A NEW STRATEGY FOR SETI:
EARTH AS AN EXOPLANET

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Abstract

Over 3,800 exoplanets have been discovered so far, although none of them are quite like our Earth in terms of the mass-radius ratio and the distance from the host star. For example, even if a few exoplanets have a mass similar to Earth’s, their radius is unknown and/or they are significantly closer to the host star than Earth is to the Sun. There are several ways of detecting exoplanets e.g. two very successful ones that led to the discovery of 94% of exoplanets i.e. transit photometry and radial velocity (RV), as well as astrometry, which is a promising method that could revolutionise the exoplanet detections in the near future. These methods can, however, be employed by an intelligent civilisation on a faraway planet to detect the Earth. In this dissertation, a new SETI strategy is developed, how detectable the Earth is from outer space. Earth’s detectability as an exoplanet is investigated to find out which stars have the best view of us. In this way, the stars in the proximity of which we are most likely to receive a SETI signal from are investigated. Signal-to-noise ratios (SNRs) of the Earth as seen from 1.6 million stars in the Milky Way are derived, first for each individual detection method and then by combining all or two specific detection methods. The detectability is measured by considering the sensitivity of the detection methods. Maps of the Milky Way are obtained which outline which portions contain the highest SNR stars. Four SETI surveys, that have a well known sky coverage, are plotted over the combined map and the resolutions of three of them along with an array of telescopes involved in the SETI research are calculated to examine their resolution as a function of wavelength. Finally, a crossmatch is made in between the target stars and the hosts of the confirmed exoplanets. Sixty-six good exoplanet matches within 1 arcsecond are revealed, three of which are terrestrial and four that are potentially terrestrial.

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Master’s of Science

A new strategy for SETI: Earth as an exoplanet

May 6, 2019
Declaration

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Abreviations

- APF: Automated Planet Finder
- ATA: Allen Telescope Array
- CHZ: continuously habitable zone
- CME: coronal mass ejection
- CoRoT: Convection, Rotation and planetary Transits
- ESI: Earth Similarity Index
- ESPRESSO: Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations
- EXPRES: EXtreme PREcision Spectrograph
- FAST: Five-hundred-meter Aperture Spherical radio Telescope
- FWHM: Full Width Half Maximum
- GHZ: Galactic Habitable Zone
- HARPS: High Accuracy Radial Velocity Planet Searcher
- HIRES: High Resolution Echelle Spectrometer
- HZ: habitable zone
- KOI: Kepler Object of Interest
- METI: Messages from Extraterrestrial Intelligence
- MMR: mean motion resonance
- MWA: Murchison Widefield Array
- PHI: Planet Habitation Index
- PLATO: PLAnetary Transits and Oscillations of stars
- PSF: point-spread-function
- RV: radial velocity
- SETI: Search for extraterrestrial intelligence
- SNR: signal to noise ratio
- TDV: transit duration variations
- TESS: Transiting Exoplanet Survey Satellite
- TTV: transit timing variations
- XUV: extreme ultraviolet
Chapter 1

Introduction

With Search for extraterrestrial intelligence (SETI) surveys and searching for exoplanets with our telescopes, we are hoping to find other forms of life in the Galaxy. As the life on Earth is the only one that we know anything about we usually target stars that are similar to our Sun, i.e. a mass between 0.5 - 1.2 $M_\odot$ (Winn & Fabrycky 2015). There have been over 3,800 exoplanets discovered so far. Around 75% of these orbit G and K type of stars (0.45 - 1.15 $M_\odot$) (Yılmaz et al. 2017). The exoplanet field has been revolutionised by the Kepler spacecraft and sensitive spectrographs e.g. High Accuracy Radial Velocity Planet Searcher (HARPS), that have made most of these detections possible (von Essen et al. 2018; Astudillo-Defru et al. 2017).

This work will consider how the Earth looks like from outer space i.e. the Earth as an exoplanet. The focus is set on the detectability of the Earth from a potential habitable planet in the Milky Way galaxy. This provides a prior for the SETI strategies by pointing out which parts of the galaxy have the best view of the Earth and are therefore most likely to contact us. Targetting these zones

\footnote{See http://exoplanet.eu/}
in future SETI surveys may potentially lead to a higher chance of detecting alien signals.

The dissertation is structured in five chapters. Chapter 2 goes in depth through the ways planets (including Earth) can be detected and what makes a planet habitable. In Chapter 3 the telescopes that lead the SETI research are described. The detectability of the Earth is analysed in Chapter 4, along with the most important SETI surveys, the resolution of the SETI telescopes and a crossmatch with the confirmed exoplanet hosts. The results and maps that I obtained are also presented in this chapter. Improvements to the research and conclusions are discussed in Chapter 6.
Chapter 2

Exoplanets: detection and habitability

2.1 History of exoplanets and motivation

The first exoplanet that was detected was HD 114762b, by Latham et al. (1989) using radial velocity (RV) measurements, although its exoplanet status wasn’t confirmed until 23 years later (Latham 2012). The first two confirmed exoplanets were discovered in 1992 orbiting the pulsar PSR 1257+12 (Wolszczan & Frail 1992), two super-Earths i.e. exoplanets with a mass below $10 \, M_\oplus$ and a radius below $2 \, R_\oplus$, where $M_\oplus$ and $R_\oplus$ are the Earth’s mass and radius, respectively, (Miguel et al. 2011) having a mass $M = 4 \, M_\oplus$ and periods of 66 and 98 days. The first exoplanet orbiting a main-sequence star detected with a high RV precision was 51 Peg b, discovered in 1995 at the Geneva Observatory using the ELODIE spectrograph (Mayor & Queloz 1995). It has a period, $P$, of 4.2 days and a mass of $0.5 \, M_J$, where $M_J$ is the mass of Jupiter. The first exoplanet detected via the transit method was HD 209548b, in 2000, with a lower mass limit of $0.7 \, M_J$ and
$P = 3.5$ days \cite{Henry2000}. The only exoplanet discovered via astrometry, HD 176051b, orbits a low mass binary star 14 pc away with a $P$ of 2.8 years \cite{Muterspaugh2010}. As the oldest exoplanets were found to orbit an 11.2 ± 1.0 Gyr old K-type star, exoplanets have been around since some of the first stars formed \cite{Campante2015}.

One of the main interests behind detecting exoplanets lies in the possibility of their habitability. This may include planets on which life could develop i.e. planets within the Habitable Zone (HZ) of their host star that could exhibit liquid water on the surface and have enough atmospheric pressure \cite{Kasting1993}, planets on which life has already developed e.g. existing megastructures \cite{Wright2015}, or a potential twin of Earth, an Earth-2, on which humans could live \cite{Pilat-Lohinger2015}. Although most people would like to think we are not alone in the Universe, there have been no signs so far to prove otherwise \cite{Enriquez2017}. However, the field of exoplanets is a fairly new area of research, which employs a few detection methods that look promising with ever-progressing technology.

With the launch of spacecraft and the increase in sensitivity, more exoplanets have been discovered. Both CoRoT \cite{Baglin2003} and Kepler \cite{Borucki2010} have detected enough exoplanets so that 75% of all known confirmed exoplanets have, as of June 2018, been discovered via the transit method. Technological advancements in the coronagraphs mounted on optical telescopes e.g. the Binocular Telescope \cite{Pedichini2017} and in high resolution Echelle spectrographs e.g. Keck High Resolution Echelle Spectrometer (HIRES) \cite{Isaacson2010}, without which RV measurements would not be possible, have, in recent years, revolutionised the area of discovering new exoplanets.
2.2 Exoplanet detection methods and sensitivity

This section will describe the main two detection methods that have yielded the most number of exoplanets (i.e. transit and RV) in depth as well as the astrometry detection method. A summary of the physics and surveys of other known exoplanet detection methods can be found in subsection 2.2.4. Figure 2.1 displays 1497 exoplanets with known semi-major axes and masses. The RV method yields the minimum mass of the planet (see subsection 2.2.1) while the transit of a planet gives the radius of the planet, as the area of the blocked light tells us how much of the radius of star is out of view (see subsection 2.2.3).

