Past, present and future stars that can see Earth as a transiting exoplanet

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In the search for life in the cosmos, transiting exoplanets are currently our best targets. With thousands already detected, our search is entering a new era of discovery with upcoming large telescopes that will look for signs of 'life' in the atmospheres of transiting worlds. Previous work has explored the zone from which Earth would be visible while transiting the Sun[1–4]. However, these studies considered only the current position of stars, and did not include their changing vantage point over time. Here we report that 1,715 stars within 100 parsecs from the Sun are in the right position to have spotted life on a transiting Earth since early human civilization (about 5,000 years ago), with an additional 319 stars entering this special vantage point in the next 5,000 years. Among these stars are seven known exoplanet hosts, including Ross-128, which saw Earth transit the Sun in the past, and Teegarden's Star and Trappist-1, which will start to see it in 29 and 1,642 years, respectively. We found that human-made radio waves have already swept over 75 of the closest stars on our list.

To obtain the dynamic picture of which stars can see Earth transit the Sun[1–4] and how many years such a viewpoint holds, we evaluated the kinematics propagated through time using the European Space Agency's Gaia Mission early Data Release 3 (eDR3)[5].

We identify 2,034 stars (https://github.com/jfaherty17/ETZ) in the Gaia Catalog of Nearby Stars (GCNS)[6] that are in the Earth transit zone (ETZ)[3] over ±5,000 years: 313 objects were in the ETZ in the past, 319 will enter the ETZ in the future, and 1,402 have been in the ETZ for some time. Given that Earth began transmitting radio waves into the solar neighbourhood about 100 years ago[7], we also identify a sub-sample of 75 stars located in a 30-pc sphere, which Earth's radio signals have already washed over.

We find a large diversity among the 2,034 objects that enter/exit the ETZ over ±5,000 years. Using the Gaia colours and absolute magnitude (M_G)[8,9] (Fig. 1), we estimate stellar spectral types and find that M dwarfs dominate our sample. That agrees with our understanding of the initial mass distribution[10] for the Milky Way disk population. The 2,034 objects contain 194 G stars like our Sun; 12 A, 2 B, 87 F, 102 K and 1,520 M stars; 7 L and 1 T dwarfs; and 109 white dwarfs (WDs) (see Table 1). At least 12 stars are also on the giant branch. There are numerous well studied stars in this list (for example, Wolf 359, Ross 128, Teegarden's Star), as well as previously unknown nearby sources identified in Gaia eDR3 (for example, Gaia EDR3 4116504399886241792).

1,402 sources can currently see Earth transit, including 128 G stars like our Sun, 10 A, 1 B, 63 F, 73 K and 1,050 M stars, as well as 2 L dwarfs and 75 WDs. SETI observations of stars in the ETZ have recently been started[11,12].

Isotopic data indicate that life on Earth started by about 3.8 to 3.5 Gyr ago[13,14], which coincides with the end of the heavy bombardment phase[15]. Although we cannot infer the time needed for life to start on any exoplanet from Earth's history, the early signs for life on Earth are encouraging. Our ETZ catalogue includes all potentially habitable world host stars, regardless of mass or evolved state, given the uncertainty of how, when and where life might arise and survive[16–20].

Of the 2,034 objects in the ETZ, 67% (1,355) are also in the restricted ETZ (rETZ)[3] (which guarantees a minimum view of Earth's transit for 10 h; see Table 1), 311 were in the rETZ in the past, 330 will enter the rETZ in the future, and 713 have been in the rETZ in the ±5,000-year time window. This sample is mainly composed of cool stars, with colours and magnitudes consistent with 6 A, 57 F, 121 G, 72 K, 1,021 M stars, as well as 5 L, 1 T dwarfs and 72 WDs.

Of the 2,034 objects in the ETZ, 117 objects lie within 30 pc (about 100 light years) of the Sun. Among those sources, 29 were in the ETZ in the past, 42 will enter it in the future, and 46 have been in the ETZ for some time. These 46 objects (2 F, 3 G, 2 K and 34 M stars and 5 WDs) would be able to see Earth transit the Sun while also being able to detect radio waves emitted from Earth[7], which would have reached those stars by now (see Table 1). Seven of the 2,034 stars are known exoplanet host stars, as shown in Table 2, where they are sorted by distance from the Sun. Four of the planet hosts are located within 30 pc of the Sun.

