Kuiper Belt dust disc); and the star Kepler-11 has 6 Earth-mass planets in attendance – with orbits all squeezed into a region having an outer radius of 0.5 au. Compared to our Solar System five of the Kepler-11 planets have orbits smaller than that of Mercury. The range and variety of planetary systems is growing all the time, and the structure of our Solar System is beginning to look more and more routine, rather than exceptional, and this brings us back to consider, one last time, the possible usefulness of the Titius-Bode law.

As suggested earlier the power of the Titius-Bode law lies not in the fact that it explains any fundamental physical process but rather that stable planetary systems must satisfy certain conditions with respect to the orbits, spacing and resonances that exist between its members. A modern-day equivalent statement of the Titius-Bode law has been articulated by Rory Barnes and Richard Greenberg, both researchers at the University of Arizona. The Barnes and Greenberg statement addresses the dynamical nature of planet formation and planetary system stability, and argues that planetary systems tend to form in such a way that they are dynamically packed. This packed planetary system (PPS) hypothesis[48] essentially argues that if a planet *can* form at some specific location within the circumstellar disk about a newly forming star, then it *will* form.

Figure 2.17 shows the planetary spacing sequence for the star HD 10180, a Sun-like star located 39 pc away. For this particular

[48] This concept is incorporated into what has become known as the packed planetary system (PPS) hypothesis. This idea was first discussed in the research paper by R. Barnes and T. Quinn, "The (in)stability of Planetary Systems" (*Astrophysical Journal*, **611**, 494, 2004). Subsequent studies appear to have confirmed its veracity. It would indeed seem that if there are no specific physical reasons to stop a planet from forming in a stable region (i.e., gravitational resonances, gravitational migration and/or gravitational scattering), then a planet will form. Perhaps the ultimate application of the PPS is that by Sean Raymond (Bordeaux Observatory, France), who has constructed a "fantasy star system" composed of two red dwarf stars. By careful construction, Raymond is able to show that 60 Earth-mass planets might conceivably be situated, on dynamically stable orbits, within the systems two habitability zones. Various mathematical "tricks" were used to establish this number of habitable worlds, and though no non-physical principles were adopted, the probability of such a system forming naturally is essentially zero. The detection of any such massively packed planetary system could probably be taken as a clear sign that the work of a Kardashev II or III civilization (see Note 55 in Sect. 2.3) had been found. Details of Raymond's methods are given on the website www.obs.u-bordeaux1.fr/e3arths/raymond/.

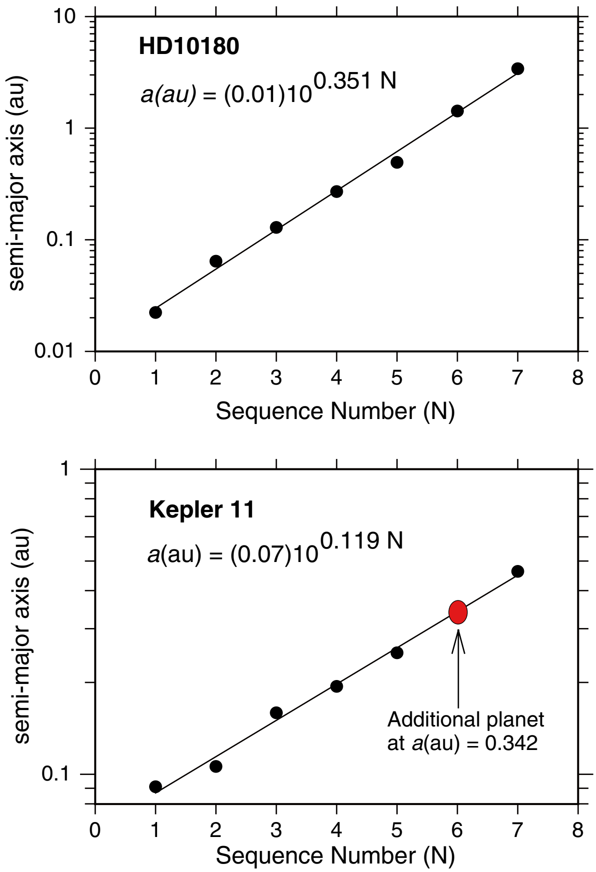

FIG. 2.17 The Titius-Bode-like laws for the stars HD 10180 and Kepler-11. The planetary system around HD 10180 appears to be a packed planetary system (PPS) – at least out to N = 7. For Kepler-11, however, if the PPS hypothesis genuinely holds true, then an additional planet should be located at sequence number N = 6

star the planet sequence appears to be complete for N = 1 to 7. There are no missed planets, and the system is fully packed. If more planets do exist in orbit around HD 10180, then they must have orbits larger than 6.4 au (corresponding to sequence numbers of 8 and above).

In contrast to HD 10180, the planetary spacings observed for Kepler-11 (also see Fig. 2.17) suggest that a planet is *missing* at N = 6. Under the PSS hypothesis this result suggests that the planet is not actually missing but rather not yet detected within the available dataset. Although the mass of the N = 6 planet in the Kepler-11 system cannot be predicted, other than it must be a terrestrial, low-mass planet, its orbital radius and period should be 0.342 au and 73 days respectively.

As we shall see in the next section, one planet has already been detected in orbit around α Cen B. Unfortunately, the manner in which the Titius-Bode law and/or the PPS hypothesis work requires the detection of at least three, and preferentially four or more, planets before any predictions about additional members can be made. We are currently at the impotent numerical end of the Titius-Bode sequence for α Cen B. If, and it is a very big if, it is assumed that the Titius-Bode law for α Cen B is similar to that for our Solar System and of the form $a(\text{au}) = \eta \times \rho^N$, N = 0, 1, 2, …, with $\eta = 0.02$ (making α Cen Bb the N = 1 planet in the sequence), then with $\rho = 2$ (approximately that derived for our Solar System) some five more planets (up to N = 6) might yet be squeezed into orbit around α Cen B. For N = 6, the orbital radius is about 1.28 au (corresponding to an orbital period of about 541 days); for N = 7, the orbital radius is 2.56 au, but this latter radius is beyond the stability limit for the star (as discussed earlier).

The numbers just presented are really pure fantasy and should not be taken seriously. They hint, at best, at what might be found. Given enough time and observational success, however, it is highly likely that some specific form of Titius-Bode-like laws will be derived for α Cen A, α Cen B and, quite possibly, Proxima Centauri.

2.12 Planets in the Divide

Within any binary system there are three zones where stable planetary orbits can exist: around each of the individual stars and around the binary system itself. Each set of configurations has been studied in the case of α Cen AB, and, for example, detailed numerical calculations conducted by Paul Wiegert and Matt Homan (then both located at the University of Toronto in Canada) in the late 1990s revealed that both stars can support stable planetary orbits out to about 4 au. Beyond this limit the gravitational perturbations of the non-parent star become significant, and a planet's orbit is rapidly destabilized.

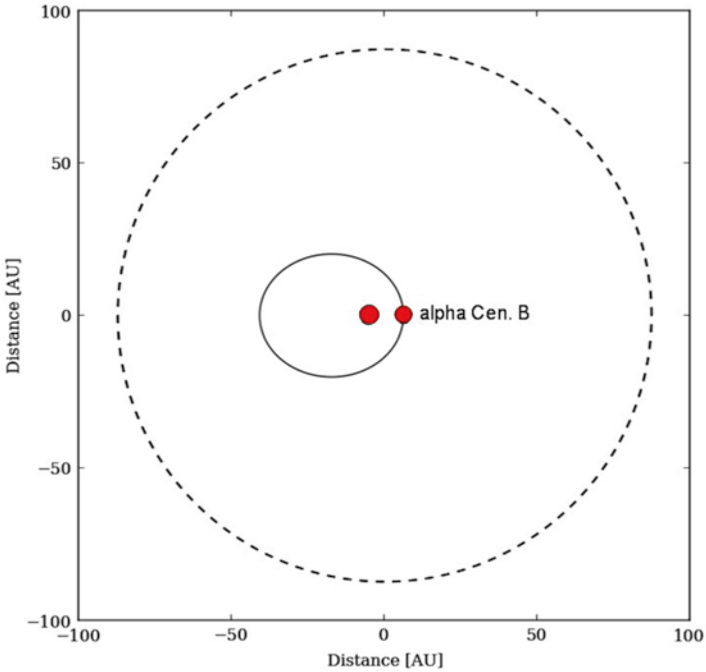

FIG. 2.18 Stability zones for co-planar planets in the α Cen AB system. The central ellipse indicates the orbit of α Cen B centered on α Cen A, the two small circular disks indicate the stability zones around each star ($a < 4$ au), while the large circle (*dashed line*) indicates the inner boundary of the outer orbital stability zone ($a > 80$ au) (see the web page calculator at: http://www.astro.twam.info/hz/)

Additionally, Wiegert and Homan showed that the inclination of the planetary orbits to that of the orbital plane of α Cen AB itself is very important. The 4 au stability limit applies if the plane of the planetary orbits is the same as that of two stars. As the orbital inclination increases, it turns out that the stability limit shrinks, and for 90° inclination orbits, the stability zone around each star is just 0.23 au in extent. Planetary orbits are also stable for distances further than 80 au from the barycenter of α Cen AB. Thomas Mueller and Nader Haghighpour (University of Tubingen, Germany) have recently developed[49] a web-based resource page that determines the stability and habitability zones for any specified binary system, and the result for α Cen AB are shown in Fig. 2.18.