Detecting an exoplanet depends on the signal-to-noise ratio (SNR) or detectability,

\[ SNR = g \sqrt{N} \frac{A}{\sigma}, \]  

(2.1)
where $g$ is a factor of order unity depending on the signal, $N$ is the number of observations, $\sigma$ is the uncertainty in the measurement and $A$ is the amplitude of the signal.

If both the transit and RV observations of the exoplanet are obtained, not only the true mass of the planet is revealed, as its inclination is known, but the density of the planet i.e. what it is made of, hydrogen, liquid water, silicates or iron is also known (Kaltenegger 2017). The density is key in calculating the composition of planet interiors, which are likely to play a significant role in whether a planet is habitable or not (Suissa et al. 2018). In the case of our planet it is believed that the tectonic activity, which has played a significant role in Earth’s habitability over eons, has been influenced by the Earth’s interior (Noak et al. 2014).

2.2.1 Radial velocity

Every planet-hosting star moves about the centre of mass of the planet-star system. The light from the star experiences RV shifts of potentially measurable semi-amplitude $K$ and period $P$ caused by the planet, which depend on the eccentricity of the orbit $e$ and $\omega_s$, the argument of periapsis, and are similar to the ones in Figure 2.2. The distance between the star and the barycentre of the planetary system, $r$, and the semi-major axis, $a$, is given by,

$$r (1 + e \cos \nu) = a (1 - e^2),$$

(2.2)

while the radial velocity $V_r$ can be calculated using,

$$V_r = K[\cos (\nu + \omega_s) + e \cos \omega_s] + \gamma,$$

(2.3)
Figure 2.2: The RV curves with varying $e$ and $\omega_*$ (Wright & Gaudi 2013).

where $\nu$ is the true anomaly i.e. the position of the orbiting body (planet) along the ellipse and $\gamma$ is the bulk velocity of the centre of mass of the star-planet system.

These parameters are outlined in Figure 2.3 where $\Omega$ is the longitude of ascending node and $P(w)$ is the position of periapsis. Neither $\Omega$, nor $i$ are known via RV but can be measured via astrometry, by measuring the angular displacement of the star on the sky (Wright & Gaudi 2013).

The mass of the planet, $M_p$, is calculated using the third Kepler law. It is necessary that both the mass of the star, $M_*$, and $i$ are known. $M_*$ is computed via high-resolution spectroscopy, parallax or theoretically. As the angle $i$ at which the planet orbit is inclined to the plane of the sky remains unknown, only
the minimum mass the planet could have $M_p \sin i$ is produced, when $\sin i = 1$ (Kaltenegger 2017, Wright & Gaudi 2013).

For the SNR calculation using the RV technique, the $A$ in Equation 2.1 is replaced by $K$ and $g$ depends on both $e$ and $\omega_*$. If the duration of observations is less than the period of the planet, the detectability also depends on the period and phase of the planet i.e. $(SNR)_{RV} \propto P^{-1} = M_p a^{-1/2} M_*^{-1/2}$ i.e. it decreases with larger periods. To detect a planet via RV, $\sigma_{RV} \ll K$, using Equation 2.1, RV is more sensitive to big planets with shorter periods (shorter than the duration of measurements). There is a minimum $M_p \simeq 1/(SNR)_{RV}$ and a maximum period $P \simeq 14,000$ days. As star mass decreases, the RV signal increases i.e. host stars of type G and early K main-sequence are more likely to have detectable RV planets (Wright & Gaudi 2013).

High velocity precisions in the measurements that are required to detect planets, especially low-mass planets i.e. Earth-like or exo-Earth can only be achieved via high resolution spectroscopy, which employs Echelle spectrographs. Their
purpose is not only to detect new exoplanets but also to follow up the discoveries made by transit photometry in space e.g. the Transiting Exoplanet Survey Satellite (TESS) ([Ricker et al. 2016](#)), as, along with transit measurements, it gives the true mass of the planet. The most precise spectrograph at this time is HARPS at the ESO 3.6 telescope in La Silla, which can achieve a velocity precision of 0.8 m/s at a wavelength of 400-700 nm. ([Fischer et al. 2016](#)).

The next generation of spectrographs includes EXtreme PREcision Spectrograph (EXPRES), made of optical fibre that will be installed at the Lowell Observatory, and the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) on the Very Large Telescope (VLT). They are expected to have high resolution, high SNR, minimum stellar jitter, and a stable point-spread-function (PSF) which will enable precisions as high as 10 cm/s i.e. high enough so that Earth-like planets may be detected ([Jurgenson et al. 2016](#) [Allart et al. 2017](#)).

Due to sensitivity reasons, the vast majority of the planets detected via RV shifts so far is represented by massive planets. One unexpected class of planets (as there is no equivalent of such planets in our Solar System) that this method is sensitive to is planets with a mass between $1-13 M_J$ and a short orbital period, ranging from a few hours to a few days but usually $P \leq 10$ days. These planets, known as hot Jupiters, e.g. ([Henry et al. 2000](#)), are often encountered within planetary systems that consist of one planet only ([Oberst et al. 2017](#)). However, Wasp-47c, discovered in 2015 via RV is a Jovian planet that lies within the WASP-47 multiplanetary system, also consisting of 3 other (transiting) planets, one hot Jupiter (WASP-47b), a super-Earth (WASP-47e) and a Neptune-like planet (WASP-47d) ([Huang et al. 2017](#)). Since then there have been a few other discoveries of hot Jupiters being in a 2-planet system with a massive outer planet
or in a 3-planet system with two Jupiter-like planets (Wright et al. 2009).

As of July 2018, the RV method has yielded 93 super-Earths, 70 sub-Neptunian planets, 10 of which are on periods less than 10 days i.e. hot Neptunes, 53 hot Jupiters, 138 warm Jupiters i.e. planets that are giants but with periods between 10-200 days (Huang et al. 2017) and 425 giants on longer orbits. Figure 2.4 presents 733 of these, which have precise mass and period measurements.

Figure 2.4: 733 RV planets with known orbital periods and masses. The radii, if known, are outlined by the colourbar. Planet data were taken from http://exoplanet.eu/. A comparison with the Earth is made i.e. the green clover-leaf. There have been no RV exo-Earths discovered so far.

2.2.2 Astrometry

Astrometric measurements are changes in the position of the star on the sky due to the influence of planets orbiting it. It aims to track the motion of the star

\[1\text{http://exoplanet.eu}\]
around the barycentre of the potential planetary system due to a hidden planet with reference to background stars. A star at a distance $d$ away from Earth produces an astrometric shift of semi-amplitude ($2A$ in Equation 2.1)

$$\theta = \frac{a M_p}{d M_*},$$  

(2.4)

assuming that the orbit of the planet is circular. A Jupiter-like planet on an orbit around a Sun-like star 20 pc away would produce a $\theta \simeq 0.24$ mas (miliarcsec) while an exo-Earth’s signal would be about 0.15 $\mu$as (Wright & Gaudi 2013, Butkevich 2018).

