A journey through time a

Martin Beech looks at the history of scientific interest in our nearest star system, αCentauri, and the recent surge in research that has resulted in the discovery of our nearest exoplanet.

From the depths of ancient Greek mythology we learn that the half-man, half-horse centaur Chiron was the immortal offspring of the Titan King Cronus, sired through a forbidden tryst with the sea nymph Philyra. Roman poet Ovid further tells us in his *Fasti* that Chiron eventually settled into a cave at Mount Pelion in central Greece, and it was from there that he became a renowned teacher of medicine, music and hunting, but had a tragic death. Accidentally shot in the foot by Heracles, with an arrow that had been dipped in Hydra's blood, Chiron was condemned to suffer a wound that never healed and continuous pain. Taking pity on Chiron, however, Zeus benevolently allowed him to die and placed his body among the stars (Ridpath 1989). Writing in his *Syntaxis Mathematica,* the great Claudius Ptolemy included Centaurus in his list of 48 original constellations. It is the brightest star in the constellation of Centaurus, α Centauri, that symbolically (although not officially) depicts the wounded left hoof of Chiron. Indeed, the ancient Arabic astronomers knew α Centauri, the third brightest naked-eye star in the entire sky, as Al Riji al Kentauris, which translates to "the Centaur's foot", and this gives us the Latinized name Rigel Kentaurus.

The mythological description of Centaurus takes us to a time perhaps four to five thousand years before the present day (Chapman 2002). The presence of α Centauri (figure 1) was known to our ancestors at a time well before recorded history began, but the discovery of its true nature only started about 300 years ago. The modern narrative opens in December of 1689, with Jesuit missionary and astronomer Jean Richaud observing comet C/1698 X1 through a small telescope from Pondicherry in India (Rao *et al.* 1984). The comet cut a trail through the constellation of Centaurus and, while recording its progress, Richaud chanced to notice that α Centauri could be resolved into a double star: "the two stars seemed to be practically touching each other". Writing nearly 150 years later, in 1847, John F W Herschel described α Centauri as being "truly a noble object", and noted that it consisted of "two individuals, both of a high ruddy or orange colour, though that of the smaller is of a somewhat more sombre and brownish cast".

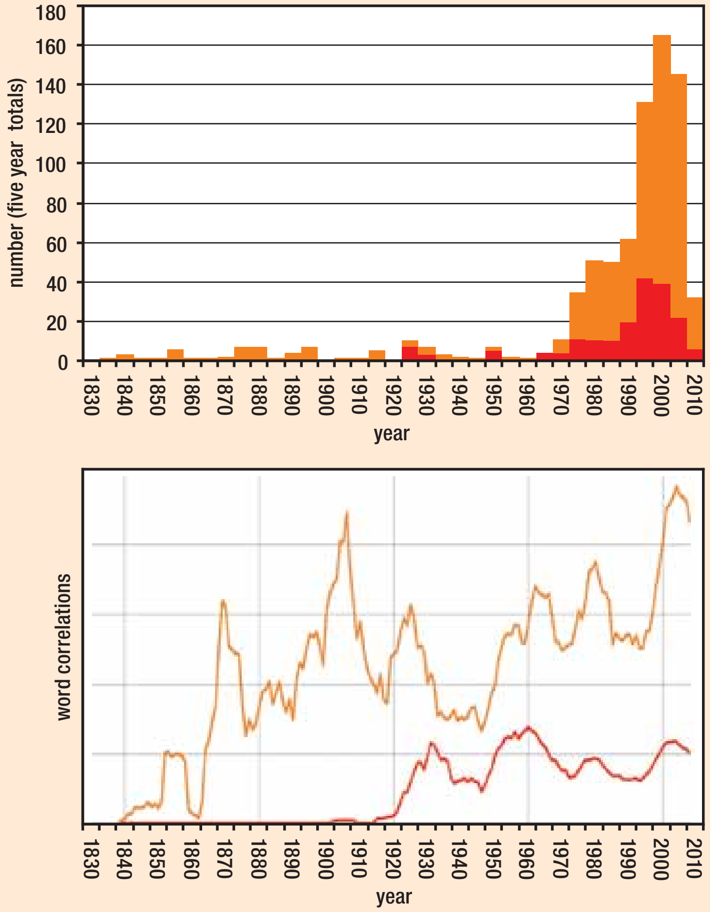
While observations of α Centauri were occasionally reported during the 18th century, its real astronomical significance was only realized in 1839, when reluctant Cape Astronomer Thomas Henderson reported upon measurements of its parallax: α Centauri, with a parallax of 747.1 ± 1.2 mas, is located at a distance of 1.339 ± 0.002 pc away, and is the closest stellar system to the Sun. Henderson's result has stood the test of time and, even in the light of more sensitive stellar surveys, α Centauri remains our closest neighbour, lifting it, thereby, beyond the realm of the ordinary.

Growing interest

Yet even with Henderson's result in place α Centauri only slowly became an object of scientific interest. Some measure of its attraction to astronomers is illustrated in figure 2, where the data relating to publications listed in the NASA Astrophysics Data System (ADS) are shown in five-year totals starting in 1830. The first paper on α Centauri in the ADS is actually ascribed to the wrong author, being attributed to the Reverend William Pearson (one of the founding members of the RAS) rather than Thomas Henderson, and concerns the 1839 announcement that it "appears probable, that these two stars have a sensible parallax of about one second of space" (Henderson 1839).

