Scientific and Societal Benefits of Interstellar Exploration

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Chapter 1

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The growing realisation that planets are common companions of stars [1–2] has reinvigorated astronautical studies of how they might be explored using interstellar space probes (for reviews see references [3-7], and also other chapters in this book). The history of Solar System exploration to-date shows us that spacecraft are required for the detailed study of planets, and it seems clear that we will eventually require spacecraft to make in situ studies of other planetary systems as well. The desirability of such direct investigation will become even more apparent if future astronomical observations should reveal spectral evidence for life on an apparently Earth-like planet orbiting a nearby star. Definitive proof of the existence of such life, and studies of its underlying biochemistry, cellular structure, ecological diversity and evolutionary history will require in situ investigations to be made [8]. This will require the transportation of sophisticated scientific instruments across interstellar space.

Moreover, in addition to the scientific reasons for engaging in a programme of interstellar exploration, there also exist powerful societal and cultural motivations. Most important will be the stimulus to art, literature and philosophy, and the general enrichment of our world view, which inevitably results from expanding the horizons of human experience [9,10]. In the longer term, interstellar colonisation will lead to increased opportunities for the spread and diversification of life and culture through the Galaxy and greatly increase the survival chances of homo-sapiens and our evolutionary successors.

Starship Science

There can be little doubt that science, especially in the fields of astronomy, planetary science and astrobiology, will be a major beneficiary of the development of an interstellar spaceflight capability. In its long history astronomy has made tremendous advances through studying the light that reaches us from the cosmos, but there is a limit to the amount of information that can be squeezed out of the analysis of starlight and other cosmic radiation. Already we can identify areas where additional knowledge will only be gained by making in situ observations of distant astronomical objects. As I noted in an earlier review of interstellar spaceflight [3], a sense of the scientific potential may be glimpsed by considering "the advantages of taking thermometers, magnetometers, mass-spectrometers, gravimeters, seismometers, microscopes and all the other paraphernalia of experimental science to objects that can today only be observed telescopically."

The scientific objectives of interstellar probes have been described previously by Webb [11] and Crawford [8], and can be divided into the following broad categories: (i) studies conducted en route (e.g. of the local interstellar medium, and other physical and astrophysical studies that could make use of the vehicle as an observing platform); (ii) astrophysical studies of the target star itself (or stars if a multiple system is selected); (iii) planetary science studies of any planets in the target system, as well as moons, asteroids and comets; and (iv) astrobiological/exobiological studies of any habitable (or inhabited) planets or moons that may be found in the target planetary system. Each of these areas has different requirements for the overall architecture of an interstellar mission and for the scientific payload to be carried. We will now briefly consider each in turn.

Interstellar medium studies

By definition, any interstellar vehicle will have to traverse the interstellar medium between the Solar System and its target star. As any target star for an early interstellar mission is certain to be within a few light years of the Sun, it follows that only the local interstellar medium (LISM) is relevant here. I have provided a detailed review of the structure of the LISM, with interstellar travel specifically in mind, in a separate article [12] to which the interested reader is referred. Briefly, the Sun is currently located close to the boundary of a small (spatial extent ≤ 10 light years), low density (n_H> ~ 0.1-0.2 cm^{-3}, where n_H is the density of hydrogen nuclei), warm (T ~ 7,500 K) and partially ionised interstellar cloud known as the Local Interstellar Cloud (LIC). Whether the Sun lies just within, or just outside, the LIC is currently a matter of debate. The LIC is only one of several broadly similar interstellar clouds within 15 light years of the Sun; for example, Redfield and Linsky [13] identified seven such clouds within this volume. These are immersed in the very empty (n_H in the range 0.005 to 0.04 cm^{-3}) and probably very hot (T ~ 10^4 to 10^6 K) Local Bubble in the interstellar medium that extends for about 300 light years from the Sun in the galactic plane before denser interstellar clouds are encountered.

These properties have been estimated by a range of astrophysical techniques and are still quite uncertain (see [12] and references therein). Key measurements that could be made from an interstellar probe and which would add enormously to our understanding of interstellar processes, would include in situ determinations of density, temperature, gas-phase composition, ionisation state, dust density and composition, interstellar radiation field and magnetic field strength, all as a function of distance between the Sun and the target star system. Such in situ measurements, even though obtained on a very local scale in the galactic context, would be invaluable for validating ('ground truth') information based on astronomical techniques that will, of necessity, continue to be used to determine interstellar medium properties at larger distances (both within our Galaxy and beyond). These measurements will also be invaluable for the planning of all future interstellar space missions. The first mission will be a pathfinder in this respect and will enable all subsequent missions to be designed with a much firmer knowledge of the properties of the material through which they will have to travel.

We note that none of these measurements impose stringent constraints on the architecture of an interstellar mission. From the perspective of interstellar medium studies a simple undecelerated interstellar probe would be sufficient to obtain the necessary measurements.

Stellar studies

We know far more about the Sun than any other star, simply by virtue of the fact that it is so close to us. Interstellar spaceflight would enable us to obtain comparable information about stars of other spectral types. Such observations are likely to lead to significant advances in stellar astrophysics, although their extent will depend, at least in part, on the time window that is available in which to make the measurements and this will have implications for the mission architecture.

There are really three reasons for our enhanced knowledge of the Sun compared to other stars: (i) vastly increased spatial resolution, which permits the observation of small scale features on the photosphere (e.g. sunspots and associated phenomena), chromosphere and corona; (ii) greatly increased brightness, which permits very high-signal-to-noise observations (that among other things facilitates the use of helioseismology to probe the Sun's interior structure); and (iii) a long time base of observations (hundreds of years of recorded human observations and millions of years of relevant geological records on the Earth and other planets).