As Equation 2.4 implies, detecting a planet via astrometry depends on how big the planet is (the bigger the more sensitivity), the mass of the host star ($\theta$ increases with decreasing mass) and how far away it is from the Earth. From Equation 2.1 we know it also depends on the number of observations (in this case the number of photons captured in a measurement) and on the measurement uncertainty. For astrometry, this is,

$$\sigma_{\text{AST}} = \frac{\lambda \sqrt{N_{\text{photons}}}}{D} \propto \frac{1}{\sqrt{F}},$$  

(2.5)

where $\lambda$ is the wavelength at which the observation is made, $D$ is either the diameter of the telescope (for one single telescope) or the baseline of the interferometer if multiple telescopes are used, $N_{\text{photons}}$ is the number of photons that enter the aperture of the telescope, and $F$ is the flux of the star. This proportionality is given by Poisson statistics (Wright & Gaudi 2013).

In the interferometry case, precisions of $\leq 1$ mas could be reached from the ground as long as the target is represented by bright stars with known reference stars, while space telescopes could achieve precisions of 1 $\mu$as (Wright & Gaudi).
This would allow the potential detection of hundreds of nearby exo-Earths (Goullioud et al. 2008).

If both RV and astrometry measurements are being made then the true mass of a planet would be known as both the inclination and the orientation of the orbit of the planets is given by astrometry. Similar to RV and transit photometry, however, astrometry is limited by its being sensitive to planets with periods less than or equal to the survey period (Wright & Gaudi 2013). Unlike these two methods, it is not affected by star spots (Makarov et al. 2009).

The only astrometry planet detected so far was yielded by a study led by Muterspaugh et al. (2010) who studied 51 binary stars in search for astrometric shifts. This planet, HD176051b, is a Jupiter-like planet 14 pc away with a semi-major axis of 1.76 AU and a period of 2.8 years. It is unknown, however, which star it orbits, the solar-like primary star or the 0.7 $M_\odot$ secondary, where $M_\odot$ is the mass of the Sun.

### 2.2.3 Transit photometry

The flux of a star that is orbited by a planet decreases when the planet transits the star i.e. passes in front of it, as shown in Figure 2.5. A planet transits a star if the distance between the planet and the star on the sky during the inferior conjunction is less than the combined radii of planet and star i.e. $r \cos i \leq R_* + R_p$, where $R_*$ is the radius of the star and $R_p$ is the radius of the planet (Wright & Gaudi 2013).

Considering that $r \cos i = a (1 - e^2)/(1 + e \sin \omega_*)$, the transit probability for isotropic orbits is

$$P_{tr} = \frac{R_* + R_p}{r \cos i},$$  \hspace{1cm} (2.6)
which, for circular orbits with $R_p \ll R_*$, can be approximated to $P_{tr} = R_*/a$ (Wright & Gaudi 2013).

The reduction in the flux of the star is proportional to the ratio of the areas of the planet and star. In the simplest case where the orbit of the planet is circular and the star has a uniform brightness, as well as $R_p \ll R_* \ll a$ and $M_p \ll M_*$, the planet is described by a rectilinear trajectory with the time taken to transit the star $T_{tr}$ approximated to be

$$T_{tr} = \frac{R_* P}{\pi a} = \left( \frac{3P}{\pi^2 G \rho_*} \right)^{1/3},$$

(2.7)

where $\rho_*$ is the equation of the mean density of the star. For an Earth-like planet orbiting a Sun-like star, the transit time is about 13 hours. Both the period $P$ and $\rho_*$ can be determined by observing a few transits (Wright & Gaudi 2013).
From Equation 2.1 the detectability,

$$(SNR)_{tr} = \sqrt{\frac{NT}{P}} \frac{\delta}{\sigma_{ph}},$$

(2.8)

where $\sigma_{ph}$ is the fractional photometric uncertainty and $\delta = (R_p/R_*)^2$ is the transit depth. For $R_p \simeq R_J$, where $R_J$ is the radius of Jupiter and $P \simeq 3$ days for a hot Jupiter orbiting a solar-type star, $P_{tr} = 10\%$, $\delta = 1\%$ and $T_{tr}/P = 3\%$. As only 0.5% of all solar-type stars are orbited by hot Jupiters, many thousands of stars are being monitored to find a transit. As the transit method is sensitive to short period, large radius planets, the target of this method is represented by low mass main-sequence stars \cite{Wright2013}.

There have been over 2,800 exoplanets detected via transit so far, less than half of which have a radius less than $2 R_\oplus$. Depending on their mass (which remains unknown for the majority of them), they could be super-Earths, exo-Earths or planets less massive than the Earth (i.e. Mars like or Mercury-like sizewise). The rest of the planets is represented by potentially sub-Neptunian planets i.e. planets with a radius below $4 R_\oplus$ and planets with a radius bigger than that. Most of the big planets, especially hot Jupiters, have had RV follow-up studies that led to their mass measurement as well. Figure 2.6 shows 2,787 of the transiting planets, which have a known radius and orbital period.

The discovery of a large number of these planets was possible because of the successful launch of Kepler in 2009, which monitored more than 100,000 stars in four years searching for planetary transits \cite{Borucki2010}. 1/400 of the sky was surveyed with a focus on low brightness stars that RV spectrographs are not quite sensitive to detect yet. When Kepler’s second reaction wheel failed \cite{Szabo2016}, it got a new mission, K2, which was extended to cover 1/27 of the
Figure 2.6: 2,787 transiting planets. The radii, orbital periods and masses (if known) of the planets were taken from http://exoplanet.eu/. A comparison with the Earth is made i.e. the green cloverleaf. No transiting exoplanets discovered so far come close to being similar to Earth.

sky and focus on all stars, even bright ones (David et al. 2018).

One of the transiting planets that stand out is K2-155d, a super-Earth with a mass of 4.9 $M_{\oplus}$, a radius of 1.9 $R_{\oplus}$ and a period of 41 days 82 pc away. It lies within a planetary system consisting of two other inner planets, another super-Earth and a sub-Neptunian planet, all orbiting an M-dwarf star with a mass of 0.65 $M_{\odot}$ (follow-up observations were made with the HARPS spectrograph). Although it is possible that it is tidally locked to the star, giving its small separation from the star $a = 0.19$ AU, it might be habitable as well (Hirano et al. 2018, Diez Alonso et al. 2018).
2.2.4 Other detection methods

There are a few other detection methods that have yielded new planets, although not as successfully as RV and transit photometry. I will outline below the techniques of four other detection methods that have led to the discovery of just over 200 planets.

Direct imaging tries to distinguish between the photons coming from the planet and the ones coming from the star and depends on the planet/star flux ratio and on the planet-star angular separation. The success of direct imaging depends on adaptive optics, used by ground-based telescopes and achieved via deformable mirrors that correct the wavefront aberrations caused by the atmosphere of the Earth as well as coronagraphy, which uses masks to decrease the starlight and make planets more visible. Still, direct imaging is more easily achieved when planets are placed further away from the parent star due to the diffraction limit i.e. only objects beyond $3 \lambda/d$ are bright enough to be individually imaged, and when the targeted planets are less than 1 Gyr old as their higher temperature produces a higher IR flux. It gives the mass of the planet and can give its semi-major axis and period as well. It is also linked to observing the spectra of planets and so can yield the atmospheres of planets (Wright & Gaudi 2013, Guimond & Cowan 2018, Derigs et al. 2014).