For the next century astronomers set about refining the parallax measurement and establishing the system's orbital parameters. It was only in the early 1970s that the current interest in α Centauri really began, and it was at this time that the first papers on atmospheric composition, physical properties and evolutionary status appeared. Most recently, much research has been directed towards radial velocity measurements and the search for companion planets. Also shown in figure 2 is a Google Ngram Viewer plot for the keyword "Alpha Centauri". This more expansive representation indicates how the star has been referenced in the general literature as well as in scientific publications, journals, newspapers and magazines. The

nd space: Alpha Centauri



2: The literary history of α and Proxima Centauri from 1830 to 2012. Top: Five-year counts of scientific publications as derived from the NASA Astrophysics Data System. Orange bars correspond to publications relating to α Centauri, while the inset red bars relate to Proxima. Bottom: Google Ngram Viewer plots for references (literary as well as scientific) relating to α Centauri (orange line) and Proxima (red). The data is derived from word correlations found in the 5.2 million books that have been digitized (up to 2008) by Google Inc.

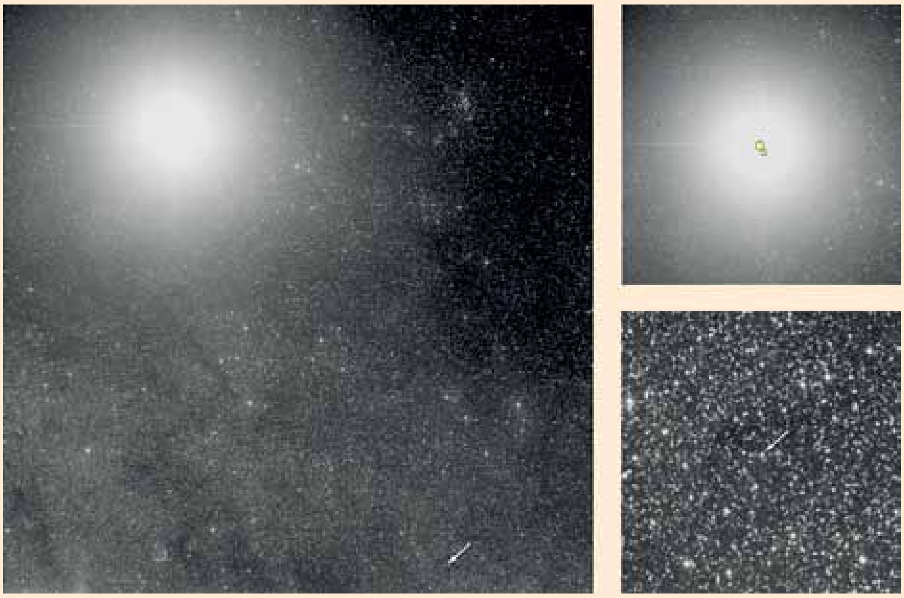
1: α Centauri is the bright yellowish star seen at the middle left. It is one of the "pointers" to the star at the top of the Southern Cross, which is seen on the right of this wide-field image, next to the dark area known as the coalsack. (ESO, Claus Madsen)

Ngram Viewer results suggest an intriguing ~30-year interval between peaks of interest, which we suggest might be a measure or reflection of a book's publishing lifetime and the career of a typical astronomer – each generation of astronomers and publishers apparently rediscovering an interest in the α Centauri system.

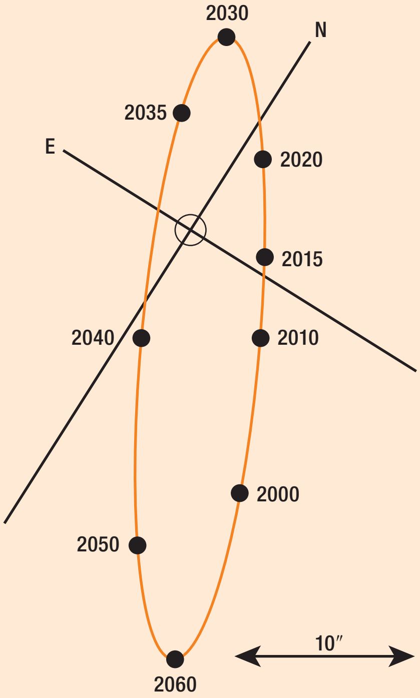
Not only does figure 2 illustrate the unfolding story of α Centauri, it also portrays the subtext relating to Proxima Centauri. Discovered by Robert Innes in 1915, the main point of initial interest concerning Proxima was its similar proper motion to that of α Centauri (Innes 1915) – and this in spite of a 2° separation upon the sky (figure 3). Proxima became an object of greater interest, however, once Joan Gijsbertus Voûte announced its first parallax determination (Voûte 1917). Not only did Proxima have the same proper motion as α Centauri, it was also located at the same distance from us – indeed, it was slightly closer to the Sun than α Cen AB. Remarkably, writing upon their closeness in distance and commonality of proper motion, Voûte questioned in his 1917 paper, "are they physically connected or members of the same drift?" In spite of nearly 100 additional years of observations, astronomers are still asking this very same question. With respect to its publication history, figure 2 indicates that Proxima has paralleled that, all be it at a lower level, of α Centauri.

So much for the human written record: published accounts take us back to the late 16th century AD. Greek mythology and, to some extent, reliable history take us back to perhaps the 12th century BC (the time of the putative Trojan Wars). Earlier than these times we enter the realm of unrecorded and decidedly unreliable history, and must turn to numerical computation to learn more about the α Centauri system. The observed parallax, radial velocity and proper motion data reveal that α Centauri became our nearest stellar neighbour some 50 000 years ago (Bobylev 2010). In addition, looking briefly to the future, uncertain as it may also be, further computations indicate that α Centauri will remain our nearest stellar companion for another 72 000 years (Matthews 1994, Bobylev 2010). Indeed, it will not reach its closest solar approach point for a further 27 000 years.