The Ross128 system at 3.375 pc is the 13th closest system to the Sun and the second closest system with a non-transiting Earth-mass exoplanet. Ross128 b would have seen Earth transit for 2,158 years, from 3,057 until 900 years ago. Teegarden's Star system, the 25th closest system to the Sun, at 3.832 pc, hosts two non-transiting Earth-mass worlds. It will enter the ETZ in 29 years[21] for 410 years. The GJ9066 system at 4.470 pc hosts one non-transiting planet and will enter the ETZ in 846 years and remain in it for 932 years. The Trappist-1 system at 12.467 pc hosts seven transiting Earth-size planets, with four of them in the temperate habitable zone (HZ). This system will enter the ETZ in 1,642 years and remain there for 2,371 years.

Three more exoplanet systems beyond 30 pc, but within 100 pc, have been in the ETZ for thousands of years: K2-240 at 73.043 pc hosts two transiting planets. The system entered the ETZ more than 5,000

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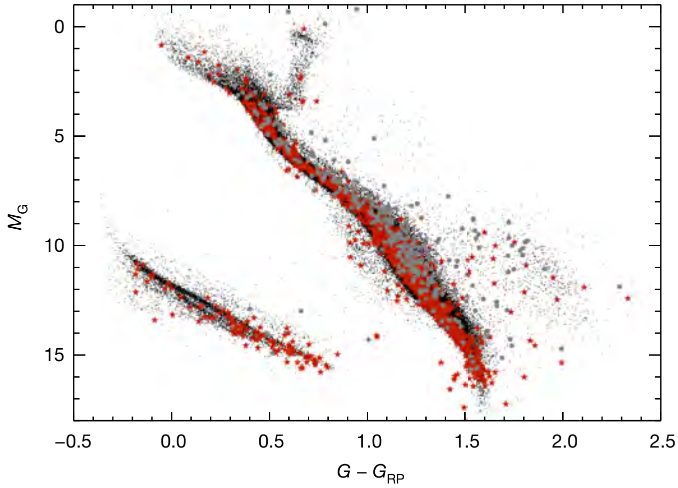

Fig. 1 | Stars that can see Earth transit since early human civilization. The colour–magnitude diagram of the GCNS (black), limited to sources with re-normalized unit weight error (RUWE) of <1.4, photometric signal-to-noise ratio >100 (in Gaia G and G_{RP} photometric passbands) and parallax uncertainties better than 5%. Overplotted are the 2,034 sources that cross the ETZ in the time interval of ±5,000 years (dark red star markers have RUWE < 1.4; grey filled circles have RUWE > 1.4). M_G is Gaia magnitude.

Table 1 | Sample of the full machine-readable table of ETZ stars, sorted by distance

Star name	ETZ			
GAIA eDR3	**Entry (yr)**	**Exit (yr)**	**Total (yr)**	**When**
3864972938605115520	−46	432	480	Past and future
3796072592206250624	−3,057	−900	2,158	Past
35227046884571776	29	438	410	Future

The full table is provided in Supplementary Information.

years ago and will remain in the ETZ well past 5,000 years into the future. K2-65 at 63.104 pc, with one transiting planet, entered the ETZ 2,183 years ago and will stay in the ETZ more than 5,000 years in the future. K2-155 at 72.932 pc hosts three transiting planets. The system entered the ETZ more than 5,000 years ago and will remain for another 3,118 years.

Estimates of the number of rocky planets in the HZ[22] in the literature are given for various values of a planet's radius and HZ limits[23,24]. New estimates place it from $0.58^{+0.73}_{-0.33}$ to $0.88^{+1.28}_{-0.51}$ planets per star[24] for the empirical HZ. The empirical HZ limits are set by the flux that a young Mars and a young Venus received when there was no more evidence of liquid water on their surfaces[22]. The inner limit is not well known, because of the lack of reliable geological surface history for Venus beyond 1 Gyr ago.