[49] See the web page calculator at: http://www.astro.twam.info/hz/.

A growing number of exoplanets are being discovered in binary systems, with the planets either in orbit around one of the stellar components, as in the case of 55 Cancri A, or in orbit around both stars, as in the case of RR Caeli and Kepler-16ABb. In the case of the solar mass component 55 Cnc A, a total of five planets have been discovered with orbital radii in the range of 0.016–5.74 au.

As a point of interest (and later discussion) the half-Saturn-mass planet 55 Cnc Af was the first planet, outside of our own Solar System, to be found within the habitability zone of another star. The system RR Caeli is composed of an M spectral type red dwarf star and an evolved white dwarf. While these two "parent" stars are separated by just 0.008 au, Shengang Qian (Yunnan Observatory, China) and co-workers showed in a recent 2012 publication that they are both orbited by a four-times Jupiter-mass planet located at a distance of some 5.3 au. In contrast to the relatively expansive RR Caeli, the first planet to be discovered in a circumbinary orbit, Kepler-16ABb is much more compact. In this latter case a Saturn-mass planet orbits the central star system at a distance of 0.7 au. The K and M spectral-type stars that constitute the system's nucleus orbit each other at a distance slightly over 0.2 au. Discovered by Laurence Doyle (SETI Institute, at Mountain View, California) and co-workers in 2011, the entire Kepler-16ABb system could fit into the orbit of Venus within our Solar System.[50] There is no currently known binary system that has a set of attendant planets in orbit around each component, but such systems should exist, and it is really only a matter of time before the first one is going to be found.

The exoplanet surveys to date reveal that planetary systems can take on many different forms, and the imperative of nature appears to be that if a stable orbital region exists then a planet will be found within it. For the α Centauri system the lesson we learn from the exoplanet surveys is that there are potentially four regions in which planets might be found. Planets may exist in orbit around each of the stars, and in orbit between α Cen AB and Proxima.

[50] When first introduced the potential view from Kepler-16ABb was likened to that from the (imagined) planet Tatooine – the famous *Star Wars* (20th Century Fox, 1977) movie home of Luke Skywalker and the infamous womp rats.

2.13 First Look

"Look and yea shall find." Speculation and theoretical discussion are all well and good, but ultimately surveys and searches have to be made. What, after all is said and done, is the "ground truth"? As we saw earlier, the possibility that a planet, or at least a perturbing object, might exist around α Cen AB was invoked by Captain William S. Jacob in 1856. Although Jacob's speculation was in reality based upon uncertain data, it at least introduced the idea that otherwise invisible planets might be detectable around stars other than the Sun.

The first detailed search for possible planets in orbit around α Cen A and B was initiated by Michael Endl (University of Texas at Austin) and co-workers in 1992. Summarizing their radial velocity measurements some eight years later, Endl et al. found no planets, but they were able to place constraints upon the regions where planets might reside. Effectively, there can be no planets more massive than 1 $M_{Jupiter}$ within 2 au of α Cen A, and no planets more massive than 2 $M_{Jupiter}$ within 4 au. For α Cen B, there are no planets more massive than 1.5 $M_{Jupiter}$ within 2 au, and no planets more massive than 2.5 $M_{Jupiter}$ within 4 au.

In terms of circumbinary planets, a deep image survey in the region immediately surrounding α Cen AB by Pierre Kervella (ESO, Garching) and Frederic Thevenin (Observatoire de la Côte d'Azur, France) revealed no co-moving objects more massive than 15 $M_{Jupiter}$ out to distances of order 100–300 au. These initial survey results effectively indicate that no large, multiple Jupiter-mass, planets exist in orbit around either α Cen A or B. Such planets may yet be discovered, however, as circumbinary, cold, Jupiter objects. If there are multiple planets in orbit about α Cen A and/or B then it is to be expected that they will be sub-Jupiter in mass, and this accordingly sets the requisite resolution limit for future radial velocity surveys to be better than at least 1 m/s (but also see below).

Proxima has also been deep searched for possible planetary companions. Early observations date back to at least 1981, when R. F. Jameson (University of Leicester, England) and co-workers used the 3.8-m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea to search for brown dwarf companions to nearby stars.

Proxima was on their survey list, but no hint of any large companion was found. The possibility of Proxima having a brown dwarf companion was raised again in 1998. At this time, Al Schultz (STSI, Baltimore) and co-workers reported that they had obtained observations with the Hubble Space Telescope's faint object spectrograph that hinted at a possible brown dwarf companion some 0.5 au from Proxima. This tentative detection, however, did not survive for very long, and within in a year new data showed that no such companion existed. Indeed, using astrometric data provided by the Hubble Space Telescope's guidance system, Fritz Benedict and co-workers were able to show in a 1999 publication that no planet more massive than 0.8 $M_{Jupiter}$ with an orbital period of between 1 and 1,000 days is in existence around Proxima.

Martin Küster (Max Planck Institut für Astronomie, Heidelberg) and co-workers have additionally shown, in another 1999 publication, that no planets within the mass range of 1.1–22 $M_{Jupiter}$ with orbital periods of between 0.75 and 3,000 days could exist in orbit around Proxima. Furthermore, Endl and Küster were able to show, in a 2008 publication, that no planet having a mass greater than about twice that of Earth can exist within the habitability zone (the region between 0.02 and 0.05 au) of Proxima. Figure 2.19 provides a graphical summary of the survey results applied to date.

Figure 2.19 indicates that at the present time there is still a large parameter space yet to be explored when it comes to detecting possible planets within the α Centauri system. We can be reasonably sure that no Jupiter-mass planets exist in orbit around either α Cen A or B. Such objects may yet exist in orbit around Proxima, but they must have orbital radii greater than 0.01 au. For planet masses less than that of Jupiter, however, the entire orbital stability zones of α Cen A and B have yet to be studied. At least one Earth-mass planet exists in orbit around α Cen B, and there is no specific reason to rule out the possible existence of others. At the present time it is possible that Earth-mass planets exist, and await discovery, within the habitability zones surrounding each of the three stars in the α Centaurus system.