Pushing deeper back in time, beyond even the time of myths, we encounter a younger and younger solar system and, indeed, as our accelerated time frame rushes past 4.5 billion years ago the planets and Sun dissolve into an evanescent disc of spinning dust and gas. And, while α Centauri could witness none of the activity of our solar system's formation, it was already a respectable 1 to 2 billion years old at the time. Estimates of the formation age of α Centauri vary considerably, with current estimates varying between 5 and 7 billion years (Thévenin *et al.* 2002, Eggenberger *et al.* 2004) – to the α Centauri system forming, to an order of magnitude, when the Milky Way galaxy was about half of its presently estimated age. In parallel with Longfellow's passing ships in the night,



3: A family portrait of the α Centauri system. (Left): α Cen AB is highly overexposed in this image so that its faint, apparent magnitude +11, companion Proxima Centauri (arrowed) is revealed. Proxima is presently located about 2° away from α Cen AB as seen on the sky. (Upper right): The region surrounding α Cen AB. (Lower right): Star field surrounding Proxima (arrowed). (ESO)



4: The orbit of α Cen B as projected onto the sky – north is up and east is to the left in this diagram; the location of α Cen A is indicated by the open circle, and the position of α Cen B is shown at various epochs by small black dots. The next periastron passage occurs in May 2035. The horizontal line is a 10 arcsecond scale bar.

the Sun and α Centauri are but undertaking a brief galactic tango, for although α Centauri is currently the Sun's nearest neighbour it is not one of the Sun's direct relations: the α Centauri system must have formed from a very different natal cloud and galactic cluster to that of the Sun and in a very different part of the galaxy.

The present day

The first research papers concerning the orbital ephemeredes for α Cen AB appeared in the early 1850s and much of the publishing record relating to the system through to the 1930s was concerned with refining its elements. It is now clear that the α Cen AB system has a relatively high eccentricity of $e = 0.52$ and a semi-major axis $a = 23.68$ au with an orbital period of 79.91 years. Although the orbit of α Cen AB is inclined at a relatively high angle of $i = 79.2°$ on the sky, it has a longitude of ascending node $\Omega = 204.9°$ (Pourbaix *et al.* 2002) and accordingly it is well oriented for radial velocity planet searches (provided any planets orbit within the same plane of the binary – see below, and figure 4). The orbital characteristics of the α Cen AB + Proxima wide binary pairing are only poorly known at present (Wertheimer and Laughlin 2006, see also Beech 2011b and references therein). While the general conclusion presented by Wertheimer and Laughlin (2006) is that the available data supports the idea that Proxima is a bound trinary member of the α Centauri system, the inclination of its orbital plane, $i = 150.9°$, appears to be significantly higher than that of the α Cen AB orbital plane with $\Delta i = 71.7°$. While it is not uncommon to find non-coplanar orbits within triple systems (Sterzik and Tokovinin 2002, Naoz *et al.* 2011), this result, if ultimately shown to be correct, may have significant implications with respect to the formation of any extended cometary cloud about α Cen AB (Martyn Fogg: personal communication – see below).

In terms of spectral characteristics, α Cen A is a G2V star, α Cen B is a K1V star, while Proxima is an M5.5V (flare) star. Being Sun-like stars it is not surprising that both α Cen A and B exhibit small amplitude, 5–30-minute period, *p*-mode oscillations (Bouchy and Carrier 2002, Carrier and Bourban 2003) and this (along with their accurately known masses, radii and parallax) singles them out as highly valuable objects for the testing of stellar evolutionary models – this is especially so with respect to constraining theories of convective energy transport. Furthermore, with a mass of $1.1\,M_\odot$, α Cen A sits right on the boundary at which the CNO energy generation cycle begins to dominate that of the PP-chain and convective stellar cores are expected to once again appear on the main sequence. Indeed, by bracketing the Sun in mass, α Cen A and α Cen B (with a mass of $0.9\,M_\odot$) essentially provide us with alternative evolutionary pictures of what our solar system could have been (Beech 2012).

As well as constraining stellar model parameters, it has long been known that convection and differential rotation in the Sun combine to form a magnetic dynamo and a 22-year magnetic oscillation (as revealed through the magnetic polarity reversal of sunspot pairs in the 11-year sunspot cycle), and presumably any such similar activity in α Cen A and B tells us something about the long-term behaviour of this phenomenon. Through analysing the X-ray flux data archived from the ROSAT, XMM-Newton and Chandrasekhar spacecraft missions, Ayres (2009) finds some evidence to suggest that α Cen B is undergoing a ~9-year coronal/magnetic activity cycle (making it slightly more active than the Sun), while α Cen A is apparently in a Maunder minimum-like phase, showing essentially no variation in its coronal X-ray output (and presumably, if one could resolve its disc, no α Cen A spots). The rotation periods for α Cen A and B are among the most accurately known for any stars and come in at 22.5 ± 5.9 days (Bazot *et al.* 2007) and 36.2 ± 1.4 days (DeWarf *et al.* 2010) respectively.