Gravitational microlensing is an exoplanet detection method that uses the fact that the gravitation of a foreground star (star or stellar remnant) will distort the light coming from a more distant background object i.e. the image is split in two and magnified (how much depending on angular separation). If the foreground star has a planet orbiting around it, the gravity of the planet will perturb the light near the two images. This method can detect both bound and free-floating
planets. It gives the mass of the planet and the semi-major axis. Unlike RV, astrometry, and transit exoplanets, microlensing planets are typically more distant i.e. a few kpc away from Earth.

In multiplanetary systems the transiting planet(s) may show perturbations from a Keplerian orbit caused by the the gravitational interaction with other planets, that may or may not transit the host themselves, known as transit timing variations or TTVs. To obtain TTVs from a planetary system at least 3 transits of the transiting planet(s) must be observed. TTVs include changes in $a$, $e$, $\omega_*$, and the period of the transit which can be especially large if the planets are near mean motion resonance (MMR), which occurs when the orbital periods of the planets are related by an integer. This method yields the mass, eccentricity and the period of the planet and sometimes (depending on whether it is also transiting or not) the radius, the semi-major axis and the inclination of the planet. There have been 7 confirmed exoplanets detected via TTVs so far, including 2 of the exoplanets from the WASP-47 multiplanetary system mentioned in subsection 2.2.1 WASP-47d and WASP-47e. The TTVs method led to the discovery of a new class of exoplanets, with low density e.g. Kepler-51 with a mass of $2\, M_\oplus$ but a radius of $7\, R_\oplus$ but it is especially sensitive to small planets and relatively long periods.

The amount of light that is received from a main sequence star, an evolved star or a stellar remnant (e.g. eclipsing binaries, pulsars, pulsating, white dwarfs) can show periodic changes, which gives rise to the timing exoplanet detection method. For pulsars and eclipsing binaries, they can be detected either by measuring the frequency variations of a certain physical characteristic of the star (which works
in a similar fashion to the RV method) or by noticing variations in the light of the star due to its moving about the barycentre of the star-planet system, given a big enough separation between the star and the planet. This method led to the first successful discovery of two (confirmed) exoplanets around the pulsar PSR 1257+12 by Wolszczan & Frail (1992), two super-Earths both with a mass of $4 \, M_{\oplus}$ and periods of 66 and 98 days. A third exoplanet around the pulsar was also confirmed, with a mass of $0.022 \, M_{\oplus}$ and a 24-day period by Wolszczan et al. (2000). For eclipsing binaries only, the orbit of the eclipsing star is gravitationally affected by the other bodies in the system and exhibits perturbations which, as with TTVs, can be large if the bodies are near MMR (Wright & Gaudi 2013). The timing method yields the mass, the period and semi-major axis of the planet.

2.3 Habitable exoplanets

This section will define and describe the habitable zone (HZ), having the Solar System’s HZ as an example, and will investigate what Earth characteristics would make another Earth or Earth-2. As a good way to compare an exoplanet with the Earth is represented by the Earth similarity index, details about this concept are given. The exoplanets already discovered that are likely to lie in the HZ of their host stars are listed, plotted and characterised. Lastly, the concept and detection of exomoons is introduced.
2.3.1 Habitable zone

The definition of the habitable zone says it is the zone a certain distance away from a star in which liquid water could exist. A rocky planet with a mass of 0.3–10 $M_{\oplus}$, a radius of 0.5–1.9 $R_{\oplus}$ and a bulk density of 0.7-1.5 $\rho_{\oplus}$ (Earth density i.e. 4.4–8.3 g/cm$^3$) that has $CO_2$, $H_2O$ and $N_2$ in its atmosphere can have a surface made primarily of water if it receives the right amount of radiation from its host star and can be described as an exo-Earth (Schulze-Makuch et al. 2011, Kopparapu et al. 2013, Schulze-Makuch et al. 2011). The received radiation depends on the flux of the host star $F = L/4\pi a^2$, which is set by the spectral type of the star, as well as on the Bond albedo of the planet and on the eccentricity of the orbit of the planet as the average stellar flux $<S>$ depends on eccentricity as

$$<S> = \frac{F}{\sqrt{1 - e^2}}. \tag{2.9}$$

The limits of the location of HZ (can be applied for all the types of stars), the inner limit $l_{in}$, and the outer limit $l_{out}$ (in AU) are given by

$$l_{in} = (l_{in\odot} - a_{in} T_* - b_{in} T_*^2) \left(\frac{L}{L_{\odot}}\right)^{\frac{1}{2}}, \tag{2.10}$$

$$l_{out} = (l_{out\odot} - a_{out} T_* - b_{out} T_*^2) \left(\frac{L}{L_{\odot}}\right)^{\frac{1}{2}}, \tag{2.11}$$

where $a_{in} = 2.7619 \times 10^{-5}$, $b_{in} = 3.8095 \times 10^{-9}$, $a_{out} = 1.3786 \times 10^{-4}$, $b_{out} = 1.4286 \times 10^{-9}$, $T_* = T_{eff} - 5700$ with $T_{eff}$ being the effective temperature of the host star in K, $l_{in\odot}$ and $l_{out\odot}$ are the Earth’s inner and outer HZ limit, respectively, $L$ is the luminosity of the host star and $L_{\odot}$ is the luminosity of the Sun (Selsis et al. 2007).

For a low-mass main-sequence star, the habitable zone semi-major axis $a_{HZ}$
is \( \sim 0.01 \) AU and the period \( \sim 1 \) day, whereas for a 2 \( M_\odot \) star, these increase to \( a_{HZ} \sim 4 \) AU and \( P \sim 6 \) years \cite{wright2013}. If a planet is placed near the outer edge of the habitable zone, its atmosphere may be formed of dense \( CO_2 \) clouds caused by its active volcanoes. This can be solved by the motion of air currents in the troposphere and an average surface temperature above 0°C. A planet placed near the inner edge of the habitable zone experiences an abundance of water in its stratosphere, which makes all the hydrogen from the atmosphere escape. As the host star evolves on the main sequence, the habitable zone boundaries given by Equation 2.10 and Equation 2.11 also change \cite{kopparapu2013}. The continuously habitable zone (CHZ) is a term used for the HZ region which remains within the HZ limits for a long period of time, depending on the spectral type of the star \cite{selsis2007}.

For our Solar System, the HZ is in between Venus and Mars with Earth being in the middle, at 0.95-1.67 AU, distance estimated by considering that the planets have no clouds in their atmospheres \cite{kopparapu2013}. The presence of \( CO_2 \), \( H_2O \), \( CH_4 \), \( N_2O \), \( NH_3 \) and CFC clouds could increase the outer limit to 2.4 AU \cite{forget1997, mischna2000, selsis2007}. It is believed Venus used to be habitable 1 Gyr ago when the Sun was 8% less bright than today \cite{kaltenegger2017, selsis2007} and that there was a water ocean instead of the current magma ocean on its surface \cite{way2016}. Models also show that Mars had liquid water on its surface 4 Gyr ago \cite{pollack1987, bibring2006} when the Sun was 28% less luminous \cite{selsis2007}. It will enter the HZ again in a few billion years, by the time our Sun will have headed toward the red giant phase, when it will increase in size and luminosity \cite{guo2010}.
2.3.2 Earth-2

Even though a rocky planet is in the HZ it may not be habitable i.e. have its surface propitious for life as this depends on several other factors beside the abundance of liquid water (Selsis et al. 2007).