Although we might expect interstellar space travel to help principally with the first two of these, we have to recognise that long before rapid interstellar spaceflight becomes feasible, astronomical instrumentation is likely to have advanced to the point where many nearby stars will be resolvable from observations conducted from the Solar System. Indeed, we have already reached the point where the radii of nearby low mass stars can be measured directly using ground-based optical interferometry and the next generation of space-based interferometers may be able to resolve surface features [14]. Similarly, the advent of very large ground- and space-based telescopes will go some way to address signal-to-noise limitations caused by the relative faintness of other stars compared to the Sun. Nevertheless, it will always be true that the spatial resolution and signal-to-noise of observations conducted from a vantage point in the vicinity of a target star will be vastly higher than comparable observations attempted from the vicinity of the Earth. So, while we should avoid exaggerating the benefits to observational stellar astronomy from interstellar missions to the closest stars, we can nevertheless be sure that such advantages do exist.

While undoubtedly scientifically valuable, stellar observations conducted from an interstellar fly-by mission would suffer from disadvantages arising from the short time span available for the highest resolution observations. Much greater benefits would result if it proved possible to decelerate at the target star system. It would then be possible to ring the star with satellites to acquire long term observations of the whole stellar surface and to obtain time-resolved, high-resolution, multi-wavelength observations of the corona and stellar wind. As such observations are of demonstrable importance for understanding of our Sun, it follows that they would also be desirable for studies of other stars, but this will require the interstellar carrier spacecraft to decelerate essentially to rest in the target star system. In addition, all stars are surrounded by circumstellar matter to varying degrees and in situ studies of this would also be of scientific interest. Undoubtedly of greatest interest would be studies of protoplanetary discs from which planets may have recently formed, or still be forming. Measurements of the density, temperature, magnetic field and, crucially, dust particle size as a function of radial distance from the star and distance from the disc mid-plane would greatly add to our understanding of planet formation processes. However, the nearest known example of a circumstellar disc of this type is around the star epsilon Eridani at a distance of 10.5 light years (see Table One later in this chapter) and, although a possible candidate for an early interstellar mission, its relatively large distance means it is unlikely to be a high priority for the first such missions.

Planetary Science

Over 1,000 planets are now known to orbit other stars [1,2], with new discoveries being made every month. The Kepler Space Telescope has already identified an additional 3,538 candidates (most of which will be confirmed as planets), and there will be many more to come as the full Kepler dataset is analysed [15]. Indeed, a conservative view of the statistics, discussed later in this chapter, implies that most stars in the Galaxy will be accompanied by planetary systems.

Future astronomical observations are certain to improve our knowledge of planetary systems around nearby stars. These discoveries are likely to be followed in the coming decades by observations conducted with increasingly sophisticated space-based telescopes able to directly image planets orbiting nearby stars (say out to 30 light years) and to obtain spectroscopic measurements of their atmospheres [16]. Indeed, it is salutary to reflect that, within the coming decades, astronomical observations will very likely have raised our knowledge of planetary systems around nearby stars to a level comparable to that obtained for the planets in our own Solar System prior to the Space Age. That is to say, we will know the number of planets in each system (down to some minimum mass that will probably be significantly less than that of Earth), together with their orbital parameters, masses and densities, presence or absence of an atmosphere, atmospheric composition, presence of large natural satellites, etc. All this can probably be learned without having to leave the Solar System.

That said, the history of the exploration of our Solar System shows that obtaining significantly more knowledge of extra-solar planetary systems will require in situ observations by spacecraft. We can be sure of this because, over the last half century, spacecraft have completely revolutionised the study of the planets of the Solar System, providing information that could never have been obtained telescopically from the surface of the Earth or its immediate vicinity. To highlight just three out of hundreds of possible examples, consider the structure of the lunar interior as probed by the Apollo seismic experiments, the fine scale (i.e. millimetres to centimetres) resolution of mineralogical and sedimentary structures at the landing sites of the Mars Exploration Rovers (with their implications for the volcanic and hydrological histories of that planet) and the discovery of lakes of liquid methane (and indeed an entire methane hydrological cycle) under the orange smog of Titan's atmosphere by the Cassini–Huygens mission. It follows that if we wish to obtain comparable knowledge of the planets orbiting other stars then we will have to go there and look.

The analogy with the exploration of our own Solar System has implications for the architecture of an interstellar mission designed with planetary science in mind. There is a hierarchy of architectural options for planetary missions, in order of increasing complexity and energy requirements, but also in increasing scientific return: (i) fly-by missions; (ii) orbital missions; (iii) hard landers; (iv) soft landers (with or without rover-facilitated mobility); and (v) sample return missions. The same general ordering will apply in the study of extra-solar planetary systems, although the relative jumps in difficulty between them are not the same in the two cases.

An undecelerated fly-by will be the easiest to implement and, for this reason, was adopted in the pioneering Daedalus study [17]. However, the exploration of the Solar System shows that, while appropriate for the initial reconnaissance of a planetary body, fly-bys are very limited in terms of the knowledge they are able to collect (and sometimes this information can be misleading, as in the case of the Mariner 4 fly-by of Mars in 1965 that revealed a lunar-like landscape and gave little intimation of the geological diversity discovered by later missions). The limitations of fly-bys in an interstellar mission will be exacerbated by the high speeds involved – the Daedalus study proposed to conduct planetary investigations from multiple sub-probes flying close to target planets at 12 percent of the speed of light. This would permit less than a second of time available for detailed observations at distances comparable to the radii of planetary-sized bodies, although perhaps several hours of useful observations might be obtained on the approach to and departure from the planet in question.