In terms of composition, α Cen A and B and Proxima have super-solar metallicities with [Fe/H] values of 0.22, 0.26 and 0.21 dex respectively (Chmielewski *et al.* 1992, Schlaufman and Laughlin 2010). Indeed, it is the commonality of proper motion, distance and chemical composition that argues for α Cen AB and Proxima being coeval in origin, rather than their simply being chance close companions at the present epoch. Furthermore, the rotation period (about 80 days) and the coronal X-ray emission luminosity of Proxima are consistent with it having an age of ~6 billion years (see e.g. figure 3 of Engle and Guinan 2011), in good agreement with the stellar model estimate derived by Eggenberger *et al.* (2004).

In terms of observable characteristics there is nothing unique or even remarkable about the actual stars that constitute the α Cen AB binary.

Likewise, Proxima is a relatively pedestrian low-mass dwarf star (but see below). Given such properties it might be thought, at first response, that the system is only deserving of cursory attention – there being more exotic objects in the universe to study. It is, however, the very unexceptionality of the α Centauri system that makes it interesting and a prime candidate for being the host of one or more Earth Mark II planets. Indeed, it is the very possibility that planets might exist about all three of the stars in the α Centauri system that has driven much of the contemporary publication spike readily visible in figure 2.

Planet quest

There is a long history of science-fiction – both literary and cinematic – speculation about planets existing within the α Centauri systems. Prior to the last two decades, however, speculation (and wishful thinking) was all anyone had to go on. In terms of known and reasonably well understood astronomy, however, we are now collectively in a much better position to consider the question of planets having formed about our closest stellar neighbour. A recent survey of Sun-like stars (spectral types G and K) by Howard *et al.* (2010) finds a 23% likelihood that such stars harbour close-in (orbital periods less than 50 days) planets with masses in the range 0.5–2.0 Earth masses (M_{Earth}). Furthermore, current research appears to indicate that terrestrial (as well as jovian) planet formation about M spectral type dwarf stars is also highly likely, and that it proceeds at a level at least comparable to that of Sun-like stars (Pascucci *et al.* 2011). As well as falling in the spectral type range for which planet formation is most definitely confirmed, the super-solar metallicities of α Cen A and B further enhances the probability of their having associated worlds (e.g. Wyatt *et al.* 2007). Indeed, to paraphrase Guedes *et al.* (2008), the situation would appear to be that if planets do not exist within the α Centauri system, then we have seriously misunderstood how planet formation works. Gregory Laughlin (University of California at Santa Cruz) takes his confidence even further, and on his weblog (http://oklo.org/author/greg; highly readable and recommended) for 5 July 2006, states that he is “willing to bet a hundred dollars that [the planets] Alpha Centauri Ab and Bb exist”. Of course, the recent dramatic announcement of 17 October by Xavier Dumusque and co-workers (2012) that planet α Cen Bb exists, not only bolsters our confidence that some aspects of terrestrial planet assembly are actually understood, but also dictates that Laughlin’s money is now partially safe.

That long-term, stable planetary orbits might exist within the environment of either α Cen A or α Cen B was first demonstrated by Wiegert and Holman (1997), with the numerical simulations indicating a 4 au (co-planar orbit) stability boundary about each star. This stability limit was found to decrease significantly, however, as the orbital inclination increased; for inclinations close to 90° the stability limit is reduced to ~0.25 au. While showing that stable orbits are possible within the α Cen AB system is one thing, demonstrating that planets might potentially grow there is quite another. On the basis that jovian planets form at distances situated beyond the ice-line, which is located at 3–4 au for newly forming Sun-like stars, it seems unlikely (from current literature) that massive planets will have formed about either α Cen A or B.

This being said, there are no specific reasons to think that the accretion growth of terrestrial planets must likewise be hindered, as, indeed, the existence of α Cen Bb indicates. The accretion growth of terrestrial planets around single and binary star systems is now a reasonably well developed area of study, and several recent investigations have looked specifically at planet formation in the α Cen AB system. Quintana *et al.* (2002) for example, find terrestrial-mass planets can form on timescales of several hundred million years, within a region of about 2.5 au around either star for a range of disc angles up to 30° degrees away from the orbital plane. Barbieri *et al.* (2002), however, find that terrestrial planets might form on timescales of order 50 My around α Cen A out to distances of order 2 au for co-planar disc simulations. Guedes *et al.* (2008) and Thébault *et al.* (2009) additionally find that planets should have formed around α Cen B. Assuming an initial co-planar distribution of planetesimals, Guedes *et al.* argue that multiple 1–2 M_{Earth} planets might reside within the region 0.5–1.5 au from α Cen B. Taking into account the details of planetesimal encounters and impact velocities, however, Thébault and co-workers argue that planet formation is only favoured within a restricted zone of 0.5 au about α Cen B. At this stage it will be the discovery of additional planets, with orbits well beyond that of α Cen Bb, that will guide the development of next-generation planetesimal accretion models.