With respect to present-day technology it is not possible to directly measure the reflex velocity induced by an Earth-mass planet situated at 1 au away from either α Cen A or B. Indeed, to achieve the latter at least an order of magnitude improvement will

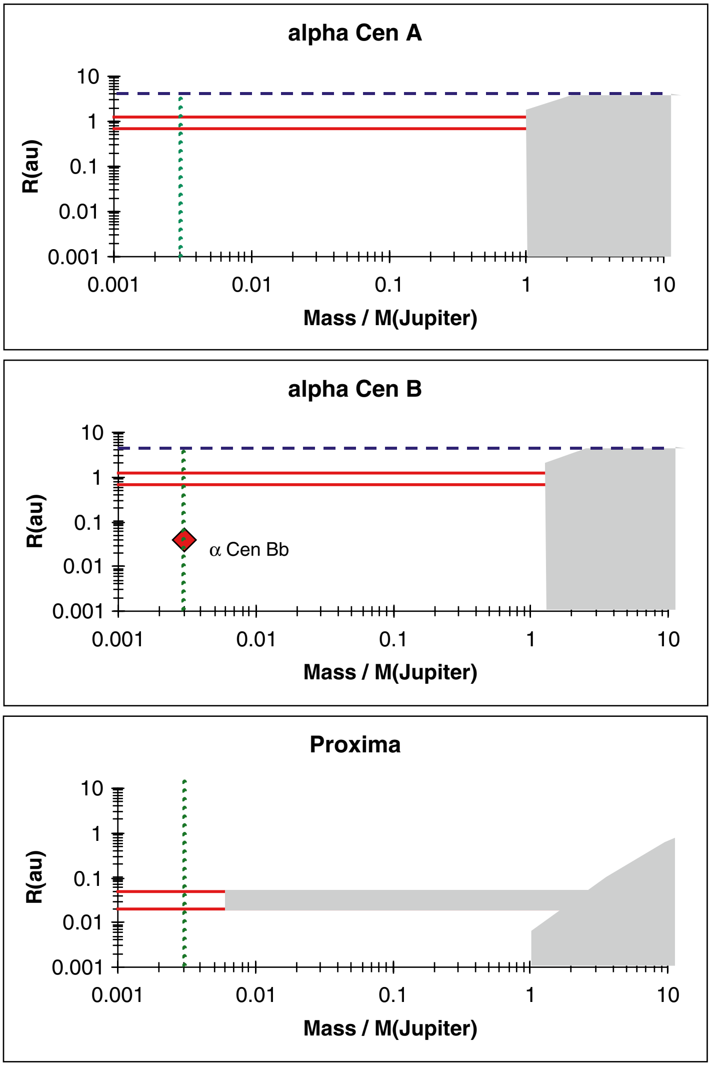

FIG. 2.19 Planetary mass and orbital radius limits for the α Centauri system. In the *top* and *middle* diagrams the *horizontal dashed line* at 4 au indicates the stability limit for planetary orbits. In all three diagrams the *solid horizontal lines* indicate the extent of the habitability zone. The *shaded regions* indicate the presently excluded zones for planets of a given mass and location. The *vertical dotted line* indicates the location at which Earth-mass planets could be found

be required in the Doppler velocity measurement techniques (see later). Improving the radial velocity precision is only part of the story, however. As we saw earlier both α Cen A and B are active, Sun-like stars, and this activity will induce additional "noise" into the radial velocity data. Moving forwards, therefore, is not only a matter of improving the precision with which radial velocity measurements are made, but also about knowing the properties and behaviors of the parent stars.

2.14 The Signal in the Noise

In order to find Earth-mass planets in orbit around either α Cen A or B, the mantras of "pile the data high" and "pile the data deep" might meaningfully be applied. Indeed, to find a planet in orbit around either one of these stars is to literally hunt for the proverbial needle in a haystack. The radial velocity data is going to be noisy, and it will contain multiple sources of variation – some periodic and some not. Before, therefore, the reflex motion of the star, due to the presence of a planetary companion, might be evident all the additional source terms will need to be extracted out from the observational dataset. The idea here is that by subtracting out the known variations, what is left, with luck, will be the signal of a planet.

To deep search α Centauri for planets was always going to be a Herculean task, but it was by painstakingly sifting out the noise that a team of 11 researchers, under the lead authorship of then graduate student Xavier Dumusque (Observatoire de Genève, Switzerland), were able to announce the discovery of α Cen Bb in late 2012.[51] To begin with, the team of observers gathered radial velocity data on α Cen B over a 3-year time interval – between February 2008 and July 2011 – and a total 459 radial velocity measurements were obtained with the HARPS spectrograph (recall Fig. 2.15).

It was decided from the outset of this study to concentrate on α Cen B, rather than α Cen A, since the former is slightly less massive and accordingly the radial velocity variation due to a terrestrial planet (for a given orbit; see Eq. 2.3) will be stronger, and this is important since the expected variations are going to be small – indeed, less than a meter per second. Given the known sources

[51] The results were announced in the prestigious journal *Nature* on November 8, 2012. Perhaps surprisingly, no byline or information was given on the journal's front cover about the remarkable discovery paper that was contained inside.

that can induce Doppler variations, the measured radial velocity (RV) can be thought of as the summation of at least eight terms. Accordingly,

$$\begin{aligned}RV = &RV(\text{binary}) + RV(\text{rotation}) + RV(\text{magnetic cycle}) + RV(\text{oscillations})\\ &+ RV(\text{granulation}) + RV(\text{instrument noise}) + RV(\text{Earth}) + RV(\text{planet})\end{aligned}$$

where the terms in brackets indicate the mechanism responsible for the radial velocity variation.

The trick and also the time-consuming part of the analysis, once having gathered the RV data, is to subtract out the unwanted RV terms. Fortunately most of the "noise" terms in the RV data are reasonably well understood, and they can accordingly be removed in a (reasonably) reliable fashion. The binary period of α Cen AB, for example, is certainly well known (79.91 years), and its contribution over the 3-year observational cycle is easily removed. Likewise, the rotation period (38.7 days) of α Cen B is also well determined, and its modulation effects can be readily subtracted out as well. The magnetic cycle for α Cen B, over which time the surface dark spot number will vary, is estimated to be of order 9 years, and to subtract out this term Dumusque and co-workers collected chromospheric activity data at the same time as the RV measurements were made.

With the chromospheric activity index data in place a radial velocity correction for the magnetic cycle activity could be made. This is perhaps the least well understood part of the process. The corrections due to surface oscillations (typically having periods of about four minutes) and surface granulation (due to rising and falling surface convection cells) were averaged out by choosing a data-collecting exposure time of ten minutes. The idea here is that over such exposure times the surface oscillations and granulation effects should average out to a very small effect. The instrumental noise is subtracted out by carefully measuring the precision and functioning of the HARPS spectrograph over time, and the final correction RV(Earth) is related to the reflex motion of the Sun (recall Fig. 2.13) and the subsequent small velocity variation that it causes in Earth's velocity towards α Cen B.

Examining each of the various RV source terms in detail, Dumusque and co-workers developed a 23-free parameter, time variable correction term to subtract out from the measured RV data. Sieving, then, the corrected radial velocity dataset (Fig. 2.20)

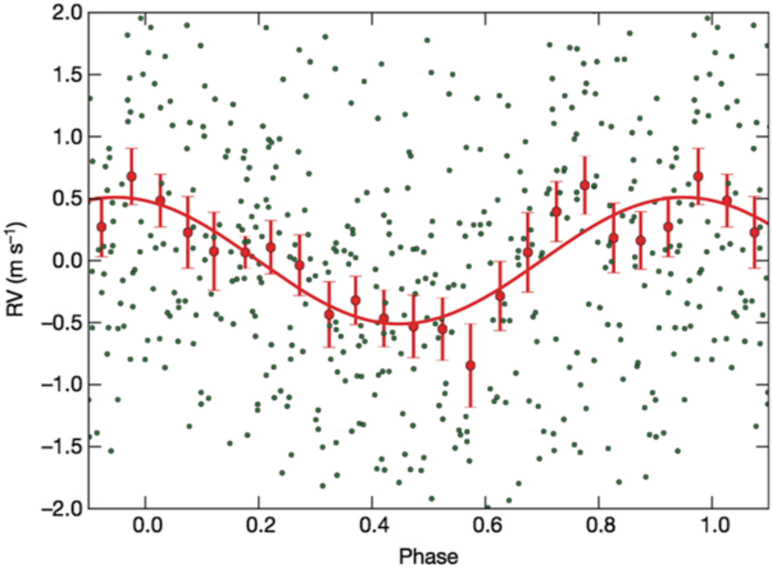

FIG. 2.20 The corrected radial velocity data (*green dots*) for α Cen B. The data points have been folded according to the period of the planet α Cen Bb (3.2357 days) and the *red dots* show time-averaged means. The best fit to the radial velocity data curve is shown in *red* (Image from doi:10.1038/nature11572. Used with permission)

for periodic behavior they found two possible signals at 3.2357 and 0.762 days. Continued statistical testing of the data eventually indicated that only the 3.2357 day signal was real, with the probability that this is a false positive result (meaning it is entirely due to noise within the data) being estimated at about 1 in 500.