The minimum orbital distance of a planet must be at least 0.01 AU, otherwise the planet would be within the star’s Roche limit i.e. not in hydrostatic equilibrium. The Roche limit is different for rocky and gas planets i.e. $P > 12$ hours for gas giants and $P > 5$ hours for rocky planets (Winn & Fabrycky 2015, Kopparapu et al. 2013). If a planet is close to the star, it may be tidally locked to the star e.g. both Mercury and Proxima Centauri b are in 3:2 resonance (rotation period:revolution period) with their host stars (Noyelles et al. 2014, Kreidberg & Loeb 2016). If the $n$ in the resonance case $2:n$ is $\neq 2$ the star rise and star set can happen at various points of the planet so the entire planet surface receives starlight. However, if $n=2$ (synchronous case), there is an area of the planet that never gets illuminated by the the star. The coverage of this area depends on the eccentricity and obliquity of the planet (Selsis et al. 2007). The synchronous case could be prevented by strong thermal tides in the planet atmosphere caused by it receiving a lot of radiation from the host star e.g. Venus (Correia & Laskar 2003). In the synchronous case the habitability of the planet wouldn’t be negatively influenced if the planet had a large atmosphere e.g. Earth which allows heat to be distributed everywhere on the surface of the planet. There is also a maximum orbital distance which is $10^5$ AU, outside of which there would be perturbations from other stars and the galactic tidal field (Kaltenegger 2017).

There are still questions regarding the composition of the atmosphere i.e. whether it has to be similar to Earth’s and whether the alien planet would need
the white light of G-type stars like the Sun or if the infrared light of an M dwarf would be good for the development of life (Winn & Fabrycky 2015). Since the Earth, Mars and Venus all have an atmosphere exhibiting clouds, a habitable planet presumably would as well. Clouds that are highly reflective could make the planet appear brighter in the visible and near infrared regimes but would obscure the gases that are found at low depths in the atmosphere (Kaltenegger 2017).

The HZ planet could be bombarded with X-ray and XUV (extreme ultraviolet) radiation as well as strong particle fluxes created by stellar winds and coronal mass ejections (CMEs) due to the magnetism of the star. These could cause the partial or complete loss of the atmosphere of the planet. A magnetosphere around the planet could protect it from this bombardment depending on its strength (Winn & Fabrycky 2015, Selsis et al. 2007).

The right gravity of a planet may have an impact as well. For example, even if the current models place Mars somewhere at the edge of the Solar System’s HZ, its lack of gravity is the cause of inactive plate tectonics which further influences the atmosphere - being really thin as the $CO_2$ is never refilled (Selsis et al. 2007). Active tectonics would also give rise to volcanoes, as on Earth, but volcanism is not a definite sign of life on other planets or moons e.g. Io. (Kaltenegger 2017).

A habitable planet would also need protection from the radiation coming from the star. Although the magnitude of the initial magnetic field required to create this protective layer surrounding the planet is not known, the presence of a magnetic field generated by the core depends on the (fast) rotation of the planet and the (high) heat flux at the Gutenberg discontinuity (Kaltenegger 2017).
Another aspect to consider is the presence of moon(s) orbiting the planet and how these influence the planet. The Earth’s moon creates tides on Earth that is a heating source which is believed to have an impact on the Earth’s climate (Zahnle et al. 2007). There have been no exomoon discoveries so far but TTV and TDV (transit duration variation) measurements look more promising with the launch of satellites such as TESS (Heller et al. 2016) and PLATO (PLAnetary Transits and Oscillations of stars) (Walton 2016).

2.3.3 Earth Similarity Index (ESI)

The Earth similarity index (ESI) is a measure of how much like Earth a given planet (or moon) is. Its value can be in the range of 0 (no similarities whatsoever between Earth and the planet) and 1 (when the planet could be considered Earth’s twin) and can be obtained via

\[
ESI = \left(1 - \frac{|x - x_0|}{x + x_0}\right)^\omega,
\]

where \(x\) is a certain property of the planet (e.g. mass, radius, escape velocity, bulk density and temperature), \(x_0\) is the Earth-equivalent of this quantity and \(\omega\) is a scaling factor (which is 0.57 for the mean radius, 1.07 for the bulk density, 0.70 for the escape velocity, and 5.58 for the surface temperature) (Schulze-Makuch et al. 2011).

There are three separate ESI estimates, one for the interior of the planet (whether rocky or not), one for the planetary surface (if it can have a temperate surface), and a combined global one. An Earth-like planet has a mass, radius and bulk density as defined in subsection 2.3.1 a mean surface temperature of 273–323 K, and an escape velocity of 4.5-15.6 km/s (allowing the existence of
nitrogen atoms in the atmosphere). Planets may be Earth-like for an ESI of at least 0.8. For example, Venus has an interior ESI of 0.98 but a surface ESI of 0.2 (Schulze-Makuch et al. 2011), which means that even if Venus looks like Earth it is overall not considered Earth-like.

Figure 2.7 shows 84 exoplanets whose known masses and radii give them the status of rocky planets. A comparison with Earth is also made. Although there are a few planets that are similar in size and mass to Earth, they are a lot closer to the host star than our planet. However, the majority of the host stars are either M-dwarfs or K-dwarfs, which exhibit different conditions e.g. radiation levels from the Earth.
2.3.4 Habitable exoplanet candidates

Planets similar to Earth are predicted to orbit 10% of all stars (Kreidberg & Loeb 2016). About 2% of these are in the habitable zone of Sun-like stars (Wandel 2017). At the time this thesis was written there were over 300 planets placed within the habitable zone of their hosts. This was calculated using the HZ limits in Equation 2.10 and Equation 2.11 using data from http://exoplanet.eu/. However, most of these have either unknown masses or radii. Figure 2.8 shows 311 planets with known semi-major axis and orbital period but mostly unknown radius, while Figure 2.9 shows 280 planets with known semi-major axis, period and mass. The following paragraphs describe a few possible exo-Earths among them.

Figure 2.8: 311 planets situated in the HZ of their host stars. The semi-major axes, orbital periods and radii (if known) of the planets were taken from http://exoplanet.eu/.

Trappist-1 System

The multi-planetary system Trappist-1, which is 12 parsecs away and contains
Figure 2.9: 280 planets situated in the HZ of their host stars. The known semi-major axes, orbital periods and masses of the planets were taken from http://exoplanet.eu/.

a 0.08 $M_\odot$ ultra-cool red M dwarf star and 7 planets, was confirmed in 2017 (Gillon et al. 2016, Dittmann et al. 2017). Although four of the planets are in the habitable zone of the star, they are closer to the star than Earth is to the Sun due to the lower luminosity of the host star. They rotate faster, are likely to be tidally locked to the star and are subject to higher electromagnetic radiation levels. This might cause increased volcanic activity which is not ideal for life development as it would cause acid rain, the lack of an ozone layer and the presence of greenhouse gases in the atmosphere (Kislyakova et al. 2017). The masses and densities of the planets are not accurately known since they are too faint to be observed by the current RV spectrographs (Dittmann et al. 2017).

**Proxima Centauri b**

The atmosphere of Proxima Centauri b, a rocky planet with a minimum mass of 1.3 $M_\oplus$ that lies within the habitable zone of the closest star to Earth, Proxima
Centauri, shows that water may exist in liquid form on the surface of the planet. The analysis of its atmosphere is only possible because of the proximity of the host star, only 1.295 pc away (Turbet et al. 2016) but because the planet does not transit its host star, its radius is not known (Dittmann et al. 2017). As with the Trappist star and unlike our Sun, Proxima Centauri is a rather active star emitting more UV radiation (Turbe et al. 2017).