The extent of gravitational stirring within any natal planetary disc(s) is predominantly determined by the close approach distance of α Cen B to α Cen A. At present this close-approach distance is 11.4 au but, as pointed out by Thébault *et al.* (2009), the current orbital characteristics need not be those of the initial system where planets might have formed. Unfortunately, however, we know next to nothing about the cluster environment out of which α Centauri emerged; nor do we know anything about its possible sibling close-encounter history (but see Adams 2010, Dukes and Krumholz 2012). This being said, close encounters with sibling systems can either result in the complete disruption of the planetary building process, or it can enhance it – this, of course, is not a good situation for the theoretician to be in, since almost any scenario may now be made to fit the limited available data. Thébault *et al.* (2009), however, suggest that the odds of α Centauri having suffered an orbit-altering encounter through a sibling system close encounter may be as high as 1 in 2 – there literally being a 50% chance that the system we see now is not the same (in terms of orbital semi-major axis and eccentricity) as that in which planets might have formed. While Thébault *et al.* (2009) investigate the possibility that the closest approach distance between α Cen A and B was larger at the time of planet formation, any sibling-induced perturbations on the α Cen AB system (to produce the orbital characteristics as presently observed) must also, at some level, have had an effect upon the bound-state and initial orbital properties of Proxima Centauri. Likewise, close sibling encounters would also have a distinct effect upon the structure and number density of any associated cometary (Oort analogue) cloud that may have formed about α Cen AB (Beech 2011a and see below).

The modelling issues that have yet to be solved are, of course, detailed and complex, but it seems clear that there are presently no overridingly strong reasons to suppose that multiple terrestrial planets have not formed within the α Cen AB system. Furthermore, the presently available data also support the idea that planets, both jovian and terrestrial, can and indeed do form around even the lowest mass stars, and accordingly there is no specific reason to exclude the possibility of planets having formed about Proxima Centauri. In terms of known analogue systems, KOI-961 (Kepler-42) – a star with a similar mass, radius and spectral type as Proxima – indicates that multiple terrestrial planets can form in orbit about stars located at the very basement of the main sequence (Muirhead *et al.* 2012). Indeed, discovered as part of the Kepler mission, KOI-961 has three associated planets with masses and orbital radii of 2.06, 2.73, 0.9 M_{Earth} and 0.006, 0.012, 0.015 au respectively – it appears that the meek (measured in stellar mass at least) may yet inherit the Earth.

In terms of searches for planets, Proxima Centauri has been most deeply probed. Benedict *et al.* (1999), for example, performed an astrometric search for companions with the Hubble Space Telescope’s Fine Guidance System, and concluded that no planet with a mass greater than 0.8 $M_{Jupiter}$ with orbital periods between 1 and 1000 days is present. Küster *et al.* (1999) additionally find that no planets exist within the mass range 1.1–22 $M_{Jupiter}$, with orbital periods between 0.75 and 3000 days. Furthermore, Endl and Küster (2008) argue that should a planet of mass greater than ~2 M_{Earth} exist within Proxima’s habitability zone (the region 0.02–0.05 au – see below), then it should have been detected with currently available observational techniques by now. We note in passing that the three planets orbiting KOI-961 (Kepler-42), our Proxima analogue, all fall interior to the inner edge of the habitability zone for an M5 dwarf star.

With respect to α Cen AB, the five-year radial velocity survey starting in 1992 conducted by Endl *et al.* (2001) revealed the following constraints: for α Cen A there are no planets more massive than 1 $M_{Jupiter}$ within 2 au, and no 2 $M_{Jupiter}$ or larger mass planets 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. On the larger scale, a deep CCD imaging survey of the region immediately surrounding α Cen AB revealed no co-moving companions with masses greater than 15 $M_{Jupiter}$ at distances 100–300 au (Kervella and Thévenin 2007).

Several research groups have recently announced the initiation of dedicated α Cen AB planet-search programmes. These include the HERCULES high-resolution echelle spectrograph located at the Mt John Observatory in New Zealand (Endl *et al.* 2009); CHIRON, the Yale University/Planetary Society high-resolution echelon spectrometer located at the Cerro Telolo Inter-American Observatory; and, of course, the highly successful work with the HARPS instrument at the ESO-run La Silla Observatory will continue. Working to a precision of a few metres per second, these new surveys should be able to pin down the existence (that is, beat down the noise in the radial velocity signal) of an Earth-mass planet, in a 1 au orbit, about either α Cen A or α Cen B after some five or so years of high-cadence data gathering (see e.g. Guedes *et al.* 2008). The Mt John Observatory group (a collaboration between researchers at the University of Canterbury in New Zealand, the University of NSW in Australia, and the University of Texas at Austin) have collected some 24 000 spectra of α Cen A and 17 000 spectra of α Cen B at a rate of about 1000 spectra per month (John Hearnshaw – personal communication). Something like 30 000 spectra of each star will be required before terrestrial-planet companions might be detected – the signal for an Earth Mark II planet resident within α Centauri is going to be difficult to find, if it is there at all, but the prize for any first detection will be monumental. The HARPS team at La Silla Observatory may have drawn first blood with their discovery of α Cen Bb, but the race is now firmly focused on finding an Earth analogue.

The near-term future

Since the discovery of 51 Pegasi b in 1995 (Mayor and Queloz 1995), the first hot Jupiter detection, the rise in the number of known exoplanets has been nothing short of spectacular. As of this writing, a total of 843 exoplanets within 665 planetary systems are known and catalogued (http://exoplanet.eu). Beyond α Cen Bb, the closest confirmed planetary system is that of Gliese 674, an M3V dwarf star located just over 4.5 pc away which sports a 12 M_{Earth} (Neptune/Uranus-like) companion with an orbital period of 4.7 days (Bonfils *et al.* 2007). The closest known super-Earth is the super-hot 6.7 M_{Earth} planet Gliese 876d (Marcy *et al.* 2005; there are actually four planets in this system), at a distance of 4.7 pc.

