SEARCHING FOR LIFE AMONG THE STARS

Professor Abraham Loeb of Harvard University discusses how access to unprecedented technologies enables new approaches in the search for primitive and intelligent forms of extra-terrestrial life

Is there life outside of the Solar System? If so, we might not be alone in the vast darkness of cosmic space. A lost set of keys is difficult to find in the darkness, but the search becomes easier under a lamp post. Astronomically, stars are the nearest lampposts, and so we naturally begin our search for the missing signals of extra-terrestrial life around them.

The recent discovery[1] of a habitable Earth-mass planet four light years away and orbiting our nearest star, Proxima Centauri, revealed a new opportunity in the search for life. Due to the proximity of this planet, Proxima b, it is easiest to use it as a first target, either for remote sensing of the faint radiation signals from biologically produced molecules such as oxygen, or for sending spacecraft that will photograph the planet's surface from a close distance. The Breakthrough Starshot initiative, whose advisory committee I chair,[2] aims to launch a lightweight spacecraft to a fifth of the speed of light using a laser beam pushing on a sail (Fig. 2),[3-6] so that the camera attached to the sail could reach nearby habitable planets like Proxima b within our lifetimes. The pursuit of this concept became feasible owing to recent advances in laser technology and the miniaturisation of electronics. Starshot will soon begin a five-year phase of technology demonstration at a funding level of $100m (~€86m), provided by the entrepreneur and physicist Yuri Milner through the Breakthrough Prize Foundation. By taking photographs during a flyby of Proxima b, we would like to find out whether the planet's surface shows signs of vegetation, volcanic activity or an oceanic glint as evident in Fig. 3.

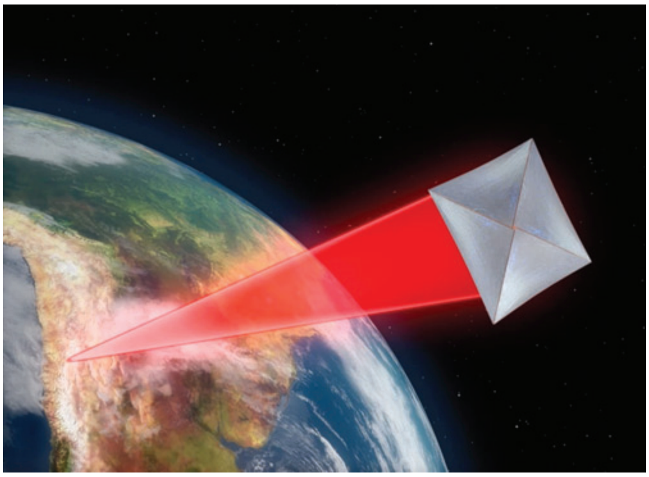

Fig. 2 The Breakthrough Starshot initiative aims to launch a lightweight spacecraft to a fifth of the speed of light using a laser beam pushing on a sail

Professor Abraham Loeb

Should we expect life to exist far from Earth?

Prior to the development of modern astronomy, humans tended to think that the physical world centres around us with the Sun and the stars thought to revolve around the Earth. Although naïve in retrospect, this is a natural starting point: when my daughters were infants, for example, they also tended to think that the world centres around them. Their development portrayed an accelerated microcosm of human history. As they grew up, they matured and acquired a more balanced perspective.

Similarly, observing the sky makes us aware of the big picture and teaches us modesty. We now know that we are not at the centre of the physical Universe, since the Earth orbits the Sun which orbits the centre of the Milky Way, which itself drifts relative to the cosmic rest frame.

However, many people still believe that we might be at the centre of the biological Universe, namely that life is rare or unique to Earth. In contrast, my personal working hypothesis, drawn from the above example of the physical Universe, is that we are not special in general, not only in terms of our physical co-ordinates but also as a form of life. Adopting this perspective implies that we are not alone; that there should be life out there, in both primitive and intelligent forms. This conclusion, implied by the principle of 'cosmic modesty', has implications. If life is likely to exist elsewhere, we should search for it in all of its possible forms.

Our civilization has reached an important milestone. We now have access to unprecedented technologies in our search for extra-terrestrial life, be it primitive or intelligent. The search for primitive life is currently underway and well-funded, but the search for intelligence is out of the mainstream of federal funding agencies. This should not be the case given that the only planet known to host life, Earth, shows both primitive and intelligent life forms. Once life develops on a planet like Earth, it is unlikely to be eradicated by astrophysical catastrophes other than the death of the host star.[7] In fact, sub-millimetre animals, such as tardigrades, are capable of surviving the harsh environment of space, and could potentially travel between planets on asteroids and comets.

Where is everybody?