Although the discussion on the occurrence rate of rocky planets is ongoing, here we use a pessimistic rate of 25% to estimate that there are potentially 508 rocky worlds in the HZ of our full sample. Restricting the selection to the distance that radio waves from Earth have travelled—about 100 light years—leads to an estimated 29 potentially habitable worlds that could have seen Earth transit and could also detect radio waves from our planet.

We found that 43% (868) of stars in our sample spend at least 10,000 years, 68% (1,380) at least 5,000 years, and 94% (1,910) at least 1,000 years in the ETZ. Sources closer to the Sun have larger proper motion values than those farther away, so stars in our closest neighbourhood move in and out of the ETZ faster than more distant objects. The average ETZ viewing window for the 100-pc sample over the 10,000 years evaluated is 6,914 years, whereas the average for the 30-pc sample is 3,973 years. However, our analysis provides only a first assessment of the time that a star keeps its vantage point to observe Earth as a transiting planet. Only 78 objects complete an entrance and exit over the ±5,000-year period.

The Universe is dynamic, changing the vantage point of other stars, from which they could find us over thousands of years—as well as ours, from which we could detect planets transiting other stars. During Earth's Anthropocene period—237 years so far, starting with the steam engine in 1784[25,26], when humans started to influence Earth's climate—1,424 stars have seen Earth transit the Sun. For a further 1,000- and 5,000-year period, that number would increase to 1,489 and 1,743, respectively.

The discussion on whether or not we should send out an active signal or try to hide our presence is ongoing[27,28]. However, our biosphere has modified our planet's atmosphere for billions of years[13,14], something that we hope to find on other Earth-like planets soon. Thus, observing Earth as a transiting planet could have classified it as a living world since the Great Oxidation Event, for a billion years already[29–31], through the buildup of oxygen and ozone in the presence of a reducing gas[23,32–36]. Here we assume that any nominal civilization on an exoplanet would have astronomical instrumentation comparable to what we have now.

Recent technosignatures[37]—like radio waves—can, in addition, indicate a technological civilization on Earth. Even though radio waves have been emitted by humans only for a comparably short time (about 100 years), they have already reached 75 stars in the past and present ETZ in our neighbourhood and are still travelling farther out.

Our analysis shows that even the closest stars generally spend more than 1,000 years at a vantage point from which they can see Earth transit; therefore, we can assume that the reverse will also be true. That provides a long timeline for nominal civilizations to identify Earth as an interesting planet.

Table 2 | Sample of the full machine-readable table of exoplanet hosts in the ETZ, sorted by distance

Star name		ETZ			
Exoplanet host	**GAIA eDR3**	**Entry (yr)**	**Exit (yr)**	**Total (yr)**	**When**
Ross 128	3796072592206250624	−3,057	−900	2,158	Past
Teegarden's Star	35227046884571776	29	438	410	Future
GJ 9066	76868614540049408	846	1,777	932	Future
TRAPPIST-1	2635476908753563008	1,642	4,012	2,371	Future
K2-65	2613211076737129856	−2,183	5,000	7,184	Past and future
K2-155	145333927996558976	−5,000	3,118	8,119	Past and future
K2-240	6257625719430982016	−5,000	5,000	10,000	Past and future

The full table is provided in Supplementary Information.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03596-y.

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Methods

The European Space Agency's Gaia mission has revolutionized our understanding of the local solar neighbourhood. Gaia released over 1.3 billion sources with 5-parameter astrometric solutions in Data Release 2 (proper motion and parallax values)[8]. Gaia's eDR3[5] catalogue contained the GCNS[6], a self-defined 'clean' and well characterized collection of objects within 100 pc of the Sun, including at least 92% of stars of stellar types down to M9[6].

We converted right-ascension and declination values to ecliptic latitude and longitude values for the full 100-pc GCNS sample to determine which stars could see Earth transit from their position. The ETZ[3] corresponds to a thin strip around the ecliptic as projected onto the sky with an ecliptic latitude width of 0.528°. The smaller rETZ[3], with an ecliptic latitude width of 0.264°, denotes the region from which Earth's transit can be seen for a minimum of 10 h.