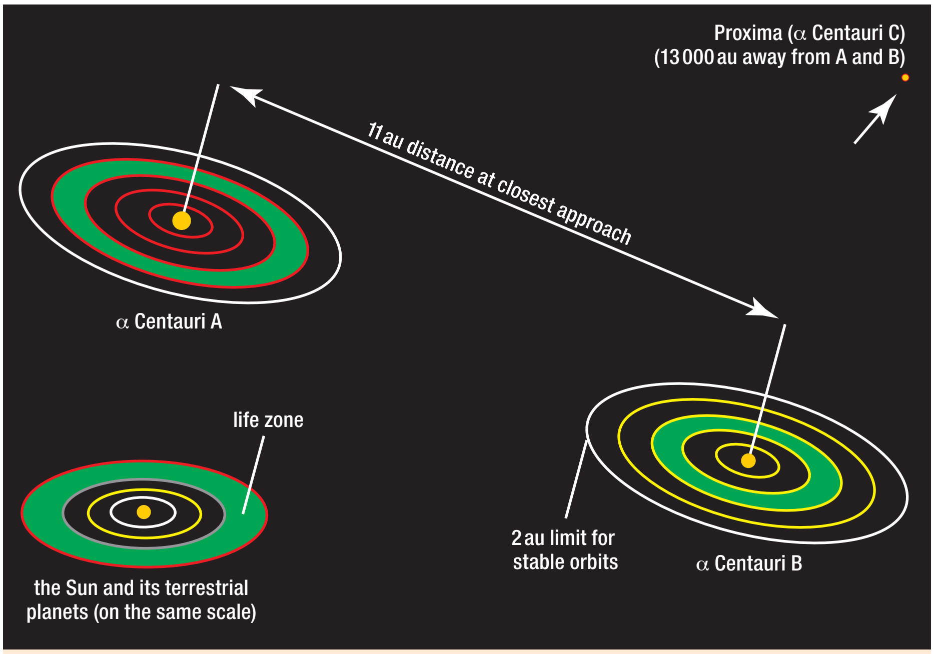
Within the sphere of radius 4.5 pc about the Sun there are 34 known stellar systems (http://www.recons.org). Of these systems, the K2V star ε Eridani, located at a distance of 3.2 pc, has a (yet to be confirmed) 1.6 $M_{Jupiter}$ planetary companion with a period of about seven years. While the radial velocity data presently leaves room for doubt about a planet, infrared and microwave wavelength observations do indicate that ε Eridani has a cometary/dust debris disc (located between 35 and 100 au) and possibly two asteroid belts at 3 and 20 au. (Project Ozma radio telescope monitoring of the star some 52 years ago found no evidence for the leakage of intelligible communication signals from ε Eridani – Drake 1960). If a planet is confirmed to exist around ε Eridani then the probability of a star system within the solar neighbourhood (radius ≤ 5 pc) supporting a planetary system is about 1 in 7.

One of the problems with any planetary search programme is to know when to stop: the non-detection of a signal (by transit, radial velocity or gravitational lensing methods) sets a threshold limit on mass (size), orbital radius, and orbital geometry, but there is always room for a smaller planet (even a dwarf planet) going undetected – absence of evidence is not evidence of absence. Direct *in situ* imaging of a system provides one possible way around this problem, but this approach creates the greater technological challenge of getting a spacecraft into interstellar space. The June 2011 decision by NASA to cancel the Terrestrial Planet Finder and Space Interferometer Mission programmes was a major blow to the search for exoplanetary systems – but a phoenix may yet rise from the ashes.

Saddened (if not angered) by the recent NASA cancellations, Geoffrey Marcy (University of California, Berkeley) made the provocative call, during a talk at the Next 40 Years of Exoplanets workshop at MIT held in May 2011, for a direct imaging, interstellar spacecraft to be launched towards α Centauri before the close of this century (Reich 2011). This is a bold idea, building even though it does upon earlier concepts, such as the British Interplanetary Society's Project Daedalus (a 1970s study concerning the design of an interstellar spaceship to visit Barnard's Star – now known to be an apparently planet-less M4V star; Choi *et al.* 2012), and the 1987–8 US Naval Academy's Project Longshot study which considered the possible exploration of α Centauri with an unmanned, fusion-powered space probe.

Striking a parallel path to that outlined by Marcy, the US Defense Advanced Research Projects Agency (DARPA) announced on 28 October 2010 the 100 Year Starship programme (http://100yss.org), making seed-funding available to those institutions interested in developing the programmes and infrastructure necessary to launch and administer an interstellar space mission within the next 100 years. It is interesting, in context, to reflect upon the fact that it was just 100 years ago that the Norwegian team of explorers led by Roald Amundsen first set foot upon Earth's South Pole. No target star has been selected for the 100 Year Starship programme to date, but α Centauri must be a prime candidate. The scientific rational and technology development required to promulgate a successful interstellar space programme are only just being considered, but we may hope that by the close of the 21st century a mission to directly image the primordial planetesimals and (presumed multiple numbers of) planets in the α Centauri system will be under way. Even if launched by 2100, however, the imaging data from any such mission is not likely to be returned for at least an additional century – a long wait, perhaps too long, for our downloaded, ever-linked, instantaneous and be-tweeted society. Only time (the great leveller) will tell if our distant descendents are to explore the α Centauri system directly or indeed to venture into interstellar space at all.