The induced reflex velocity variation due to α Cen Bb has an amplitude of just 0.51 m per second (indicated by the red curve in Fig. 2.20), and its (minimum) mass and orbital radius are 1.13 Earth masses and 0.04 au, respectively. The analysis by Dumusque and co-workers provides a minimum mass for α Cen Bb, since it is not yet known what the orbital inclination of the system is. The effect of varying the inclination of the orbit with respect to our line of sight is illustrated in Fig. 2.21. The published value of 1.13 Earth-masses for α Cen Bb is based on the assumption that we are seeing right into the orbit (corresponding to an inclination of exactly 90°). If the inclination is exactly 90° then transits will also take place in our line of sight, but no such signal has as yet been recorded.

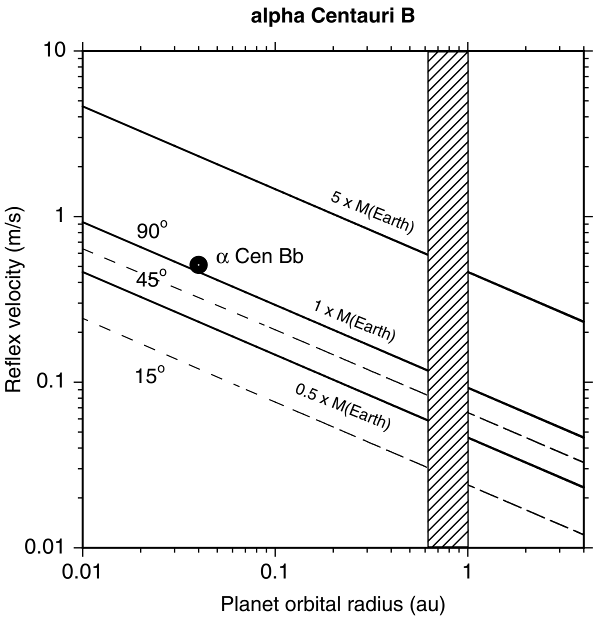

FIG. 2.21 Reflex velocity versus orbital radius for various mass planets. The solid lines correspond to orbital inclinations of 90°. The two *dashed lines* labeled 45° and 15° correspond to a 1 Earth-mass planet and illustrate the effect of reducing the orbital inclination

For orbital inclinations smaller than 90°, the deduced mass for α Cen Bb will increase. While α Cen Bb appears to be an Earth-analog planet it is not an Earth Mark II since it orbits α Cen B well inside of its habitability zone (Fig. 2.22 and see below) (shaded region in Fig. 2.22 and see below).

A few words of caution are now due. The subtraction procedure developed by Dumusque and co-workers, although performed to the highest standards of analysis and rigor, may nonetheless contain some subtle effect that resulted in the apparent periodic planet signal at 3.2357 days. Reproducibility of results being one of the most important cornerstones of science behooves us therefore to record that the detection of α Cen Bb is still preliminary, and affirmation of its true existence awaits efforts by other research groups using independent datasets. Not only this, additional analysis of the subtraction procedure itself is required; the scheme used by Dumusque et al. is not necessarily unique and/or the best to apply. Indeed, Artie Hatzes (Thuringian State Observatory,

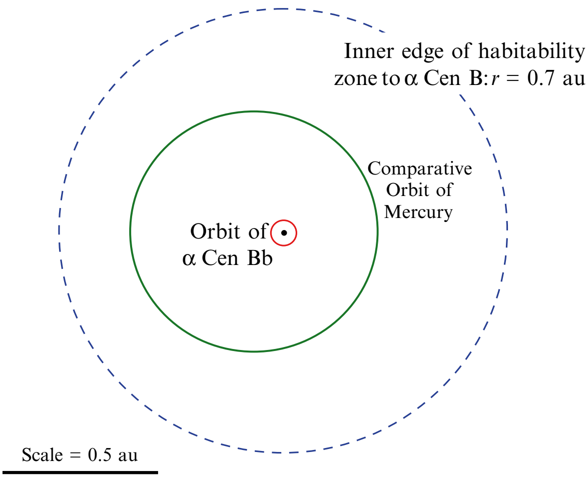

FIG. 2.22 The orbit of α Cen Bb shown in comparison to our Solar System. The 0.04 au orbital radius of α Cen Bb places it some ten times closer to α Cen B than Mercury is to our Sun. The location of the inner boundary ($r = 0.7$ au) of the habitability zone around α Cen B is shown by the *dashed circle*. The scale bar indicates a distance of 0.5 au

Germany) has re-analyzed the α Cen B RV dataset obtained by Dumusque and co-workers and finds that different results might occur if the raw data is divided up and analyzed in slightly different, but perfectly allowable, ways. "The detected *planet* seemed to be highly sensitive to the details in how the activity variations are removed," concluded Hatzes in a May 21, 2013, preprint (arxiv.org/pdf/1305.4960v1.pdf). Hatzes is not claiming in his analysis that Dumusque and co-workers are wrong, or that α Cen Bb does not exist. What he is very appropriately saying is that more, indeed, much more observational data is required to fully bring out the all-important planet signal.

The observational technique used by Dumusque and co-workers is that of Doppler shift measurements. Such observations are being used to reveal the reflex motion of α Cen B. An alternative, perhaps more direct, approach to looking for (confirming) α Cen Bb is to search for transit variations. In this case, as discussed earlier, slight drops in the brightness of α Cen B would be evident each time (once per orbit) any planet moved across its disk in our line of sight. The key point, however, is whether the orbit of any planet is orientated such that transits might be observed from Earth. It was noted earlier that the probability that a randomly orientated system might show planetary transits is $P_{transit} = (R_S + R_P)/a$. Adopting the appropriate values for an Earth-sized planet in orbit around α Cen B with an orbital radius of 0.04 au, we have $P_{transit} \sim 10\ \%$.

The possibility of observing planetary transits is not high for α Cen B, but then neither is it zero. Accordingly, an international team of observers, including Xavier Dumusque, has used the Hubble Space Telescope to monitor α Cen B for the subtle brightness dips due to a planetary companion in transit. Lead investigator for the HST observations is David Ehrenreich (Observatoire de Genève, Switzerland) and the data-gathering run was conducted during a 26-h observing window (corresponding to sixteen orbits of the spacecraft) in July of 2013. The precision of the observations is such that the light dips due to an Earth-sized planet in transit across α Cen B should be detectable (if the orbital plane is favorable for observing transits from Earth). As of this writing no announcements have been made concerning the results of the HST study, but if a transit is captured then not only will this confirm the existence of α Cen Bb, it will also provide a direct measure of the planet's radius. Once the radius is known then the density of the planet can be determined, and this will provide important information about the exact composition and structure of α Cen Bb. Additionally, the HST observations will potentially provide a spectrum of α Cen Bb, and although it likely has no extensive atmosphere (see below) it may leave a vapor trail (possibly of surface-evolved sodium) behind it as it orbits α Cen B.

What would it be like to stand on the surface of α Cen Bb? The answer to this question partly depends upon which hemisphere you might be located, but either way the prospects would be decidedly grim. "Farewell happy fields where joy forever dwells: Hail horrors, hail infernal world, and thou profoundest Hell" – so writes John Milton (1608–1674) in *Paradise Lost*, and in many ways this sums up the outlook for an observer on α Cen Bb. As we shall see below, α Cen Bb is sufficiently close to α Cen B that it will be tidally locked. This dictates that one hemisphere will experience perpetual daylight, always facing towards α Cen Bb, while the other hemisphere will be cast in permanent night. The one hemisphere will be hellishly hot, while the other will be hellishly cold.

On the daylight hemisphere α Cen B will loom large with an angular diameter of 11.5° on the sky. This is some 23 times larger than the Sun appears to us from Earth. The influx of surface energy from α Cen Bb will be a staggering 430,000 W per m^2 (312 times larger than the Sun's energy flux at the top of Earth's atmosphere), and the resultant surface temperature will be around 1,200 K. The very rocks on the daylight hemisphere of α Cen Bb will ooze and fold, and no solid land masses will exist to support a would-be surface observer.

Moving towards the permanent nighttime hemisphere α Cen B will fall lower and lower in the sky, eventually disappearing, never thereafter to rise. From here on in the temperature will drop precipitously to the biting cold of interstellar space. No sunrises to heat the ground and no atmosphere exists to circulate any of the dayside heat. From the permanent night hemisphere, the brightest object in the sky will be α Cen A – which at intervals of 80 years (see Appendix 3 in this book) will rise to a maximum brightness of magnitude −22 – making it technically just a little fainter than the Sun appears to us on Earth. Its angular diameter, however, will be about a tenth that of the Sun (as seen by us on Earth). Indeed, from α Cen Bb, α Cen A will shine like a piercing diamond in the sky. For all of the pointillist brilliance of α Cen A, however, the nighttime hemisphere of α Cen Bb will be wrapped within the frozen embrace of a withering cold. These are not the Elysian fields. In short, α Cen Bb is not a place you would ever want to visit – other than, that is, by using a means of virtual telepresence.