Our first radio signals have by now leaked out to a distance of more than a hundred light years, and we might soon hear a response. Rather than being guided by Fermi's paradox, "where is everybody?" or by philosophical arguments about the rarity of intelligence, we should invest funds in building better observatories and searching for a wide variety of artificial signals in the sky.

Civilisations at our technological level might produce mostly weak signals. For example, a nuclear war on the nearest planet outside the Solar System would not be visible even with our largest telescopes. In such a case, only when we reach some threshold sensitivity, we will start to see an abundance of artificially produced signals. It is also possible that advanced civilisations mute their techno-signatures on purpose in fear of invaders. Interestingly, very advanced civilisations which are not fearful of being discovered could potentially be detectable out to the edge of the observable Universe through their most powerful 'Starshot-like' beacons.[8]

The evidence for an alien civilisation might not be in the traditional form of radio communication signals. Rather, it could involve detecting artefacts on planets through the spectral edge from solar cells,[9] industrial pollution of atmospheres,[10] artificial lights[11] or bursts of radiation from artificial beams sweeping across the sky.[12] The latter type of signal is to be expected if another civilisation has mastered by now the technology of lightsails that we hope to develop with Starshot.[8,12] Finding the answer to the question 'are we alone?' will change our perspective on our place in the Universe and will open up new interdisciplinary fields of research, such as astro-linguistics (how to communicate with aliens), astro-politics (how to negotiate with them for information), astro-sociology (how to interpret their collective behaviours), astro-economics (how to trade space-based resources), and so on. We could shortcut our own gradual progress by learning from civilisations that have benefitted from a head-start of billions of years.

Fig. 3 Oceanic glint, Hawaii, US

There is no doubt that noticing the big picture taught my young daughters modesty. Similarly, the Kepler satellite survey of nearby stars has allowed astronomers to infer that there are probably more habitable Earth-mass planets in the observable volume of the Universe than there are grains of sand on all the beaches on Earth. Emperors or kings who boasted after conquering a piece of land on Earth resemble an ant that hugs with great pride a single grain of sand on the landscape of a huge beach.

Life on other planets

Over the past year, astronomers have discovered Proxima b[1] and three more potentially habitable planets out of seven around another nearby star, TRAPPIST-1, which is ten times further.[13] If life has formed on one of these three, it has likely been transferred to the others.[14]

These two dwarf stars, TRAPPIST-1 and Proxima Centauri, whose masses are 8% and 12% of the mass of the Sun respectively, will live for up to ten trillion years, about a thousand times longer than the Sun. Hence, they could potentially support life in the distant future; long after the Sun will die and turn into a cold white dwarf. I therefore advise my wealthy friends to buy real estate on Proxima b, as its value will likely go up dramatically in the future. But this also raises an important scientific question: 'is life most likely to emerge at the present cosmic time near a star like the Sun?' By surveying the habitability of the Universe throughout cosmic history from the birth of the first stars 30 million years after the Big Bang to the death of the last stars in ten trillion years, one reaches the conclusion[15,16] that unless habitability around low mass stars is suppressed, life is most likely to exist near dwarf stars like Proxima Centauri or TRAPPIST-1 trillions of years from now.

The chemistry of 'life as we know it' requires liquid water, but being at the right distance from the host star for achieving a comfortable temperature on the planet's surface is not a sufficient condition for life. The planet also needs to have an atmosphere. In the absence of an external atmospheric pressure, warming by starlight would transform water ice directly into gas rather than a liquid phase. The

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Fig. 4 Sunset, Maui, US

warning sign can be found just next door: Mars has a tenth of the Earth's mass and has lost its atmosphere. Does Proxima b have an atmosphere?

Habitable planets around dwarf stars like Proxima Centauri are tidally locked (because of their proximity to their faint host), showing the same face to their star as they orbit it. Hence, their day and night sides are permanent. The borderline between these sides must therefore show a permanent sunset.

Oceanic tides on such planets should be more prominent than on Earth due to the stronger tidal force from the host star. These tides may exert a positive influence on biotic processes – abiogenesis, biological rhythms and photosynthesis. As a result, large-scale algal blooms in the oceans can serve as potential temporal biosignatures in the reflectance light curves of these planets.[17]

The atmosphere and any surface ocean it sustains, will moderate the temperature contrast between the permanent day and night sides of Proxima b. Hence, the James Webb Space Telescope, which is scheduled for launch in October 2018, will be able to distinguish between the temperature contrast expected if Proxima b is bare rock, compared to the case wherein its climate is moderated by an atmosphere or an ocean.[18] Radio observations can inform us about the strength of Proxima b's magnetic field,[19] which is also important for retaining its atmosphere.