While the direct spacecraft imaging and investigation of the α Centauri system is likely to be played-out (if played-out at all) over a quarter-millennium timescale, the near-term prospects for planet detection remain high and will be significantly improved with the commissioning of the James Webb Space Telescope – currently scheduled for launch in 2018. Indeed, Kaltenegger and Taub (2009) have argued that with the new space telescope it will be possible to make detailed transmission-spectroscopy studies of the atmospheres surrounding any transiting Earth-analogue planets within the α Centauri system. The possibility of atmospheric analysis becomes especially interesting, of course, if an Earth-analogue planet is found within the habitability zone (HZ) of its parent star (Horner and Jones 2011). For α Cen A and B the HZ resides in the region 0.7–1.25 au (see figure 5). Having an orbital radius of just 0.04 au, therefore, α Cen Bb is situated deep inside of the inner HZ boundary of α Cen B, and it will also be tidally locked. With a surface temperature well in excess of 1000 K, the star-facing hemisphere of α Cen Bb will be a hellish world of oozing rock and continuous blinding starlight; its space-facing hemisphere, in contrast, will be a dark and frozen domain with only the periodic passage of



5: The closest approach distance of α Cen A and B and the relative sizes of their orbital stability and the habitability zones. (NASA)

α Cen A to animate and brighten its otherwise Stygian skies. Given its orbit and synchronized rotation state, the likelihood of α Cen Bb supporting any long-lived and/or extensive atmosphere seems, at best, very remote, but this will also depend upon such factors as volcanic outgassing, magnetic field effects, and the planet's actual mass. For low-luminosity Proxima, the HZ is located between 0.02–0.05 au. The probability that a transit might be observable in any given stellar system is $P_T \approx R^*/a_p$, where R^* is the radius of the parent star and a_p is the semi-major axis of the planet (Borucki and Summers 1984). For α Cen A and B, P_T is of order 1% for a planet on a circular orbit of radius 0.7 au; for Proxima, P_T is of order 3% for a planet on a circular orbit of radius 0.02 au. The probability of α Cen Bb undergoing observable transits is $P_T \approx 10\%$. The odds are not especially favourable, therefore, for planetary transits being visible from Earth, but then, neither are they zero.

Next steps and the known unknowns

On timescales of many years to multiple decades into the future, where might research relating to the α Centauri system go? Clearly the search for planets will continue for the foreseeable future, with the likelihood, given present technological abilities, that by (say) 2025 some form of definitive answer will be established; there being either multiple planets about one, two or all three stars in the system, or just a lonely α Cen Bb. Indeed, given the great complexity of the analysis involved, an independent verification of the true existence of α Cen Bb is still required. If additional planets do exist and if transits are observable, then transmission spectrum data will need to be collected, over many orbits, to look for possible biomarkers and wide-scale geological activity such as that related to volcanic emissions (Kaltenegger *et al.* 2010). The light-scattering characteristics of additional planets could also be studied to reveal the presence of oceans (Fugger *et al.* 2010), and to map-out large landmass configurations (Fujii and Kawahara 2012). If the planets are there and are found within the next decade, then by the mid-21st century we could in principle know an awful lot about their atmospheres, their surface topology and any seasonal weather changes – exciting possibilities indeed.

As well as the planet formation question, a clear explanation of the triple-system architecture of α Centauri has yet to be elucidated. Did, for example, the wide separation of Proxima from α Cen AB result from a close encounter with another star or stars, and if so was that encounter in the recent (several billion years) past or during the system's formative epoch when still embedded within its natal cluster (Kouwenhoven *et al.* 2009, Dukes and Krumholz 2012)? The available data suggest, at best, a marginally bound status for Proxima, and it has been touted as a possible candidate for the testing of alternate theories of gravity – such as the MOND paradigm (see Beech 2009, 2011b and references therein; Hernandez *et al.* 2012). When and by what mechanism(s) and, indeed, by what physics the current properties of the α Centauri system came about are clearly topics for further study.

In terms of stellar characteristics only the properties of Proxima seem to be at odds, albeit only slightly, with respect to standard expectation. Specifically, Proxima's observed flare activity, first described by Harlow Shapley (1951), appears to be somewhat higher and longer-lived than might be expected for a star of its apparent 6.5 billion year age. Using Sloan Digital Sky Survey data, West *et al.* (2008) find a flare activity cut-off age for M5V stars at about 7.0 ± 0.5 billion years, a result that presumably relates to the spin-down timescale and the passage of a threshold rotation rate below which the dynamo mechanism responsible for magnetic field generation is quenched. The available photometric data indicate that Proxima has a rotation period of 83.5 days (Benedict *et al.* 1998), indicative of a projected rotation velocity $v \sin i < 0.1$ km/s. The flare activity associated with Proxima, in which the X-ray luminosity can vary by factors of order 10 to 100 on a timescale of minutes (Güedel *et al.* 2004), will presumably have a profound effect upon the habitability of any associated planet(s), even if they do orbit within its canonical HZ (Odert *et al.* 2010).

The fact that Proxima, with a mass of $0.123\,M_\odot$ (Ségransan *et al.* 2003), will have a fully convective interior sets us an additional problem with respect to its flare activity. The problem is at least two-fold. First, it is not clear how a magnetic field capable of producing flare activity can be generated and maintained, and second, it is not clear how that field might be modulated to explain the observed 2 ± 1-year flare activity cycle (Benedict *et al.* 1998, Cincunegui *et al.* 2007, Mauas *et al.* 2012). The standard solar α-Ω dynamo model will not operate under the fully convective conditions at work within Proxima's interior, but it is possible that an α^2 dynamo, relying predominantly on convective motion (and some rotation), might be at work there (Chabrier and Küker 2006, Browning 2008). The α^2 dynamo begins to operate efficiently, producing a large-scale, co-rotating, asymmetric magnetic field, once the Rossby number (the ratio of the rotational period to the convective turnover time) is less than ~10 (Chabrier and Küker 2006). For Proxima, the estimated Rossby number is of order 0.5 (see Beech 2011a and references therein), and accordingly an α^2 dynamo should be active within its interior, though how all this translates to the observed flare activity and chromospheric X-ray emission has yet to be fully determined (Fuhrmeister *et al.* 2011).