**LHS 1140 b**

At a distance of $12.47 \pm 0.42$ parsecs, LHS 1140 is a 5 Gyr old red dwarf star 15\% the mass of the Sun and half its metallicity that is transited by a super-Earth planet, LHS 1140 b. Via transit and radial velocity measurements it was estimated that it has a mass of $6.65 \pm 1.82 M_\oplus$, a radius of $1.43 \pm 0.10 R_\oplus$, a period of 24.7 days and an eccentricity of 0.29 (Dittmann et al. 2017). These figures indicate the planet is of rocky composition and lies in the habitable zone of the host star. The investigation of the planet’s atmosphere is likely to be made with the next generation of telescopes.

**Gliese 581 system**

The four planet system Gliese 581 lies 6.27 pc away and has three potentially rocky super-Earth planets in the habitable zone. The closest one, Gliese 581 e, lies at 0.03 AU, with a minimum mass of $1.94 M_\oplus$. The other two, Gliese 581 c and Gliese 581 d, have masses and radii $5.36 M_\oplus$ and $0.07 AU$, and $7.09 M_\oplus$ at 0.22 AU, respectively. Gliese 581 d is the most likely to be in the habitable zone of the M3 star with a mass of $0.31 M_\odot$ and 6.27 pc away. If it were to be on a highly eccentric orbit, it could receive 8% more radiation from the host star than if on an almost circular orbit and it wouldn’t be tidally locked to the star. The radial velocity measurements give it an eccentricity of 0.38. Models that predict
CHAPTER 2. EXOPLANETS: DETECTION AND HABITABILITY

the existence of \(H_2O, CH_4,\) and \(N_2\) in the atmosphere of the exoplanet as well as a surface temperature above 273 K give Gliese 581 d the status of habitable planet \(\text{(von Paris et al. 2010)}\). However, since no transits of the system have been observed, the radii of the exoplanets are unknown.

2.3.5 Exomoons

Even if the majority of the currently discovered exoplanets that lie within the HZ of their hosts are most likely giant planets and therefore not suitable for life, they might be orbited by rocky exomoons that are also within the HZ that might be habitable. Given that in our Solar System the two gas giants are orbited by many moons i.e. Jupiter has 79 moons and Saturn 62 \(^2\) Jupiter-like exoplanets might host exomoons as well. Our moon and Mars’ moons Phobos and Deimos that lie within the HZ of the Sun may be without life, but the probability is likely to improve as the number of considered planets increases \(\text{(Hill et al. 2018)}\).

There have been no exomoon discoveries so far. The RV method cannot be used to detect exomoons as the RV signal of the star cannot be further split to distinguish between a planet and a moon. A small fraction of the transit signal of a planet could be due to a moon; this can only be observed for planets that are at a small separations from the host so that the more transits are captured the more likely it is to differentiate the transit signal. This distance dependence can be removed by following up transit observations with TTVs and TDVs of the planet. If there is a \(\pi/2\) difference between TTVs and TDVs, the signal is likely to have been caused by a moon. Microlensing signals coming from a moon orbiting a planet are possible because the moon would modify the caustic of the planet \(\text{(Kipping et al. 2015, Hwang et al. 2018, Heller 2017b, Kipping 2009)}\). When the

\(^2\)See http://www.dtm.ciw.edu/users/sheppard/satellites/
planets are far away from the star, direct imaging can separate the planet from the star and might be able to detect the moons shadows and transits while the moons cross the planet as well as to measure the locations of the planet-moon photocentre for a given object that may or may not be part of the stellar system (Cabrera & Schneider 2007, Heller 2016, Agol et al. 2015).

As the habitability of a moon is increased by it having an atmosphere, only objects with a mass greater than $0.25 \, M_⊕$ have enough gravitation to hold an atmosphere. Moons with a mass in between $0.25 - 0.5 \, M_⊕$ may be similar to Mars while bigger satellites might have a habitat that is Earth-like if the XUV radiation of the host is sufficiently low (less than 100 times the Sun’s current XUV flux). This moon would be different from any moon from the Solar System that we know of, as the biggest moon, Jupiter’s Ganymede is only $0.025 \, M_⊕$ (Lammer et al. 2014).

2.4 The Earth as an exoplanet

This section will discuss how the Earth can be detected from outer space by a potential intelligent civilisation, the characteristics that make Earth stand out from the other planets and place it on the habitability map. The concept of communication between two planets that see each other’s transit is introduced, with a focus on Earth’s transit zone.

2.4.1 Ways of detecting the Earth

As a transiting planet, Earth would be visible in multiple wavelengths. Figure 2.10 outlines the gases that are present in the Earth’s transmission spectrum
at four different wavelengths, ultraviolet, visible, near infrared and infrared for a Sun-like star and an M dwarf. The starlight that enters a planet’s atmosphere is refracted by the gases that make up the atmosphere, following that the deeper a gas is, the more starlight it refracts. The refraction of starlight from the deep region of the atmosphere of an exoplanet that transits a star causes the deflection of the starlight away from a distant observer. This puts a lower limit to the parts of the exoplanet’s spectrum that would be seen. For Earth, this limit is 12 km i.e. the deepest gases that occupy the region of the atmosphere below 12 km are invisible to a distant observer that watches us transiting the Sun. Water, the element associated with the development of life, lies within the deepest 10-15 km of our atmosphere and therefore is unlikely to be detected by the observer.

However, the $CH_4$ (infrared), $N_2O$ (visible, infrared), $O_2$ (ultraviolet, visible, infrared), $O_3$ (ultraviolet, near infrared, infrared), $CH_3Cl$ (infrared) and $CO_2$ (visible, near infrared, infrared) gases that lie higher up in the atmosphere could be detected and might indicate directly or indirectly the presence of an active habitat. The detectability of gases also depends on the amount of starlight. Since an M dwarf’s flux is less than Sun’s flux, the gases’ depths are lower in the atmosphere of the transiting planet. Even the Earth in the past had different spectra than the current ones as the light it received from the Sun changed every few hundreds of million years as did the composition of the atmosphere (Kaltenegger 2017).

A distant observer could also use spectroscopy to observe the Earth. RV observations could detect the gases mentioned above as well after calculating the energy transitions of the emission spectrum (Kaltenegger 2017).
Figure 2.10: The Earth’s transmission spectrum in a) ultraviolet, b) visible, c) near infrared and d) infrared as it transits the Sun (black line) and an M dwarf star (red line). Reproduced from Kaltenegger (2017).
2.4.2 What makes Earth habitable from outer space?

Apart from the gases discussed in subsection 2.4.1 that would make the Earth potentially interesting or habitable to an outer observer, there are other gases like $CCl_2F_2$ (also known as Freon-12 and used as an aerosol in industry) and $CCl_3F$ (also known as Freon-11 and formerly used as a refrigerant) from Earth’s current atmosphere that represent traces of our technology. Although they are detectable in infrared, their quantity in Earth’s atmosphere is not significant and spectroscopic detections might prove to be challenging (Des Marais et al. 2002, Selsis et al. 2002, Kaltenegger et al. 2009).

When $CH_4$ and $O_2$ as well as $CH_4$ and $NO_2$ are present together in the atmosphere of a planet in a large enough quantity to be captured by telescopes and are not easily produced by nonliving processes in the environment, the planet is likely to be habitable as these combinations can only be produced by lifeforms and are hence called biosignatures (Lederberg 1965, Lovelock 1965, Lippincott et al. 1967). From space a combination of $O_2$ and $CH_4$ in the Earth’s atmosphere can be detected with low resolution, $R < 100$, spectrographs (Des Marais et al. 2002). However, a combination of $CH_4$ and $NO_2$ is not detectable (Segura et al. 2005, Kaltenegger et al. 2007, Grenfell et al. 2011). Even if an individual gas can be easily detected on its own, it is not a biosignature as it can be produced by the environment (Harman et al. 2015). For instance, $CH_4$ can be produced when $CO_2$ reacts with hydrogen released by the interaction between iron and water in hydrothermal systems (Grenfell et al. 2010, Zendejas et al. 2010).