2.15 Bend It Like Proxima

In addition to employing Doppler and transit survey methods to find exoplanetary systems, a third search method, based upon the gravitational bending of light rays, has also been successfully developed to find new worlds. The monitoring requirements for the gravitational microlensing technique are essentially the exact opposite of those used in the transit method. Rather than looking for a periodic decrease in the brightness of a star, it is a characteristic brightness increase that is looked for.

Not only does the brightness of a background source star (or galaxy) increase during a lensing event, the apparent position of

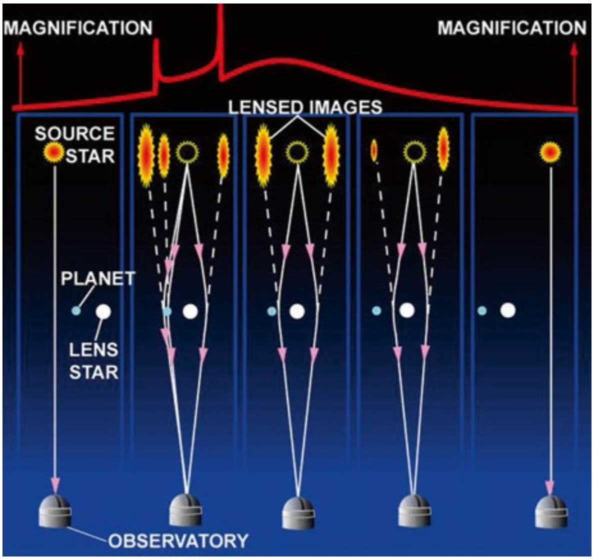

FIG. 2.23 Schematic diagram for the gravitational bending of light by a "lens" star situated between a "source" star (or galaxy) and the observer. If a planet is in orbit around the lensing star then it can produce an additional microlensing effect (Image by Dave Bennett, University of Notre Dame. Used with permission)

the lensed star (or galaxy) also shifts slightly in the sky. The amount of shift depends upon the mass of the lensing object; the bigger the mass, the greater the positional offset produced. The essential geometry behind the gravitational lensing technique is illustrated in Fig. 2.23.

The gravitational microlensing technique of planetary detection typically comes into its own when very distant star fields are being monitored, since such fields provide a large number of potential sources to lens. As of the time of this writing, with 1,047 known exoplanets having been detected in 794 planetary systems, some 25 exoplanets in 23 planetary systems have been discovered through the microlensing effect.

The first exoplanet detected by the lensing technique has the ungainly catalog name of[52] OGLE-2003-BLG-235/MOA-2003-BLG-53b. This planet has a mass some 2.6 times greater than that

[52] In the ever-more chaotic and contrived world of acronyms, we have Optical Gravitational Lensing Experiment (OGLE) and Microlensing Observations in Astrophysics (MOA).

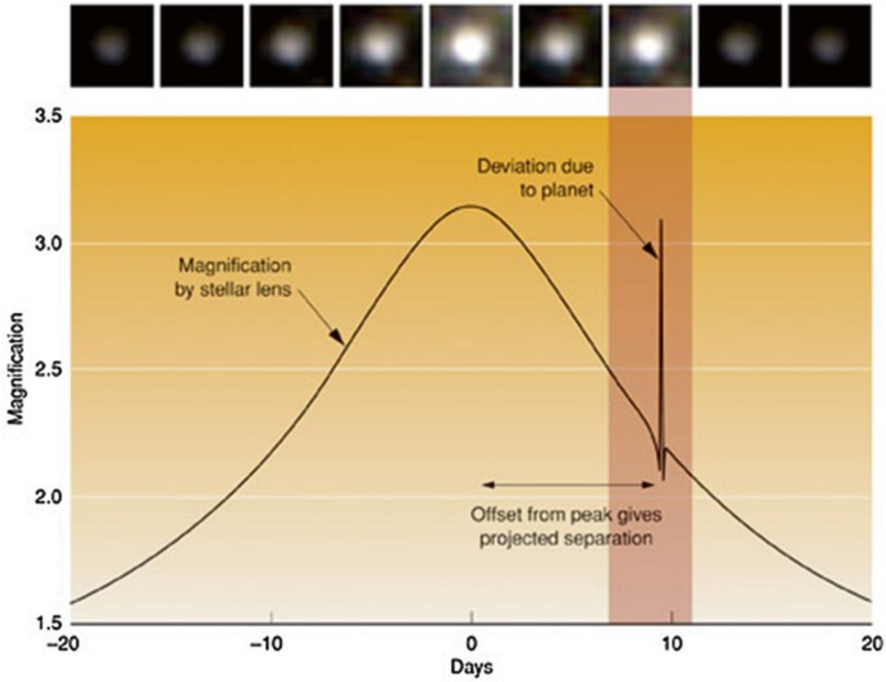

FIG. 2.24 Schematic variation in light curve brightness as the lens star moves in front of a source star during a gravitational microlensing event. The short spike in magnification is due to the presence of a planet in orbit around the lensing star (Image courtesy of the Lawrence Livermore National Laboratory)

of Jupiter, and it orbits a K spectral-type parent star (slightly less massive than the Sun) at a distance of some 4 au. Discovered in 2003, the planet and its parent star are situated at a distance of about 5,800 pc from the Sun in the galactic bulge surrounding the very center of our Milky Way Galaxy.

Key to the success of the microlensing technique (as illustrated in Fig. 2.23) is the alignment of a foreground object (the lens) with a distant light source provided by another star or a distant galaxy. For a very close alignment in the observer's line of sight the gravitational field of the lensing object will produce multiple and brighter images of the background source, and it is this brightening, typically lasting from weeks to months, that is searched for. If the foreground lensing object is a star with a planet, then this can, if the geometry is just right, result in a shortlived but even greater brightening of the background source (Fig. 2.24).

Just as with the transit surveys, the planet-induced brightening spike, however, will only last for a few hours, and this, of course, acts against the chances of it being detected unless near full-time monitoring techniques are employed.

Two important results to have appeared from the various microlensing surveys run to the present time are the identification of a large population of rogue planets within the Milky Way, and the deduction that, "Stars are orbited by planets as a rule, rather than the exception."[53] Both of these results are remarkable, and they present a dramatic shift in historical thinking. First, the latter of the two findings tells us that planet formation is both a natural part and a common outcome of the star formation process. Indeed, a 2012 microlensing study report published in the journal *Nature* by Cassan (Institut d'Astophysique de Paris) and co-workers indicates that on average every star in the Milky Way Galaxy has 1.6 ± 0.8 planets in the mass range from 5 Earth masses to 10 Jupiter masses, with orbital radii between 0.5 and 10 au. The result, that unbound Jupiter-mass planets not only exist but actually outnumber stars by a factor of approximately two to one, was also a microlensing survey result, this time published in the journal *Nature* by Takahiro Sumi (Osaka University) and MOA[54] co-workers in 2011. These rogue planets, no doubt, formed within the gas and dust disks that are associated with newly forming stars, but due to the combined processes of planet migration and gravitational scattering interactions have been launched onto lonely, unbound trajectories that carry them through the cold of interstellar space.

In contrast to the paths followed by rogue planets, Proxima has a well-known proper motion path across the sky, and accordingly systematic searches of star catalogs can be used to predict the exact times when lensing events, with Proxima being the lens, might occur. Samir Salim and Andrew Gold, at Ohio State University in Columbus, performed just such a search in late 1999 and found three occasions (in 2006, 2010 and 2013) on which Proxima

[53] This quotation is taken from the research paper by A. Cassan et al., "One or more bound planets per Milky Way star from microlensing observations" (*Nature,* **481**, 167, 2012).

[54] See, T. Sumi et al., "Unbound or distant planetary mass population detected by gravitational microlensing." – paper available at arxiv.org/abs/1105.4544v1. MOA (see Ref. 52) is a long-running and highly successful collaboration between astronomers in New Zealand and Japan using gravitational lensing techniques to study dark matter, exoplanets and stellar atmospheres.