Theoretically, Earth-sized planets in the habitable zone around dwarf stars display much lower prospects of being habitable relative to Earth, owing to the higher incident ultraviolet fluxes and stronger stellar winds that can easily strip their atmosphere given their closer proximity to their host star. Based on all available data on dwarf stars, the likelihood for life around Proxima Centauri and TRAPPIST-1 is several orders of magnitude smaller than on Earth.[20]

The big picture

Finally, a broader cosmic perspective about our origins would also contribute to a balanced worldview. The heavy elements that assembled to make the Earth were produced in the heart of a nearby massive star that exploded. A speck of this material takes the form of our bodies, during our lives, but returns to Earth following death (with one exception, namely the ashes of astronomer Clyde Tombaugh, who discovered Pluto, which were put on the New Horizons spacecraft and are making their way beyond our Solar System). What are we then, if not just a transient shape that a speck of material takes for a brief moment in cosmic history on the surface of one planet out of so many? Despite all of this, life is still the most precious phenomenon we treasure on Earth. It would be amazing if we find evidence for 'life as we know it' on the surface of another planet, and even more remarkable if our telescopes could trace evidence for an advanced technology on an alien spacecraft roaming through interstellar space.

References

1 Anglada-Escudé, G. *et al*. A Terrestrial Candidate in a Temperate Orbit Around Proxima Centauri, *Nature* Vol. 536, p. 437-440, 2016

2 http://breakthroughinitiatives.org/Leaders/3

3 Manchester, Z. & Loeb, A. Stability of a Light Sail Riding on a Laser Beam, *ApJ*, Vol. 837, p. L20-L26, 2017

Fig. 5 Ground above the clouds, Haleakala Observatory, Maui, US

4 Christian, P. & Loeb A. Interferometric Measurement of Acceleration at Relativistic Speeds, *ApJ*, Vol. 834, p. L20-L25, 2017

5 Hoang, T. Lazarian, A. Burkhart, B. & Loeb, A. The Interaction of Relativistic Spacecrafts with the Interstellar Medium, *ApJ*, Vol. 837, p. 5-21, 2017

6 Hoang, T. & Loeb, A. Electromagnetic Forces on a Relativistic Spacecraft in the Interstellar Medium, *ApJ*, submitted, 2017; preprint available at https://arxiv.org/abs/1706.07798

7 Sloan, D. Batista, R. A. & Loeb, A. The Resilience of Life to Astrophysical Events, *Nature Scientific Reports*, Vol. 7, article 5419, 2017

8 Lingam, M. & Loeb, A. Fast Radio Bursts From Extragalactic Light Sails, *ApJ*, Vol. 837, p. L23-L28, 2017

9 Lingam, M. & Loeb, A. Natural and Artificial Spectral Edges in Exoplanets, MNRAS (in the press), 2017; preprint available at https://arxiv.org/abs/1702.05500

10 Lin, H. Gonzalez, G. A. & Loeb, A. Detecting Industrial Pollution in the Atmospheres of Earth-like Exoplanets, *ApJ*, Vol 792, p. L7-L11, 2014

11 Loeb, A. & Turner, E. L. Detection Technique for Artificially Illuminated Objects in the Outer Solar System and Beyond, *Astrobiology*, Vol. 12, p. 290-290, 2012

12 Guillochon, J. & Loeb, A. SETI via Leakage from Light Sails in Exoplanetary Systems, *ApJ*, Vol. 811, p. L20-L26, 2015

13 Gillon, M. *et al*. Temperate Earth-Sized Planets Transiting a Nearby Ultracool Dwarf Star, *Nature* Vol. 542, p. 456-460, 2016

14 Lingam, M. & Loeb, A. Enhanced Interplanetary Panspermia in the TRAPPIST-1 System, *PNAS*, Vol. 114, p. 6689-6696, 2017

15 Loeb, A. Batista, R. A. & Sloan, D. Relative Likelihood for Life as a Function of Cosmic Time, *JCAP* Vol. 8, p. 40-52, 2016

16 Loeb, A. On the Habitability of Our Universe, chapter for the book *Consolidation of Fine Tuning*, edited by R. Davies, J. Silk and D. Sloan (Oxford University, 2017); preprint available at https://arxiv.org/abs/1606.08926

17 Lingam, M. & Loeb, A. Implications of Tides for Life on Exoplanets, *Astrobiology*, submitted, 2017; preprint available at https://arxiv.org/abs/1707.04594

18 Kreidberg, L. & Loeb, A. Prospects for Characterizing the Atmosphere of Proxima b, *ApJ*, Vol. 83, p. L12-L18, 2016

19 Burkhart, B. & Loeb, A. 2017, submitted to *ApJL*, preprint available at https://arxiv.org/abs/1706.07038

20 Lingam, M. & Loeb, A. Physical Constraints on the Likelihood of Life on Exoplanets, *Int. J. Astrobiology*, Vol. 10, p. 1-11, 2017

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