The reflected light off Earth’s surface which is changed by the Earth’s vegetation could be detectable from space at a wavelength of 700 nm, while minerals’
signature peaks at 750 nm (Seager et al. 2010). For an exoplanet, these wavelengths could increase or decrease depending on the photosynthesis-equivalent process taking place on the surface (Kiang et al. 2007a,b). The work of coral reefs on Earth, which absorb life-threatening UV radiation and re-radiate it at longer less harmful wavelengths, could also be a biosignature (Kaltenegger 2017).

2.4.3 Communication via transit

Observers on a planet that observe the transit of a faraway planet and are aware that their transit can also be detected by the faraway planet can use their transit as a means of communication. This can be done by emitting low frequency signals that could not be explained by natural electromagnetic energy sources (Forgan 2017). These include positioning of triangles around the star that create transit curves which are different from the typical curves created by a planet (Arnold 2005) and transmitting laser pulses at an optical wavelength in the direction of the observer that distort the transit curves of the planet to mask them from an outer observer or to make them appear to have been created by an intelligent civilisation. In the latter case, it is not necessary to alter the transit of civilisation’s own planet; a planet closer to the host star, and therefore one that exhibits more transits e.g. Mercury could be used to broadcast the existence of the civilisation (Kipping 2009). The electromagnetic signals transmitted during transit represent a continuous means of communication between two civilisations which see each other’s transit that can go on as the host stars travel through the Galaxy even when the pair of planets is not aligned anymore so that they both see each other’s transit. (Forgan 2017)

For Earth, a portion of the sky that contains stars from the locations of which
Earth’s transit can be observed i.e. transit zone has been identified (Filippova & Strelnitskij 1988, Conn et al. 2008, Heller & Pudritz 2016). According to (Heller & Pudritz 2016) there are 45 K and 37 G stars within 1 kpc of Earth that can see Earth’s transit around the Sun. As 10% of all Sun-like stars are orbited by a terrestrial planet (Dressing & Charbonneau 2013, Kaltenegger & Sasselov 2011, Petigura & Marcy 2013), 8 of these stars have an Earth-like planet orbiting them.

As the Sun orbits the centre of the Galaxy, new stars enter the transit zone of the Earth, that could consist of millions of stars, considering that the Sun has orbited the centre 20 times in its lifetime. Simulations of the communications of civilisations within the galactic habitable zone (GHZ) i.e. a metal rich part of the Milky Way disc that favours planet formation (Lineweaver et al. 2004) via their transit (excluding binary host stars of civilisations) show that at a given moment around 35 civilisations out of 400 are able to communicate. However, once communication has been established, it can be maintained for 1 Gyr, time which can accommodate at least 30 exchanges between the two civilisations, considering the diameter of the GHZ is 20 kpc and the signals travel at the speed of light (Forgan 2017).

Wells et al. (2018) found that from a random point in the sky, a distant observer can see the transit of three Solar System planets, at most, with probabilities 2.518% for one transiting planet e.g. Earth, 0.229% for two transiting planets e.g. Mars and Earth, and 0.027% for three transiting planets e.g. Mercury, Mars and Earth. They also surveyed the known exoplanets, 68 of which, at the time of the study, were in a favourable location so as to observe the Earth’s transit around the Sun. Out of these, 3 could be Earth-like planets that have GKM host stars. No known Earth-like exoplanets lie in the Earth’s transit zone but it is
estimated in the study that 3 such planets could exist orbiting GK stars and 7 such planets in an orbit around M stars.
Chapter 3

SETI surveys

Ever since the first radio transmitter on Earth was built, radio waves have started putting the Earth on the interstellar map. The first wireless signal, which was sent out over 100 years ago by Marconi (Garrett 2013), has travelled more than 100 light years within the Milky Way, telling potential intelligent beings that we are here. Today, apart from many devices from our everyday life that not only make our lives easier but also transmit radio waves e.g. smartphones, there are telescopes that are on the lookout for potential signs left by another intelligent civilization, projects known as the search for extraterrestrial intelligence or SETI.

The first section of this chapter will focus on the motivation behind SETI research, including the Drake equation, and some early SETI projects, while the next two sections will be considering the past/current and future projects, respectively. The last section will summarise the Messages from Extraterrestrial Intelligence (METI) efforts and discuss its status within the scientific community.
3.1 SETI surveys background and motivation

SETI research is based on the Drake equation (1961),

\[ N = R_\ast \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L, \]  

(3.1)

where \( N \) is the number of civilizations in the Galaxy whose electromagnetic emissions are detectable, \( R_\ast \) is the star formation rate in the Galaxy, \( f_p \) is the fraction of those stars that have planets, \( n_e \) is the average number of planets on which life could develop, \( f_l \) is the fraction of habitable planets on which life actually appears, \( f_i \) is the fraction of planets on which intelligent life evolves, \( f_c \) is the fraction of intelligent civilizations that develop interstellar communication and \( L \) is the length of time civilizations keep sending the signals into space (Worden et al. 2017).

Accurate values for the first three terms on the right hand side of Equation 3.1 have been obtained via observations in recent years, the star formation rate in the Galaxy is \( R_\ast = (2.71 \pm 0.59) \times 10^{-11} \text{yr}^{-1} \) (Licquia & Newman 2015), \( f_p \approx 1 \) (Wandel 2015) and \( 0.15^{+0.13}_{-0.06} < n_e < 0.61^{+0.07}_{-0.15} \) (Kopparapu 2013). Since there are at least 100 billion stars in the Milky Way, there is a good chance that \( N \) is larger than 0 (Worden et al. 2017).

This Drake optimism is balanced by the Fermi pessimism (i.e. the Fermi paradox), according to which the lack of intelligent life in the Galaxy (no alien signal detections yet) is related to the comparability between the time taken by civilisations to become technologically advanced and the time the Galaxy lives for (Gurzadyan & Penrose 2016). The oldest star in the Galaxy, HD 140283, is (14.46 ± 0.31) Gyr old (Bond et al. 2013) whereas Earth is 4.46 ± 0.02 Gyr and the Galaxy colonisation time is estimated to last only 1-100 million years. The
age of the Galaxy gives more than enough time for colonisation of the Galaxy either by advanced civilisations or by their probes that are able to self-replicate. Not seeing any signs of an intelligent civilisation might therefore be because intelligent civilisations might exist but die out before other civilisations appear (Allegre et al. 1995, Tipler 1980, Hart 1975).

Life outside our planet on a faraway planet, either past or present, may be discovered either through biological process signs on the surface of the planet via rovers e.g. Mars’ subsurface (Webster et al. 2015) (this is limited by the distance travelled to get to the planet), inferred biological activity from gases present on the planet (Roth et al. 2014), artificial gases in the atmosphere or on the surface of the planet (Seager 2014), Dyson spheres made by very technologically advanced civilisations (Wright et al. 2014) or by looking for communication signs of an intelligent civilisation (Enriquez et al. 2017).