While the α^2 model theoretically allows for the development of a long-lived magnetic field, it does not, at present, explain the flare activity cycle. Once again, it may be that within the flare activity of Proxima we are seeing environmental effects at work, with the variation possibly relating to cometary impacts (Beech 2011a). Indeed, given that planets have formed about α Cen A and B then some form of Oort cometary cloud structure might well be expected (Hill 1981). Measure for measure, with respect to the solar system's Oort cloud, Proxima presently sits close to the region in which the greatest number density of cometary nuclei should reside. Future *in situ* spacecraft mapping (that is, the determination of the extent and radial variation in nuclei number density) of any cometary cloud about α Cen AB, might, at least in principle, tell us something about its most recent close stellar encounters, and may further help to define the orbital extent and perturbation history of Proxima Centauri.

A circumbinary disc of icy planetesimals and cometary nuclei (analogues of our solar system's Edgeworth–Kuiper belt and Oort cloud) could well form about α Cen AB irrespective of the actual growth of planets around α Cen A and/or B. The possible extent and stability of such discs has recently been investigated by Martyn Fogg (personal communication). Working to define the characteristics of possible target stars for the Project Icarus interstellar spacecraft (http://www.icarusinterstellar.org; see also Crawford 2010), Fogg found strong disc disruption (as a consequence of Kozai resonance) if Proxima had an orbital inclination larger than ~40° to that of the orbital plane of α Cen AB. Fogg's study assumed that Proxima moved on an orbit with $a = 8500$ au and $e = 0.78$ – based upon calculations by Beech (2011b). Once again, these results underscore the urgent need for a better determination of the orbit of Proxima. Ignoring the gravitational influence of Proxima, Jaime *et al*. (2012) find that the closest stable and co-planar circular orbit for a circumbinary planet about α Cen AB is set at a radius of 360 au. This result, should it turn out to be robust, suggests that it might yet be worthwhile to extend the optical planetary search beyond that presented by Kervella and Thévenin (2007), and to perhaps push the survey wavelength into the infrared region where a circumbinary dust-ring might await discovery.

The far distant future

Moving ever deeper into the future, far beyond the 21st century, α Centauri will continue to track further and further away from the Sun; each system ploughing its independent course about the galactic centre. A million years from now, α Centauri will no longer be visible to the naked-eye from Earth and, as a result of proper motion, the entire Centaurus constellation will have shifted beyond present recognition. Once again, the Centaur will have passed into the realm of ancient memory and the shape-shifting world of mythology.

On the timescale of stellar evolution, the characteristics of the α Centauri system will hardly change for a further 3 billion years (Beech 2012). It will be at this time that α Cen A, having exhausted the hydrogen within its central core, will begin its advancement to red giant status, swelling dramatically in size and greatly increasing in luminosity. With these changes the habitability zone of α Cen A will be swept outwards to a region well beyond that in which stable planetary orbits might exist. Not only this, as α Cen A enters its advanced helium burning, asymptotic giant branch, phase of evolution, its energy output will become sufficiently high to sterilize the habitability zone of α Cen B. At present α Cen A would have a minimal heating effect on any habitable Earth-analogue planet orbiting α Cen B (Forgan 2012). In apocalyptic resonance, should habitable planets actually exist within the α Cen AB system then the demise of their biospheres will take place about a billion years after the destruction of our own (a result brought about, in our case, by the increased luminosity of the Sun and the onset of a runaway moist greenhouse heating effect).

As α Cen A moves through its giant and asymptotic giant branch phases of evolution, it will begin to lose more and more mass via an enhanced stellar wind. Indeed, as it enters its final white dwarf configuration it will have slimmed down to about 60% of its present bulk. For Proxima Centauri this mass loss will prove critical, and its gravitationally bound status will eventually be compromised. Indeed, in about 3.5 billion years from now the α Centauri system is likely to lose its outermost red dwarf component. No longer gravitationally bound to α Cen AB, Proxima will begin to move along an independent path about the galactic centre. As time continues to tick by, α Cen B will, in about 10 billion years, begin to evolve away from the main sequence. Numerical studies of the two-body problem with isotropic mass loss (Beech 2012) indicate that as the α Cen AB system loses more and more mass, its orbital eccentricity increases towards unity, resulting eventually in complete system disaggregation. Indeed, in about 12.5 billion years the α Centauri triple system will be no more, having fully separated into three independently moving objects: a red dwarf star (Proxima) and two ~0.6 $M_\odot$ mass white dwarfs (the remnants of α Cen A and B).

With a mass of just over 0.1 $M_\odot$, Proxima has a stellar lifetime that is measured in multiple trillions of years. Indeed, it is remarkable to think that before Proxima begins to enter its final degenerate white dwarf cooling phase (set some 6 trillion years from now – Adams *et al.* 2004), not only will the up-coming collision between the Milky Way galaxy and Andromeda (set to take place in about 4 billion years time) be mythical ancient history, but also galactic star formation itself will have ceased. In fact the entire visible universe, along with the cosmic background radiation, will have changed beyond all present-day recognition. ●

Martin Beech, Campion College, University of Regina, Canada (beechm@uregina.ca).

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