Of the 302,197 stars in the 100-pc GCNS sample, we identify 1,402 objects currently located at ecliptic latitude between ±0.264°. We compared our sample with an earlier study[4] that found 1,004 main-sequence stars in the ETZ using the Transiting Exoplanet Survey Satellite (TESS)[38] Input Catalog (TIC)[39] matched to Gaia DR2[8]. We find that in the updated eDR3 Gaia catalogue, 21 of the original objects are now either outside of 100 pc (20) or are unreported in Gaia eDR3 (1). Thus, our sample has 983 sources in common with the earlier sample of stars that can see Earth transit now. We note that the earlier sample of 1,004 stars[4] excluded evolved stars from their selection and limited the Gaia quality flag in the TIC to unity.

The reliability of the astrometry is critical to determining the robustness of a candidate in the ETZ. As such, we use the RUWE value from the catalogue to flag potentially poor candidates. As recommended[6], a RUWE near unity is the signature of a robust astrometric solution. Values larger than 1.4 are considered suspect for various reasons, including unresolved binarity, variability and crowding.

In our full sample of 2,034 objects from eDR3 (https://github.com/jfaherty17/ETZ), which are in the ETZ for a ±5,000-year period, 349 objects have RUWE > 1.4. Similar to the procedure used to discover the nearby L dwarf WISE J192512.78+070038.8[40], which was in the Galactic plane, we visually inspected each source using the citizen-scientist-developed image viewing tool Wiseview[41] to ensure that crowding did not insert a false detection.

We also examined the Gaia colour–magnitude diagram (CMD) for all targets to flag any targets appearing in suspect areas. Figure 1 shows the CMD for the GCNS (black), for $(G - G_{\mathrm{RP}})$ colours, limited to sources with RUWE < 1.4, photometric signal-to-noise ratio >100 (in Gaia G and G_{RP}), and parallax uncertainties better than 5%. Overplotted are the 2,034 sources that cross the ETZ in the time interval of ±5,000 years (dark red star markers have RUWE < 1.4, grey filled circles have RUWE > 1.4). Data are available at https://github.com/jfaherty17/ETZ. We also examined the Gaia $(G_{\mathrm{BP}} - G_{\mathrm{RP}})$ CMD to complement the analysis. Both Gaia CMDs show scatter across the stars, which is a function of several parameters such as varying stellar temperatures, binarity and age[9,42,43]. We note that the $(G - G_{\mathrm{RP}})$ colour is discerning for the lowest-temperature sources (for example, M dwarfs), whereas the $(G_{\mathrm{BP}} - G_{\mathrm{RP}})$ colour is helpful for a close examination of the higher-mass sources. We primarily used the $(G - G_{\mathrm{RP}})$ CMD to determine a spectral type estimate of each source; however, we turned to the $(G_{\mathrm{BP}} - G_{\mathrm{RP}})$ colour for confirmation in the case of higher-mass stars and WDs.

The vast majority of our ETZ sources lie within the full GCNS sample's scatter on the CMD. However, a small number of sources show photometry or astrometry that is likely to be suspect even for objects with RUWE < 1.4, given the substantial number of objects with Gaia $(G - G_{\mathrm{RP}}) > 1.5$. That might be a sign of a given object's intrinsic properties (such as age, metallicity and binarity). Table 1 lists parameters for the full 2,034 ETZ sample (data at https://github.com/jfaherty17/ETZ), including relevant Gaia astrometric and photometric information and our estimation of the spectral type for each source from its CMD position. We also cross-matched our full sample against literature estimates of mass, effective temperature, radii, bolometric luminosity, metallicity and log(g) (g, gravity) for Gaia sources. Table 1 lists all values with the respective catalogue references for the parameter noted[39,44–46].

To identify stars that have seen and will see Earth as a transiting planet, we propagate motions backwards and forwards in time. To do this, we use the right ascension, declination, parallax, proper motion in right ascension (μ_{ra}) and proper motion in declination (μ_{dec}) values from the GCNS. We note that we did not eliminate sources that were CMD or RUWE outliers (see Table 1 for detailed information). We used the full 100-pc sample and iterated in 1-year bins backwards and forwards in time. We list all astrometric information, including RUWE, in Table 1 so the reader can choose different criteria for follow-up.