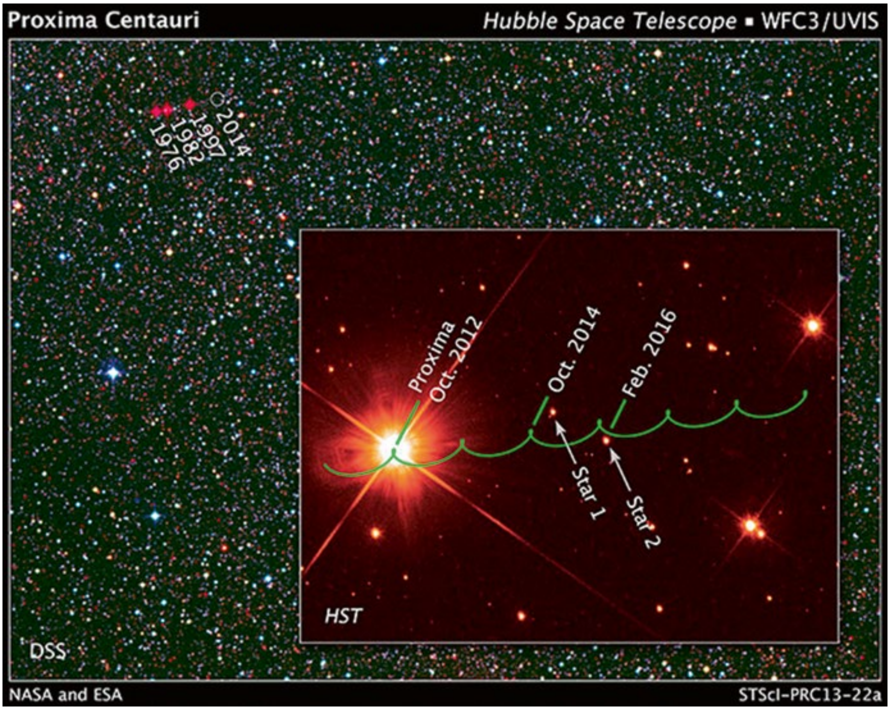

Fig. 2.25 The proper motion track (*lower right-hand corner*) of Proxima Centauri over the time span 2011–2018, showing the times and sky locations where the background star occultations will take place in 2014 and 2016. The background star field and the locations of Proxima (since 1976) are shown in the *upper left-hand corner* of the image (Image courtesy of ISTS and NASA)

would lens background stars. Unfortunately, none of these predicted events were monitored. A similar study led by Kailash Sahu, of the Space Telescope Science Institute in Baltimore, however, has additionally revealed that Proxima lensing events will take place in October 2014 and February 2016. These latter two events nicely bookend a remarkable set of centennial celebrations, with 2015 not only marking the 100th anniversary of Proxima's discovery by Robert Innis but also the 100th anniversary of Einstein's first public presentation on general relativity (the scientific theory behind gravitational lensing) at a meeting of the Prussian Academy of Sciences in Berlin.

The proper motion track of Proxima from 2014 to 2018 is shown in Fig. 2.25 (recall also Fig. 1.12 for α Cen A and B). Precise measurement of the shift, anticipated to be between 0.5 and 1.5 milliarcseconds, in the positions of the lensed stars, over total event time intervals of just a few hours, will enable the direct determination of Proxima's mass to unprecedented accuracy. Indeed, the gravitational lensing method is the only direct method available to astronomer by which a single star's mass can be determined. Normally a star must be located within a binary system (such as in α Cen AB) for its mass to be derived. In addition, if the geometry is just right, and if luck is with us, the lensing events could also reveal the presence of close-in, Earth-sized planetary companions to Proxima. Importantly, and in contrast to the normal situation in which it is purely random chance that determines whether a lensing event will take place, and when it does it is a one-off affair, with Proxima its known path in the sky means that multiple and predictable lensing events take place. And, while one particular lensing encounter might not have the correct geometry for the detection of close-in planets, another one just might.

2.16 The Sweet Spot

Assuming that multiple numbers of planets are eventually discovered within the α Centauri system, then one of the most intriguing follow-on questions that can be asked is, "Could life have evolved upon any one or more of them?". This is indeed a profound historical question, not just of α Centauri but of all stars within the Milky Way. Once again, however, we live in a remarkable epoch where observational studies can potentially provide us with a direct answer to the question. And, while as yet we have only a poor understanding about the origins of life, that is, the workings of the initial 'spark' that changes a collection of inanimate atoms and molecules into a self-regulating, reproducing, conscious living entity, we do know at least some of the conditions required for that primordial 'spark' to come about.

On Planet Earth life has been maintained and protected by the existence of an atmosphere and a liquid ocean, and the conditions for these two features to exist over billion-year timespans are well understood in terms of planet size, atmospheric constitution and distance from the Sun. It is through this basic understanding that the concept of the habitability zone (HZ) has come about.[55] For Sun-like stars the region in which a terrestrial mass planet might support an atmosphere capable of providing sufficient pressure for liquid water to exist at its surface has an inner boundary radius of about 0.95 au and an outer boundary radius of about 1.4 au. In approximate terms, the locations of the inner and outer habitability zone boundaries are proportional to the square root of the parent star's luminosity:

$$r_{inner}\left(au\right) = 0.95\sqrt{L} \text{ and } r_{outer}\left(au\right) = 1.4\sqrt{L} \tag{2.7}$$

where the luminosity is expressed in solar units.

As we have seen earlier α Cen A and B are approximate Sun analogs, so their habitability zones will be similar in extent to that for our Solar System (Fig. 2.26). Since α Cen A is more luminous than the Sun (Table 2.2), however, its habitability zone is displaced further outward than that for our Solar System, and indeed, the straight translation of Earth to α Cen A at 1 AU would place it in a region too hot for liquid water to exist on its surface. A translation of Earth to an orbit around α Cen B would place it close to the outer, cold edge of the habitability zone, making it a somewhat less hospitable place for life (as we know it) to thrive. Not only would Earth be habitable at 1 au from α Cen B, but so, too, would a transplanted Venus, since at 0.724 au it would sit beyond the innermost, hot edge of the habitability zone. A straight transplantation of Earth to an orbit around Proxima would place it well outside of the habitability zone, resulting in a frozen and lifeless world.

The line marked tidal lock radius in Fig. 2.26 corresponds to the boundary interior to which an Earth-sized planet would rotate in such a fashion that the same hemisphere of a planet will always face the parent star. The line, as shown, corresponds to the distance for tidal lock to have occurred in a time of six billion years. The time t_{lock} for the tidal locking condition to come about is dependent upon the planet's orbital radius a and the mass of the parent star M – approximately, for Earth-mass planets,

$$t_{lock}\left(\text{yrs}\right) = 10^{12}\left(a^6 / M^2\right) \tag{2.8}$$

[55] A web-based calculator for estimating the inner and outer habitability zone radii has been developed at the University of Washington. It can be accessed at http://depts.washington.edu/naivpl/content/hz-calculator.

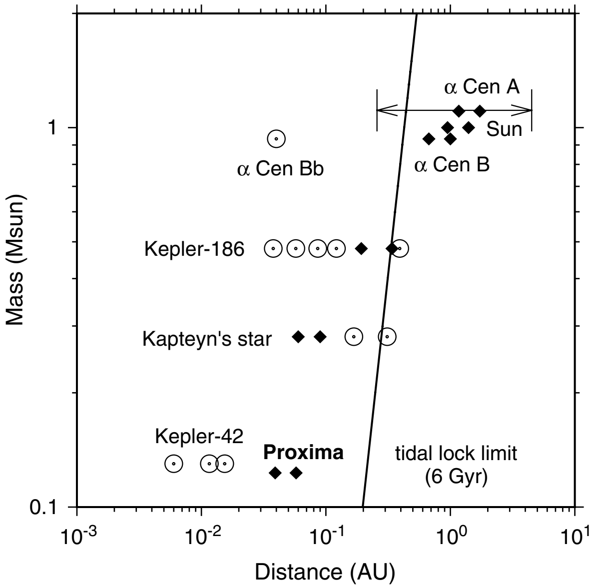

FIG. 2.26 The inner and outer edges of the habitability zone (*filled diamonds*) for the stars in the α Centauri system compared to that for the Sun and Solar System. The *diagonal line* indicates the boundary at which an Earth sized planet would become tidally locked after 6 Gyr – the age of the α Centauri system. The *dotted circles* indicate the locations of planets within the Solar System (Mercury to Jupiter), α Cen Bb and the Proxima analog system Kepler-42. The planet locations for Kepler 186 and Kapteyn's stars are also shown. The *horizontal line* through the α Cen A habitability zone points shows the outer stability radius for co-planar (4 au) and 90° (0.23 au) inclination planetary orbits

where a is expressed in astronomical units and M in solar masses.