Much more scientific information would be obtained if it proved possible to decelerate an interstellar vehicle (or at least any sub-probes designed to conduct planetary observations) from its interstellar cruise velocity. The benefits will be immediately obvious by comparing the results of the initial fly-by reconnaissance of Mars by Mariners 4, 6 and 7 with those of the early orbital missions (i.e. Mariner 9 and Vikings 1 and 2) that discovered, amongst other things, the giant Tharsis volcanoes, the Valles Marineris canyon system and numerous dried-up river valleys indicating a warmer, wetter Martian past. Of course, even more detailed information has resulted from the handful of soft landers and rovers that have successfully reached the surface.

Although in terms of Solar System exploration there is a big jump in energy requirements between orbital missions and soft landers, this would not be a major consideration in terms of an interstellar mission – the energy differential between orbital insertion and a soft landing is trivial in comparison to that of decelerating a probe from a significant fraction of the speed of light. As for Solar System missions, landers would permit a range of geochemical, geophysical and astrobiological investigations that are simply not possible from an orbiting spacecraft. Thus, despite the added complexity involved, the potential scientific benefits are such that the designers of any interstellar mission capable of decelerating at its destination should consider including sub-probes that are capable of actually landing on the surfaces of suitable planets.

The most ambitious Solar System missions involve sample return, which allow detailed investigation of planetary materials in terrestrial laboratories. However, for any reasonable extrapolation of foreseeable technology, sample return is essentially impossible from an extra-solar planetary system on any reasonable timescale. It follows that the kinds of sophisticated geochemical (and biological) analyses that today require samples to be returned to Earth will have to be automated for in situ robotic operation within the target planetary system. Fortunately, by the time we will be in a position to build interstellar probes, the capabilities of autonomous laboratory analyses should have advanced considerably beyond present capabilities.

Astrobiology/Exobiology

Astrobiology is the science relating to the search for life elsewhere in the Universe, especially the astronomical and planetary environments that may nurture it. By adding to our knowledge of other stellar and planetary environments, the in situ scientific investigations outlined above would be of considerable astrobiological value even if no indigenous life is present in the target system. Nevertheless, it is clear that the greatest scientific interest would be in the discovery and characterisation of any life-forms that may be present. If such extraterrestrial organisms are found, their study will presumably become the subject of a new sub-discipline of biology where, by definition, the study of living things properly belongs [18].

As noted above, before rapid interstellar space travel becomes possible we will almost certainly have identified which of the nearest stars are accompanied by planetary systems. Indeed, we are likely to know the basic architecture of these systems in some detail and Solar System-based instruments will have the capability of detecting any molecular biosignatures that may be present in the atmospheres and/or on the surfaces of these planets [16]. We can therefore be confident that astronomical observations will be able to establish a hierarchy of priorities among any planets that may be detected around the nearest stars: (i) planets where bona fide bio-signatures are detected; (ii) planets that appear habitable (e.g. for which there is spectral evidence for water and carbon dioxide, but no explicit evidence of life being present); and (iii) planets that appear to have uninhabitable surfaces (either because of atmospheric compositions deemed non-conducive to life or because they lack a detectable atmosphere), but which might nevertheless support a subsurface biosphere. Thus, when planning an interstellar mission with astrobiology/exobiology in mind, we are likely to have a priority list of target systems prepared well in advance.

As for the planetary science cases discussed in Section 2.3 and for the same reasons, it is not immediately obvious that simple fly-by missions could add significantly to information likely to be obtained by the astronomical observations from the Solar System. There will be some advantages: even travelling at a significant fraction of the speed of light, probes (or sub-probes) targeted to fly close to planets could presumably perform much more detailed analyses of their atmospheric compositions than would be possible astronomically from the Earth. Nevertheless, it seems clear that only an interstellar probe that decelerated into its target star system would be able to deploy the kind of instrumentation that biologists would need to begin an investigation of an alien biosphere in any detail.

We can get an idea of the kind of instruments that would be required by considering those that have either been used (e.g. the Viking biology package [19] and the Phoenix high-resolution microscope [20]), or are planned to be used (e.g. the Urey organic molecule analyser [21] and the Life Marker Chip [22]), in the search for life on Mars. Doubtless much more sophisticated analytical tools will be available by the time of the first interstellar mission. However, it seems clear that deployment of instruments such as these would require the soft-landing of suitably instrumented sub-probes on a planetary surface – such analyses cannot be done while flying through the target system at ten percent of the speed of light!

Cultural and Societal Motivations for Interstellar Exploration

In addition to the scientific reasons for wanting to travel to the stars there are also a number of compelling cultural and societal reasons. As I have argued previously [23], many of these societal benefits would result from any large-scale programme of space exploration, beginning in our own Solar System. However, exploration and colonisation on interstellar scales will greatly increase the potential benefits, to which we now turn.

Survival

Currently humanity exists on a single small planet adrift in what is at best an uncaring and at worst a dangerous Universe. Our civilisation and perhaps even our existence as a species is therefore vulnerable to a range of natural hazards that could affect the habitability of our planet (examples include asteroid and comet impacts, large volcanic eruptions and unanticipated changes in solar activity). Moreover, we have to recognise that we are also at risk from ourselves, through the accidental or deliberate misuse of our own technology (obvious examples include nuclear or bacteriological warfare or terrorism, and irrecoverable environmental degradation). While there are in principle technological means to mitigate the former risks and political means to mitigate the latter, the fact remains that humanity will remain vulnerable to extinction while we remain a single-planet species. As Shepherd [24] put it, in what was arguably the first ever detailed discussion of the technical possibility of interstellar spaceflight, "Humanity dispersed over many worlds would appear to be more secure than humanity crowded on one single planet."