Ideally, to conduct this analysis, we would use full spatial and velocity information. However, only a small subsample of objects in Gaia eDR3 have radial-velocity measurements. Therefore, we proceeded with only tangential velocities and the projected positions across the sky over time. Although we cannot account for sources moving towards or away from us, in a short-time-frame analysis, the tangential motion of a source across the sky drives the impact on its position in the ETZ. Therefore, radial velocity has a minimal effect on the analysis. However, to truly understand the volume of sources analysed, one would want all astrometric components. A dedicated radial-velocity campaign for these objects will be necessary to accomplish that.

To compile a list of past and future host stars in the ETZ and how long they spent with a view of Earth transiting, we converted the GCNS positions into X, Y, Z Cartesian coordinates using subroutines from the Banyan Sigma kinematic analysis code[47]. We then propagated the X, Y, Z positions forwards and backwards using proper-motion values from Gaia eDR3 and a zero value for the radial velocity. We then converted the new X, Y, Z Cartesian coordinates back to ecliptic longitude and latitude in intervals of one year, and checked whether the host stars had entered/exited the ETZ. We used the visualization tool OpenSpace[48] to examine the sample as we proceeded with iterations. Using that software, we could move time forwards and backwards and see how the sample changed in position over time. In this way we could visually confirm all stars. Using this iterative method, we found 2,034 potential exoplanet host stars in the ETZ in the past, present and future.

Given that all stars are in motion around the centre of the Galaxy, over time, the linear projection of a star's motion will deviate considerably from the circular orbit of a star around the Galaxy. The Solar System's estimated time to complete one orbit is ~250 Myr. Using a geometric approximation, we find that after ~150 Myr the deviation between the linear approximation and the circular orbit would approach the size of the ETZ window. Therefore, we chose a conservative ±5,000-year period for our analysis. This time frame both conservatively accommodates the projected positions over time and includes a critical portion of human development on Earth. Furthermore, a period of ±5,000 years covers ample time for another nominal civilization to have detected and studied Earth through the rise of modern human civilization.

We approximated the sizes of the ETZ and rETZ entrance and exit windows using the uncertainties in astrometric parameters. For each of the 2,034 stars in our sample, we ran 100 iterations of their position propagated using randomly sampled 1σ uncertainties in right ascension, declination, parallax, μ_{ra} and μ_{dec}. We evaluated the ETZ and rETZ entrance and exit points for each of the 100 iterations, and we report the standard deviation of the sample as the window uncertainties in Table 1. The majority of stars have such small astrometric errors that the windows have negligible uncertainties. Moreover, with 43% of objects spending more than 10,000 years in the ETZ, many stars enter and exit the ETZ well before/after our analysis.

The length of time that any given star within 100 pc stays in the ETZ in our analysis is determined by the magnitude and direction of the proper motion, which generally scales with distance. Thus, sources closer to the Sun have generally larger proper motion values than those further away. For instance, the median total proper motion for the 30-pc sample in the GCNS is about 300 mas yr^{-1}, whereas the median value for objects out to 100 pc is about 85 mas yr^{-1}. That means that sources closer to the Sun will move through the ETZ faster than those at larger distances. We find that over these 10,000 years, only 78 objects complete an entrance and exit. Most stars in our sample (1,954) have either entered the ETZ before our analysis started or entered the ETZ and will stay beyond our analysis timeframe.

109 of the objects in our catalogue are WDs, dead stellar remnants. Whereas most searches for life on other planets concentrate on main sequence stars[23,34,35], the recent discovery of a giant planet around a WD[19] opened the intriguing possibility that we might also find rocky planets orbiting evolved stars[16–20,49]. Characterizing rocky planets in the HZ of a WD would answer intriguing questions on lifespans of biota or a second 'genesis' after a star's death[50].

Stars with a vantage point from which they could see Earth transit—and thus see an interesting planet for deliberate broadcasts—are priority targets for searches for life and extraterrestrial intelligence[1–4]. Observations of such stars have recently started[11,12]. In addition, NASA's TESS has entered the extended mission phase, with a plan to observe stars across the ecliptic, including those with a vantage point from which to see Earth transit the Sun.

Data availability

All data are available in the Supplementary Information and at https://github.com/jfaherty17/ETZ.

Code availability

Code used in the analysis is available at https://github.com/jfaherty17/ETZ.

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Additional information

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