Equation 2.8 indicates that the closer a planet is to its parent star, the shorter is the tidal locking time. Likewise, for a given orbital radius, the more massive the parent star, the shorter is the tidal locking time. Clearly, again from Fig. 2.26, α Cen Bb is situated well inside of the tidally locked region. Any Earth-sized planets that might be located within the habitability zones around α Cen A and/or B, however, will, on the other hand, not have reached a tidally locked state.

It is not fully clear yet what the consequences of tidal lock might be on a potentially habitable planet – i.e., one with an atmosphere. It is clear, however, that the heating of one planetary hemisphere and not the other will have a dramatic effect on atmospheric structure, wind circulation and surface temperature distribution. As to whether such planets can support life is still unclear. Where such affects will be critical is for any Earth-sized planets that might orbit Proxima Centauri. As Fig. 2.26 indicates, any planets that might be situated within the habitability zone around Proxima will be tidally locked, and consequently the possible existence of and indeed the very evolution of any associated biosphere can only be speculated on at the present time. The scientific community right now appears to be split as to the exact consequences of tidal locking on the habitability of a planet; some researchers argue that such conditions must of necessity preclude the existence of any surface habitability zones, while others suggest that regions situated close to the day-night divide boundary might just support an active biosphere.

Although the habitability zone will move outwards as Proxima ages and its luminosity increases, at no time will the outermost edge of the habitability zone move beyond the tidal lock radius. Planets may well exist within the canonical habitability zone around Proxima, but it is far from clear as to whether we should expect to ultimately see the evolution and/or presence of any indigenous life forms.

The announcement of the first Earth-sized planet to be discovered within the habitability zone of a red dwarf star, planet Kepler-186f, was made in April 2014. This planet, which is one of five detected in the system, is located towards the extreme outer edge of the habitability zone of Kepler-186 (see Fig. 2.26), and it receives about the same energy flux as Mars from our Sun. To stay warm enough for water to exist on Kepler-186f, therefore, it would need something like a dense CO_2 atmosphere to provide a strong greenhouse heating effect. Such an atmosphere might conceivably be produced through volcanic outgassing, and more importantly, may also be detectable with next generation instruments.

Although in principle low-mass, Earth-like planets can exist around Proxima in orbits with radii of many astronomical units, the same cannot be said for α Cen A and or B. As discussed earlier, the binary companionship of these two stars limits the size of the stability region to about 4 au (recall Fig. 2.18). This stability region, however, encompasses the habitability zone, and accordingly

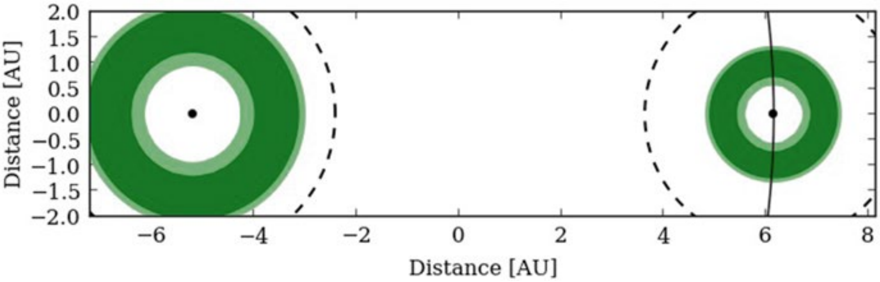

FIG. 2.27 The habitability zones (*shaded*) of α Cen A (*left*) and B (*right*). The scale is in astronomical units, and the *dashed curves* indicate the limit for stable planetary orbits. Although the extent of the habitability zones does not change during the orbit, the figure shows α Cen A and B at their closest approach (Image derived from Mueller and Haghighipour. (See the web page calculator at: http://www.astro.twam.info/hz/.) Used with permission)

Earth Mark II may yet exist within the closest star system to us. Figure 2.27 shows the expected extent of the habitability zones associated with α Cen A and B.

2.17 Alpha Centauri C?

From the very first moment of its discovery Proxima Centauri presented astronomers with a puzzle. First, Robert Innis noted in his initial communication that Proxima had a proper motion almost identical to that of α-Centauri, and he suggested that the two systems might be associated, making up thereby a small, common proper motion star cluster.

When Joan Voûte discovered that Proxima was at essentially the same distance as α Centauri he questioned, "Are they physically connected or members of the same drift?" Ninety years on from its first airing Voûte's question has still not been resolved. At issue, specifically, is the question, if Proxima is gravitationally bound to α Centauri, then what is its orbital path around α Cen AB? For Proxima to be moving in a bound (that is, elliptical and periodic) orbit around α Cen AB the total energy E of the system must be less than zero. If $E \geq 0$ then Proxima cannot be gravitationally bound to α Cen AB, and its relative closeness to α Cen AB must be a pure (and remarkable) coincidence of the present epoch. The total energy E of the system will be the sum of the kinetic energy and the gravitational potential energy as measured from the system's (α Cen AB + Proxima) center of mass. Accordingly, for a bound orbit it is required that:

$$E = \frac{1}{2}\left(\frac{M_{AB}M_{Prox}}{M_{AB} + M_{Prox}}\right)V^2 - G\frac{M_{AB}M_{Prox}}{r} < 0 \tag{2.9}$$

where M_{AB} is the combined mass of α Cen A and α Cen B, M_{Prox} is the mass of Proxima, V is the relative velocity of Proxima about α Cen AB, r is the relative distance of Proxima, and G is the gravitational constant.

With $M = M_{AB} + M_{Prox}$ Eq. 2.9 can be recast to set an upper limit on the relative velocity of Proxima:

$$V < \sqrt{\frac{2GM}{r}} \tag{2.10}$$

Since all of the quantities in Eq. 2.10 are measurable, the question now is what is actually observed. The result depends upon the observed masses of the stars, their separation r (which is based on their angular separation in the sky and the system parallax) and the relative velocity of Proxima compared to α Cen AB.

Dealing with the right-hand side of Eq. 2.10 first, the condition on the relative velocity based on the measured masses and separations is $V < 0.399 \pm 0.012$ km/s.[56] In contrast to this number, the measured velocity of Proxima relative to α Cen AB is only poorly known. Pourbaix and co-workers (see Appendix 3 in this book) have measured to high precision the radial velocity of α Cen AB and find $V_{AB} = -22.445 \pm 0.002$ km/s. At the present time, however, the best estimate for the radial velocity of Proxima is $V_{Prox} = -21.8 \pm 0.2$ km/s, and accordingly $V = V_{AB} - V_{Prox} = 0.645 \pm 0.2$ km/s.

From the observed radial velocity values it would appear that Proxima is not gravitationally bound to α Cen AB. The problem, however, is that the entire issue of whether Proxima is gravita-

[56] This number (and the associated uncertainty) is taken directly from the research paper by the author, "Proxima Centauri: a transitional modified Newtonian dynamics controlled orbital candidate?" (*Monthly Notices of the Royal Astronomical Society*, **399**, L21, 2009).

tional bound to α Cen AB is (almost) entirely contained within the uncertainty of the radial velocity measurement deduced for Proxima. At the very best, at this stage, it can only be concluded that Proxima is just, or only marginally, bound to α Cen AB. It literally hovers on the divide between being α Cen C, the third star in the triple system with α Cen A and B, and Proxima, the star that just happens to be remarkably close to α Cen AB at the present time.

A study conducted by Jeremy Wertheimer and Gregory Laughlin (both at the University of California, Santa Cruz) put the question of Proxima's boundedness to the test by looking at the energy values associated with a series of cloned systems.[57] These systems were constructed by taking the observed values for system parameters and then randomly adding or subtracting terms within the range of the allowed observational uncertainty. A total of 10,000 clones were constructed, and it was found that about 44 % of such systems ended up having a negative total energy, indicating that Proxima was gravitationally bound to α Cen AB. The odds, at least from the presently available data, that Proxima can truly be designated α Cen C are currently no better than even.