Although it is true that many of the existential threats facing humanity (e.g. asteroid impacts and enhanced terrestrial volcanic activity) would be greatly alleviated by establishing human colonies elsewhere in the Solar System, others (e.g. unanticipated solar or galactic events) could in principle render the entire Solar System uninhabitable. Of course, on the longest (albeit multi-billion-year) timescales we know that the inexorable evolution of the Sun towards becoming a red giant star will eventually completely sterilise first the Earth, then Mars and eventually even the moons of the outer Solar System [25]. Ultimately, therefore, the survival of humanity (and, on longer timescales, our evolutionary successor species) and indeed of terrestrially-evolved life itself will depend on interstellar colonisation.

Diversification of Life, Culture and Intelligence in the Galaxy

In addition to 'mere' survival, the expansion of humanity (and ultimately post-humanity) into space opens up opportunities for the diversification of culture, what John Stuart Mill termed "different experiments of living" [26], that would otherwise not occur. As long ago as 1948 this was recognised as a potential benefit of space colonisation by the English philosopher Olaf Stapledon when, in a lecture to the British Interplanetary Society [27], he expressed the view that "The goal for the solar system would seem to be that it should become an interplanetary community of very diverse worlds each inhabited by its appropriate race of intelligent beings, its characteristic 'humanity'… Through the pooling of this wealth of experience, through this 'commonwealth of worlds' new levels of mental and spiritual development should become possible, levels at present quite inconceivable to man."

Although, as envisaged by Stapledon, opportunities for diversification of culture will presumably result from colonising the planets and moons of the Solar System, these will remain very limited compared to the possibilities resulting from interstellar colonisation. Readers interested in exploring some of the possibilities are referred to chapters in the books *Interstellar Migration and the Human Experience* [28] and *Starship Century* [29] and, of course, to countless science fiction stories too numerous to mention here.

As Stapledon himself realised (see discussion in [30]), the scope for human (and post-human) colonisation and diversification throughout the Galaxy depends crucially on the presence or absence of other intelligent species. We do not yet know how common, or otherwise, extraterrestrial intelligence may be, but the so-called Fermi Paradox (i.e. the observation that the Earth has not itself been colonised by other technological civilisations [31-33]) suggests that other civilisations may be very rare or even non-existent. If our Galaxy, or at least our part of it, really is devoid of other intelligent civilisations, it follows that the future of intelligence in the Galaxy will depend on us. It may then be desirable for humanity (or post-humanity) to start moving out through the Galaxy colonising uninhabited planets because this would enhance the diversity and creative potential of intelligent life in the Universe. We must however recognise, as Stapledon also foresaw, that these alien planetary environments are unlikely to be such as to support human life directly and that terraforming the planets (i.e. rendering them more Earth-like) and/or genetic engineering the colonists (to adapt them to the local environments), is likely to be necessary.

There is one further important point to make. Not only do we not know how common extraterrestrial intelligence is in the Galaxy, we do not as yet even know how common life itself is. It may be that the transition from non-life to life is so unlikely that it only happens very rarely and for all we know it may have happened only once (see discussion by Paul Davies [33]). If our astronomical searches and eventual follow-up interstellar probes do reveal life to be absent even on apparently habitable planets then the question will arise as to whether we should seed them with life derived from Earth. As discussed by Francis Crick [34], even if it proves too difficult to send human beings to the stars, we can certainly envisage spreading Earth-life to other planetary systems, perhaps in the form of micro-organisms specifically genetically engineered to survive the journey and thrive on a particular target planet. If one accepts that life, with its vast potential for growth and diversity, is preferable to non-life then this could be seen as a desirable activity (although great care would need to be taken to ensure that the target planets really were uninhabited – damaging an indigenous biosphere by introducing life from Earth would be unconscionable). Conceivably, therefore, the future evolution of all life in the Galaxy and not just human (and post-human) intelligent life, may depend on interstellar exploration and colonisation activities initiated by humanity within the next few centuries.

Avoiding Intellectual Stagnation and 'the End of History'

In 1989 the American political philosopher Francis Fukuyama published a remarkable essay entitled *The End of History?* in an obscure American journal [35]. The essence of Fukuyama's argument (subsequently expanded in his book *The End of History and the Last Man* [36]) was that humanity might be approaching the end of a long ideological evolution toward a stable form of political organisation (specifically that the whole world will soon be organised on liberal democratic principles). Although subsequent events (perhaps most worryingly the increasing influence of fundamentalist religious ideologies in some parts of the world) may suggest that Fukuyama was overly optimistic, a general trend towards democratic and liberal values has been apparent in world history for several centuries and seems likely to continue. However, despite the essentially optimistic nature of the argument, Fukuyama himself was ambivalent towards this outcome because he believed that an end to human ideological competition would also mean an end to human achievement and creativity. As he put it [35]: "The end of history will be a very sad time. The struggle for recognition, the willingness to risk one's life for a purely abstract goal, the worldwide ideological struggle that called forth daring, courage, imagination and idealism, will be replaced by economic calculation, the endless solving of technical problems, environmental concerns and the satisfaction of sophisticated consumer demands. In the post-historical period there will be neither art nor philosophy, just the perpetual care-taking of the museum of human history."

In contrast to this rather depressing vision of the future, what we really want to do is build a human civilisation that is both stable and dynamic. That is, a civilisation that is at peace with itself, but which is nevertheless an exciting place in which to live and, crucially, one whose history remains open. As I argued an initial response to Fukuyama's ideas [9], an ambitious programme of space exploration is ideally and, perhaps uniquely, suited to satisfying these socially desirable objectives.