Although this march-of-the-clones result is fair enough as it stands, alternative observational evidence suggests that Proxima really does form a trinity with α Cen A and B – that Proxima has the same estimated age and composition as α Cen A and B, and the sheer improbability that it would, when randomly observed, reside so close to α Cen A and B, all hint at a common origin. If one assumes that Proxima is indeed gravitationally bound to α Cen AB, then this sets very precise limits on the allowed radial velocity for Proxima, with $-22.3 < V(\text{km/s}) < -22.0$. The next step in answering the question "Is Proxima Centauri really equivalent to α Cen C?" will be entirely based upon obtaining a much more precise value for its radial velocity. Again, if one accepts that Proxima is gravitationally bound to α Cen AB, then what sort of orbit does it have? Wertheimer and Laughlin conclude that the orbit must be highly elliptical ($e \approx 0.9$) and have a major axis of order 2.6 pc (corresponding to $a = 272{,}212$ au). The orbital period would accordingly be of order 100 million years. Such an orbit could not possibly

[57] J. Wertheimer and G. Laughlin, "Are Proxima and Alpha Centauri Gravitationally Bound?" (*Astronomical Journal,* **132**, 1995, 2006).

be stable for more than a few cycles, however, and Proxima would soon be stripped from the gravitational grasp of α Cen AB. The size of the orbit can be much reduced (within the allowed uncertainties) if one adopts the argument that Proxima is most likely to be observed when it is close to apastron,[58] and in this case an orbit with a semi-major axis $a \sim 8{,}000$ au results, and the corresponding orbital period, comes down to about one million years.

The gravitationally bound status of Proxima is presently hidden within the uncertainty to which its radial velocity can be measured. Intriguingly, as well, a fundamental change in our understanding of the way in which gravity actually works might be hidden in the observational uncertainties. Early in the twentieth century, Einstein revolutionized the way in which we think about gravity – expressing it as an effect due to the curvature of spacetime – and he modified Isaac Newton's famous formula (as presented in the *Principia Mathematica,* first published in 1687) to account for the conditions of very high accelerations. For objects such as Proxima, which are moving in extremely low acceleration regimes, however, yet another change might come into play.

The idea of introducing a modified Newtonian dynamic (MOND) domain was first discussed within the context of galaxy rotation curves, and was presented as an alternative to postulating the existence (of the still mysterious) dark matter. Described in a series of fundamental research papers[59] published by Mordehai Milgrom (Weizmann Institute of Science, Israel) since the early 1980s, MOND relies on the postulate that in very low acceleration domains the way in which the gravitational force behaves changes. Indeed, Milgrom argues that once the acceleration acting on an object drops below a new fundamental (natural constant) value $a_0 \approx 1.2 \times 10^{-10}$ m/s^2, then its motion will become increasing different to that expected from the straightforward application of Newton's formula.

In effect, in the MOND domain, velocities should be higher than otherwise expected for the observed masses and separations.

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[58] This expectation follows directly from Kepler's second law of planetary motion, which requires slower speeds and hence greater dwell times at apastron; the reverse situation applies at periastron.

[59] A good place to begin with respect to investigating the history and development of ideas pertaining to MOND is the website www.astro.umd.edu/~ssm/mond/.

For a standard two-body, Keplerian orbit with a small mass object orbiting around a larger central mass and interacting under a pure Newtonian gravitational interaction, the predicted orbital velocity V will decrease as the inverse square root of the orbital radius r: specifically $V^2 = GM_{AB}/r$. In this manner, the further distant the object is, the smaller will its orbital speed be.

For the same system in the domain where MOND applies, however, the orbital velocity will vary in an entirely different manner – namely as: $V^4 = a_0 GM_{AB}$. Indeed, in the MOND case the orbital velocity remains constant. (This, in fact, was the observed feature of galaxy rotation curves that resulted in MOND being developed.)

So, where does Proxima sit with respect to the pure Newtonian and MOND domains? Using the canonical values for M_{AB} and the observed separation distance of Proxima, the acceleration is $a_{prox} = 5.4 \times 10^{-11}$ m/s^2. Interestingly, therefore, it seems that $a_{prox} \approx ½\, a_0$ and accordingly Proxima resides in the domain where MOND should be expected to apply. Indeed, the velocity of Proxima predicted by the MOND formula gives $V = 0.424 \pm 0.001$ km/s[60] – which is slightly larger than the standard Newtonian bound state limit ($V < 0.399 \pm 0.012$ km/s) but close to the lower limit allowed for the measured relative velocity of Proxima ($V = 0.645 \pm 0.2$ km/s). In the MOND situation, the orbit of Proxima around α Cen AB could be entirely circular, or, as found in a more detailed analysis,[61] it might have a slightly eccentric, $e = 0.2$, orbit with a semi-major axis of $a = 12{,}527$ au. A set of possible orbits for Proxima are shown in Fig. 2.28.

At this stage, nothing is for certain, and the entire question of Proxima's gravitationally bound status (that is, it being α Cen C) and the question concerning the existence of a MOND regime (and literally a new domain of gravitational physics) is hidden within the uncertainties that accompany the present radial

[60] This number (and the associated uncertainty) is taken directly from the research paper by the author, "Proxima Centauri: a transitional modified Newtonian dynamics controlled orbital candidate?" (*Monthly Notices of the Royal Astronomical Society*, **399**, L21, 2009).

[61] See the author's research paper, "The orbit of Proxima Centauri: a MOND versus standard Newtonian distinction" (*Astrophysics and Space Science*, **333**, 419, 2011).

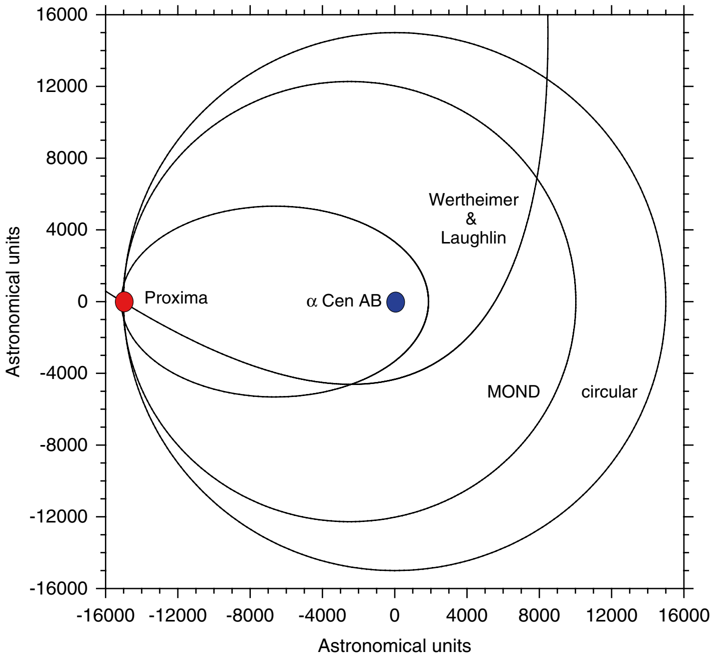

FIG. 2.28 Four possible orbits for Proxima around α Cen AB. The scale is given in astronomical units, and α Cen AB resides at the origin. The curve labeled *circular* is exactly that, and is the case where Proxima orbits α Cen AB at a fixed distance. The curve labeled *MOND* corresponds to the orbit having $a = 12{,}527$ au, $e = 0.2$. The curve labeled *Wertheimer and Laughlin* shows a fragment of the orbit deduced in Note 57. The smaller elliptical orbit is computed on the bases that Proxima is currently located at apastron, with respect to α Cen AB, and that it passes no closer to α Cen AB than the Hill sphere radius. (The Hill sphere radius, as introduced by American astronomer George William Hill in 1878, defines the limit interior to which the orbit of a smaller body will be significantly perturbed by the gravitational influence of the much heavier central body about which it orbits. In the case of Proxima the limitation is that its orbit is not significantly perturbed by passing too close to either α Cen A or α Cen B. The derivation for the Hill sphere radius used in Fig. 2.28 is given in Note 61.) The latter is taken as being the smallest possible elliptical orbit for Proxima, and it has an associated orbital period of 53,500 years

velocity measurements for Proxima. Reducing the uncertainty in the measurements is clearly a topic for future study and elucidation. For indeed, within its number resides the answer to two of the deeper and more carefully protected secrets of the α Centauri system.

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