Fukuyama was especially concerned that a homogenised future world would mean an effective end to human creativity because many traditional sources of artistic and intellectual stimuli would have dried up. I think it must be true that new sources of intellectual stimuli will be required if human (and eventually post-human) culture is not to stagnate, because ultimately all our science, art, and philosophy is built on what John Locke [37] called 'simple ideas' – that is ideas based on sense perception and reflection on these perceptions. It follows that we cannot imagine genuinely new things, but instead need to discover them. This is the ultimate cultural benefit of all exploration.

In the present context, it is clear that space exploration presents a vast new field of activity with literally infinite potential for discovery and intellectual stimuli of multiple kinds – certainly a far richer range of stimuli than we could ever hope to experience by remaining on our home planet. As was the case for the survival and diversification issues discussed above, humanity will begin to experience these intellectual and cultural benefits by exploring and colonising our own Solar System, but it is on the far larger stage of interstellar exploration that they will really come into play.

Possible destinations: Stars and Planets Within 15 Light Years

Given the sheer technical difficulties of achieving interstellar spaceflight on a human timescale (see discussion in references [3-7], and other chapters in this book), for the foreseeable future only the very nearest stars are likely to be candidates for exploration. Here I consider a radius of 15 light years from the Sun to enclose the volume likely to be of interest for the early phases of an interstellar exploration programme (i.e. a distance that could be covered in 100 years at an ambitious cruising speed of 15 percent that of light).

Within 15 light years of the Sun there are approximately 58 stars, in 39 separate stellar systems. These are listed in Table One. The number is approximate for several reasons. Firstly, at the outer boundary the errors on the distances can amount to a few tenths of a light year, which could mean that some stars notionally just beyond 15 light years might actually be closer (and vice versa). Secondly, not all stars within this volume may yet have been discovered, although this is only likely for the very dimmest red or brown dwarfs; that this is a very real possibility was reinforced by the 2013 discovery of the nearby brown dwarf binary WISE J104915.57-531906.1 at a distance of only 6.6 light years [38] – suddenly we found that the Sun has a new third-closest star system! Thirdly, perhaps surprisingly, there are still slight discrepancies between the various astronomical catalogues of nearby stars.

Probably the most authoritative recent compilation of nearby stars and the one on which the number of 58 stars is based (with the addition of WISE J104915.57-531906.1), is the Research Consortium on Nearby Stars (RECONS) list of the 100 nearest star systems [39]. Of these 58 stars, there is one star of spectral type A (Sirius); one F star (Procyon); 2 G stars (alpha Centauri A and tau Ceti); five K stars; 41 M stars (red dwarfs); 3 white dwarfs; and five probable brown dwarfs (Table One). A visual impression of the spatial distribution of these nearby stars (restricted to a distance of 12.5 light years for clarity) is given in Figure One on the next page.

Excellent summaries of known extra-solar planets can be found in the Extra-Solar Planet Encyclopaedia maintained by Jean Schneider at Strasbourg Observatory [2] and the NASA Exoplanet Archive [41]. Of the stars listed in Table One, four are currently known or suspected to have accompanying planets. These are alpha Centauri B (a member of the closest star system to the Sun at a distance of only 4.36 light years, although this planet has yet to be confirmed);

epsilon Eridani (a single K2 star at a distance of 10.5 light years); tau Ceti (a single G8 star at a distance of 11.9 light years, although in this case also the existence of planets is at present somewhat controversial); and GJ 674 (a M3 red dwarf at a distance of 14.8 light years).

In the following sections I briefly describe what is known about these nearby planetary systems, before moving on to a discussion of the implications of the known statistical properties of more distant planetary systems for the actual frequency of planets within 15 light years from the Sun.

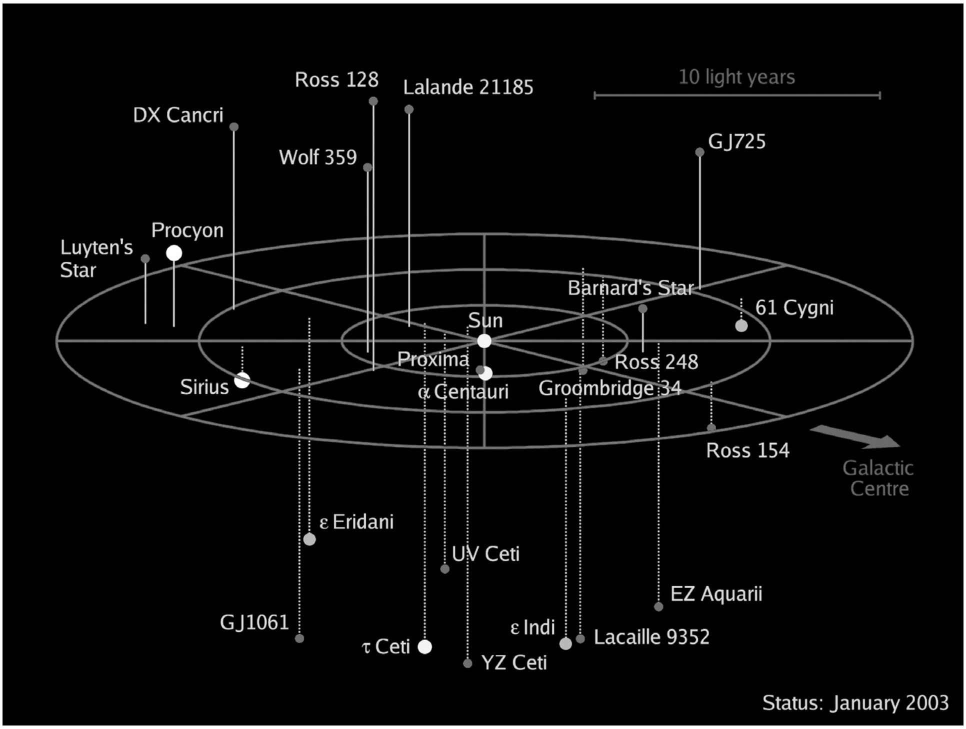

Figure One: a 3D map of all known stellar systems in the solar neighbourhood within a radius of 12.5 light-years as of January 2003. The colour is indicative of the temperature and the spectral class – white stars are (main sequence) A and F dwarfs; yellow stars like the Sun are G dwarfs; orange stars are K dwarfs; and red stars are M-dwarfs, by far the most common type of star in the solar neighbourhood. The blue axes are oriented along the galactic coordinate system, and the radii of the rings are 5, 10, and 15 light-years, respectively. Image: ESO/R–D Scholz et al (AIP).

alpha Centauri

In one of the most exciting astronomical discoveries of recent years, researchers using instruments at the European Southern Observatory in Chile reported in November 2012 the detection of an Earth-mass planet orbiting alpha Centauri B [42]. The planet was reported to have a minimum mass of 1.13 Earth-masses (the exact mass depends on the unknown inclination of the orbit), with an orbital radius of 0.04 astronomical units (AU; where 1 AU is the radius of Earth's orbit) and an orbital period of just 3.24 days. This is far too close to the star for the planet to be habitable (being one tenth of Mercury's distance from the Sun!) and, depending on its unknown surface composition, its surface temperature is probably about 1470 K (1,200 degrees Celsius). Nevertheless, the detection of one planet orbiting alpha Centauri B would augur well for the presence of others in potentially more habitable orbits, although these will be more difficult to detect using current methods.

If confirmed by future work, this discovery is of enormous significance for starship planners because it proves that the most accessible star system to the Sun contains at least one planet and probably more. However, it has to be said that the detection of this planet is right on the limit of current observational techniques and, as a result, the detection cannot yet be considered secure. Indeed, in mid-2013 a re-analysis of the data failed to confirm its existence [43]. Further observations are therefore urgently required to confirm or refute the existence of this planet orbiting alpha Centauri B.

Even if this particular planet is not confirmed, however, it is entirely possible that other, as yet undetected, planets exist within the alpha Centauri system. Super-earths in the habitable zones of both alpha Centauri A and B should be just about detectable with current techniques, although confirming (or disproving) the existence of Earth and sub-Earth-mass planets in habitable orbits will be very challenging technically and is unlikely to be possible in the near future. Nevertheless, the statistics on the frequency of planetary systems, suggest that such planets are quite likely to be present.

Table One

Star systems within 15 light years of the Sun [38,39]. GJ is each star's number in the Gliese-Jahreiß catalogue [40]; l, b are each star's galactic longitude and latitude, respectively, where l=0 points towards the galactic centre and b is the angle above or below the galactic plane.

	GJ	Popular Name	Spectral Type	Distance (ly)	l (deg)	b (deg)
1	551	Proxima Cen	M5.5V	4.2	313.9	–01.9
	559	alpha Cen A	G2V	4.4	315.7	–00.7
	"	alpha Cen B	K0V	"	"	"
2	699	Barnard's Star	M4V	6.0	031.0	+14.1
3	–	WISE J104915 A	L7.5	6.6	285.2	+05.3
	–	WISE J104915 B	T0.5	"	"	"
4	406	Wolf 359	M6V	7.8	244.1	+56.1
5	411	Lalande 21185	M2V	8.3	185.1	+65.4
6	244	alpha CMa A (Sirius)	A1V	8.6	227.2	–08.9
	"	alpha CMa B	DA2	"	"	"
7	65	Luyten 726-8 A	M5.5V	8.7	175.5	–75.7
	"	Luyten 726-8 B	M6V	"	"	"
8	729	Ross 154	M3.5V	9.7	011.3	–10.3
9	905	Ross 248	M5.5V	10.3	110.0	–16.9
10	144	epsilon Eridani	K2V	10.5	195.8	–48.1
11	887	Lacaille 9352	M1.5V	10.7	005.1	–66.0
12	447	Ross 128	M4V	10.9	270.1	+59.6
13	866	EZ Aqr A	M5V	11.3	047.1	–57.0
	"	EZ Aqr B	M?	"	"	"
	"	EZ Aqr C	M?	"	"	"
14	280	alpha CMi A(Procyon)	F5IV-V	11.4	213.7	+13.0
	"	alpha CMi B	DA	"	"	"
15	820	61 Cyg A	K5V	11.4	082.3	–05.8
	"	61 Cyg B	K7V	"	"	"
16	725	Struve 2398 A	M3V	11.5	089.3	+24.2
	"	Struve 2398 B	M3.5V	"	"	"
17	15	(A) GX And	M1.5V	11.6	116.7	–18.4
	"	(B) GQ And	M3.5V	"	"	"

Table One continued

	GJ	Popular Name	Spectral Type	Distance (ly)	l (deg)	b (deg)
18	845	epsilon Ind A	K5Ve	11.8	336.2	–48.0
	“	epsilon Ind B	T1	“	“	“
	“	epsilon Ind C	T6	“	“	“
19	1111	DX Can	M6.5V	11.8	197.0	+32.4
20	71	tau Ceti	G8V	11.9	173.1	–73.4
21	1061	–	M5.5V	12.0	251.9	–52.9
22	54.1	YZ Ceti	M4.5V	12.1	149.7	–78.8
23	273	Luyten’s Star	M3.5V	12.4	212.3	+10.4
24	–	Teegarden’s Star	M7V	12.5	160.3	–37.0
25	–	SCR1845-6357 A	M8.5V	12.6	331.5	–23.5
	–	SCR1845-6357 B	T	“	“	“
26	191	Kapteyn’s Star	M1.5V	12.8	250.5	–36.0
27	825	AX Mic	M0V	12.9	003.9	–44.3
28	860	Kruger 60 A	M3V	13.1	104.7	+00.0
	“	Kruger 60 B	M4V			
29	–	DEN J1048-3956	M8.5V	13.2	278.7	+17.1
30	234	Ross 614 A	M4.5V	13.3	212.9	–06.2
	“	Ross 614 B	M8V	“	“	“
31	628	Wolf 1061	M3.0V	13.8	003.4	+23.7
32	35	Van Maanen’s Star	DZ7	14.1	121.9	–57.5
33	1	–	M3V	14.2	343.6	–75.9
34	473	Wolf 424 A	M5.5V	14.3	288.8	+71.4
	“	Wolf 424 B	M7V	“	“	“
35	83.1	TZ Ari	M4.5	14.5	147.7	–46.5
36	687	–	M3V	14.8	098.6	+32.0
37	3622	LHS 292	M6.5V	14.8	261.0	+41.3
38	674	–	M3V	14.8	343.0	–06.8
39	1245	V1581 Cyg A	M5.5V	14.8	078.9	+08.5
	“	V1581 Cyg B	M6.0V	“	“	“
	“	V1581 Cyg C	M?	“	“	“

Similarly, in the case of Proxima Centauri (alpha Centauri C), there are as yet no actual detections of orbiting planets, but statistically super-earth-mass planets are known to be common around such red dwarf stars [44]. It is true that planets more massive than five Earth-masses orbiting Proxima within the habitable zone would have been detected by now (as would any planets more massive than about 20 Earth masses in more distant orbits [44]), but Earth- or Mars-mass planets could easily be present but are currently undetectable.

Clearly much more observational work is required to determine the presence or absence of planets in the alpha Centauri system. Given the system's proximity to the Sun and that it is already scientifically very interesting because it contains three stars of different spectral types, and because the path to it passes through a particularly diverse part of the local interstellar medium [12], the confirmation that planets are present would likely ensure that alpha Centauri remains at the top of the priority list for humanity's first interstellar mission.

epsilon Eridani

The planet orbiting epsilon Eri is a giant planet, with a mass about 1.5 times that of Jupiter [45]. It has a highly eccentric orbit, which brings it as close to its star as 1.0 AU (i.e. the same distance as the Earth is from the Sun) and out as far as 5.8 AU (i.e. just beyond the orbit of Jupiter in our Solar System), with a period of 6.8 years. Although this would span the habitable zone in the Solar System (i.e. the range of distances from a star on which liquid water would be stable on a planetary surface given certain assumptions about atmospheric composition), this orbit lies wholly outside the likely habitable zone for a K2 star like epsilon Eridani. Also, being a gas giant, this planet itself it not a likely candidate for life and its eccentric orbit would not help in this respect (although it is possible that the planet may have astrobiologically interesting moons, perhaps similar to Jupiter's moon Europa, which could in principle support sub-surface life).

There is an unconfirmed detection of another planet in the epsilon Eridani system, of intermediate mass (a tenth of Jupiter's mass) in a very distant (40 AU) orbit [46]. It is possible that the system contains lower mass, more Earth-like, planets that might be more interesting targets for investigation, especially closer to the star than the giant planet that is known to exist. Epsilon Eridani is also known to be surrounded by a disc of dust [47] that may be derived from collisions between small planetesimals (i.e. asteroids and/or comets) and which is an indirect argument for smaller planets also being present. Only further research will tell how many planets actually reside in the epsilon Eridani system and whether any are of astrobiological interest. The existence of at least one planet, along with the dust disc (itself of great astrophysical interest), would make epsilon Eridani a high scientific priority candidate for interstellar exploration if it were not for its distance of 10.5 light years. Although within the 15 light year radius considered here, this is still a very challenging distance for the first attempt at an interstellar voyage.

tau Ceti

Tau Ceti is notable as the closest single G-type star to the Sun and has long been of interest to astronomers as a possible Solar System analogue. However, until recently there was no indication of it having a planetary system. This changed in early 2013 when an international group of astronomers led by Mikko Tuomi at the University of Hertfordshire published a paper [48] arguing that the star's radial velocity variations were consistent with the presence of up to five planets with minimum masses between 2.0 and 6.6 Earth-masses, with orbital distances between 0.1 and 1.4 AU. Although this tight spacing of multiple super-earth-mass planets within about one astronomical unit of a solar-type star might seem unusual, it is actually quite consistent with the statistical properties of planetary systems around more distant stars as determined by NASA's Kepler Space Telescope (discussed in Section 4.5 below). Moreover, tau Ceti is also orbited by a disc of dust [49] that supports, but does not prove, the presence of a planetary system.

Clearly this would be a very exciting result if confirmed, not least because the two outermost planets (a 4.3 Earth-mass world orbiting at 0.55 AU, and a 6.6 Earth-mass planet orbiting at 1.35 AU) probably bracket the habitable zone.

Although the habitability of super-earth-mass planets is unknown, it is possible that they might be accompanied by lower mass habitable moons. Unfortunately, however, it has to be said that the statistical significance of these planet detections is quite low and, for the reasons discussed above in the context of the postulated planet orbiting alpha Centauri B, it is far too soon to consider these detections to be confirmed. Further observations are therefore urgently required. It is also true that, as for epsilon Eridani, the distance of 11.9 light years would make tau Ceti a very challenging exploration target even if its planetary system is confirmed.

GJ 674

At a distance of 14.8 light years GJ 674 is on the limit of the distance range considered here. With a mass of about 11 Earth masses the known planet orbits its star every 4.7 days, in a moderately elliptical orbit at a mean distance of 0.04 AU [50]. This is a similar orbital distance as the possible planet orbiting alpha Centauri B and, even though GJ 674 is a much cooler star, this is probably too close to be habitable. Nevertheless, as one planet exists around this star it is possible that others will be discovered in more habitable orbits as observations continue. Only time will tell, but in any case the distance of this star probably renders it of marginal interest for direct investigation.

Statistical Properties of Exoplanets: Implications for the Prevalence of Planets Within 15 Light Years

Over the last few years our knowledge of the statistical prevalence of exoplanets has improved considerably as a result of increasingly sensitive measurements by ground-based telescopes [44, 51] and results from Kepler [15, 52]. For an excellent up-to-date summary of this fast-moving field, interested readers are referred to a recent review article in the journal *Science* [1]. Briefly, these may be summarised as follows:

• The vast majority (at least 75 percent) of solar type stars (i.e. stars of spectral types F, G, K) have a planet of some kind with orbital periods less than

10 years (surveys are not yet complete for longer orbital periods).

• Over half (about 60 percent) of solar type stars harbour at least one planet with a period up to 100 days (recall that in our Solar System Mercury has an orbital period of 88 days) and that multiple super-earth-mass planets are common in these short period orbits. However, most of these planets will probably be too hot to be habitable.

• Similar statistics apply for red dwarf stars (i.e. stars of spectral type M), where again about 60 percent are found to have super-earth-mass planets with orbital periods up to 100 days [44]. Although longer period (and lower mass) planets probably also exist, it is these shorter period ones that are the most interesting because, owing to the lower luminosities of red dwarf stars, many of these are theoretically within the habitable zone.

• Estimates for the fraction of M-dwarf (red dwarf) stars with Earth to super-earth-sized planets in the habitable zone range from 15 percent to over 60 percent [53]. Statistics for the fraction of solar-type (F/G/K) stars with planets in the habitable zone are not yet complete owing to greater difficulty in detecting these.

High though these estimates already are for the prevalence of planets, the actual fraction of stars with planets is likely to be considerably higher still. This is because both the ground-based radial velocity and the Kepler transit surveys are still incomplete. For example, neither method can yet reliably detect Earth (and still less sub-Earth) mass planets in habitable (approximately one astronomical unit) orbits around solar type stars. Nor can the radial velocity method yet detect giant planets (and still less low-mass planets) with orbital periods longer than about 20 years (i.e. planets in Saturn-like or more distant orbits), yet such planets presumably do exist. Clearly if we already know that about 75 percent of stars have planets and that this is a lower-limit, then it seems certain that, once all the statistics are in, we will find that essentially all stars will have planets of one kind or another. Indeed, the near ubiquity of planets is supported by the independent technique of gravitational lensing observations of distant stars, which imply that each star in the galactic disc is, on average, orbited by at least 1.6 planets with orbital radii in the range 0.5 to 10 AU [54].

Clearly, if almost every star in the Galaxy has a planetary system it follows that almost every star within 15 light years of the Sun (i.e. essentially all those listed in Table 1) will also have planets, even if we have not detected most of them yet. Therefore there will be no shortage of exploration targets for interstellar spacecraft once the capability is developed.

Conclusions

In this chapter I have argued that, once we have developed the technical capability to engage in it, interstellar exploration will advance human knowledge in multiple areas. In particular, it will advance our knowledge of the interstellar medium, stellar astrophysics, and planetary science beyond what can be plausibly achieved by astronomical instruments based in the Solar System. Its most exciting scientific potential, however, lies in the area of astrobiology – if future astronomical observations indicate the presence, or even the possible presence, of life on planets orbiting nearby stars then the incentive to develop the means to make in situ observations of these alien biospheres may become irresistible.

Moreover, the benefits of interstellar exploration will extend far beyond science. Indeed, a wide array of potential cultural and societal benefits can also be identified. These include the long-term survival of humanity (and our post-human successor species), increasing the opportunities for spreading and diversifying life and intelligence through the Galaxy and providing a literally never-ending source of cultural and intellectual stimulation (for both the subset of humanity left behind and the interstellar explorers and colonisers themselves).

As noted earlier in this chapter, there is probably no shortage of planets within 15 light years of the Sun that would lend themselves to scientific investigation by humanity's early attempts at interstellar exploration. It appears that many of these planets will lie within the habitable zones of their host stars, which will make them of great astrobiological interest. Although it is important to realise that most of these will be orbiting red dwarf stars (Table One) and, while they may support indigenous micro-organisms (or genetically engineered terrestrial micro-organisms if a decision is made to introduce them), conditions on most of these 'habitable' planets are unlikely to be appropriate for human colonisation.

Even if Earth- (or Mars-) mass planets are located orbiting within the 'habitable zones' of nearby solar-type stars (such as alpha Centauri A/B or tau Ceti) it still seems most unlikely that they would be amenable to colonisation by Homo sapiens without either considerable modification of the planetary environments (see e.g. [55]) or of human physiology, or both (a probable necessity recognised by Olaf Stapledon in 1948 [27]). That said, it may be that as humanity moves out into the Galaxy we and our successors may cease to be interested in planets as places to live, relying instead on the stellar energy and cometary/asteroidal raw material resources of planetary systems we encounter. It seems almost certain that most of the stars within 15 light years of the Sun and, indeed far beyond, could support human (and eventually post-human) civilisations on that basis indefinitely.

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