The narrowest signal natural source transmitters are represented by masers at 300 Hz (Grimm et al. 1987). Signals whose frequency is narrower than this are believed to be signs of a technological advanced civilisation. Of particular interest is the frequency between 500 MHz – 10 GHz known as the terrestrial microwave window, which lies between the low frequency spectrum of the Galaxy and the area in which the \( H_2O \) and \( O_2 \) emissions and absorptions occur in the atmospheres of planets. Since the alien transmitter is likely to be rotating (a planet or a spaceship) and the Earth itself is both rotating and orbiting the Sun there is a drift in the frequency of the narrowband signal. One example of such signal comes from Voyager-1, as shown in Figure 3.1. A signal that is pulsed at regular intervals with a period less than 2 minutes and a bandwidth inversely proportional to its duration is also considered an artificial sign. These signals then have to be distinguished from the background noise from space and the
Figure 3.1: Voyager 1 signal is a perfect example of an artificial signal that the SETI surveys are looking for. Top: integrated spectrum that is drifting (blue) and the applied correction to it (red). Bottom: the frequency as a function of time. Drifting is caused by the Earth moving relative to the spacecraft. Reproduced from (Isaacson et al. 2017).

interference from Earth’s own technology (Harp et al. 2016, Siemion et al. 2013).

Past SETI surveys only employed analogue technology at a single narrow frequency channel (Siemion et al. 2010) and included surveys centred on the 21 cm line (Cocconi & Morrison 1959), the 18 cm hydroxil lines (Tarter et al. 1980), the positronium spin-flip line (Steffes & Deboer 1994, Mauersberger et al. 1996) and the tritium hyperfine line (Valdes & Freitas Jr. 1986).

3.2 Recent and current projects

Nowadays we have the means necessary to detect the signs of a civilisation within the Galaxy with a technological power similar to us. Our radio telescopes
allow the implementation of a wide frequency band that contains over a billion frequency channels and surveys over large areas of the sky (Enriquez et al., 2017; Siemion et al., 2010), so that nothing is missed out.

In this section I will review the major recent and present SETI survey projects as well as the telescopes used to accomplish them, three of which are shown in Figure 3.2.

3.2.1 Project Phoenix

After NASA’s project High Resolution Microwave Survey came to an end in 1993, its efforts to find narrowband continuous and pulsed radio signals produced
CHAPTER 3. SETI SURVEYS

by an intelligent civilisation either intentionally directed at us or transmitted to another location were continued by the SETI Institute via private funding in the form of Project Phoenix. The telescopes that have been used to survey close stars at a frequency 1-3 GHz as well as all-sky stars at a frequency of 1-10 GHz are Parkes, Green Bank, Arecibo, the Lovell telescope and the Allen Telescope Array. A total of 200 stars are observed in a year (Turnbull & Tarter 2003, Backus & Project Phoenix Team 2002).

3.2.2 Breakthrough Listen

Having started in 2015, the Breakthrough Listen project aims to observe 1 million stars close to Earth in the search for artificial signals. It operates from the 2.4 m Automated Planet Finder (APF) optical telescope at the Lick observatory in California, the 100 m Green Bank radio telescope in Virginia and the 64 m Parkes radio telescope in Australia (Vogt et al. 2014, Isaacson et al. 2017). Additional future telescopes include the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in China and the 76 m Lovell radio telescope at the Jodrell Bank Observatory in the UK (Enriquez et al. 2017). Both Breakthrough Listen radio telescopes are capable of detecting signals sent to us on purpose by advanced civilizations as well as “leaked” signals created if they would communicate to one another from large distances (like different planets) at a frequency between 1-12 GHz. If they would try to contact us directly, the signal we would receive would be much stronger (Worden et al. 2017).
CHAPTER 3. SETI SURVEYS

Green Bank Telescope (GBT)

Enriquez et al. (2017) observed 692 stars from the Hipparcos catalog (Perryman et al. 1997) that are visible with GBT, and have well known parameters such as distances, at a frequency of 1.1–1.9 GHz, which comprises the water hole frequency range between 1.4–1.7 GHz. The study was run from January 2016 to February 2017. The analysed signals need to be distinguished both from a human made devices and from natural occurring sources/processes. Very narrow bandwidths i.e. $\sim 1$ Hz yield spectral details and make this job easier. As there were no successful SETI detections, it was concluded that less than 0.1% of the stellar systems within 50 pc of Earth host intelligent civilisations. In the future, the frequency range is planned to be extended to 1–12 GHz and the survey is going to focus on 1,185 stars.

Siemion et al. (2013) looked for signals with a frequency $< 5$ Hz in the direction of 86 stars that are known to host exoplanets in 2011. As no ET signals were found, the study concluded that less than $\sim 1\%$ of the transiting exoplanets are narrowband transmitters.

Isaacson et al. (2017) focused on the 60 closest stars to Earth and 1649 Hipparcos stars (Perryman et al. 1997) of various spectral type and metallicity within 50 PC of Earth and at declinations above 20° and frequency 1.1 - 1.9 GHz, without any successful discoveries.

Parkes Telescope

The Parkes telescope was used along with GBT and Arecibo during Project Phoenix (Backus & Project Phoenix Team 2002) to observe 800 stars 65 pc away at 1-3 GHz in frequency with no results. In the future, it will be used to observe
stars from the Galactic plane and the bulge of the Galaxy at a frequency of 0.7-4 GHz (Isaacson et al. 2017).

Automated Planet Finder

APF’s surveys are focused on finding optical laser emissions which could be used by an advanced civilisation as a low energy communication method, the disadvantage of this being the large extinction of the emissions. The target star is within 50 pc and is studied 36 nights a year (Isaacson et al. 2017).

3.2.3 Arecibo

Arecibo is a 305 m diameter radio telescope in Puerto Rico. Previous and current projects include Astropulse, Serendip (Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations) and Seti@home. The target of Seti@home, which began in 1999, is represented by narrowband signals 0.075 Hz in frequency, spike and Gaussian-like patterns, and pulses. Astropulse searches for microsecond pulses and has found 112 interesting signals, featured in Figure 3.3. The Serendip project began 32 years ago and it has evolved along with the technology gaining improved sensitivity and increasing number of channels. Both types of signals, narrowband and short pulses can be detected (Siemion et al. 2010, Korpela et al. 2011).

3.2.4 Allen Telescope Array

The Allen Telescope Array (ATA) is an array of 42 dishes, each consisting of 2 reflectors, a primary with the diameter of 6.1 m and a 2.1 m secondary, used
CHAPTER 3. SETI SURVEYS

Figure 3.3: The SETI candidates (the blue dots) found by Arecibo’s Astropulse project. The dashed lines delimit the area of the sky that Arecibo is able to cover. Reproduced from (Korpela et al. 2011).

to lower down the interference (Welch et al. 2017). ATA is located in California and conducts SETI observations 12 hours each day (Harp et al. 2016).

Harp et al. (2016) observed 7.3 million stars around confirmed exoplanets (which included 65 HZ exoplanets) and Kepler Objects of Interest (KOIs), at a 1-12 GHz frequency from 2009-2015 but came up with no signs of advanced technologies.

Fly’s Eye project works by having the 42 ATA antennae pointed in different directions and covering a large portion of the sky. In 2011 it covered 150 square degrees of the sky in the search for microsecond pulses. The only detections came from pulsars (Siemion et al. 2010, Korpela et al. 2011, Siemion et al. 2012).
3.3 Murchison Widefield Array

The Murchison Widefield Array (MWA) is located in Australia and is made up of 128 tiles made of 16 polarised antennae located 3 km of each other that can be directed to any part of the sky via a computer (Sokolowski et al. 2017). First operated in 2013, it has 8,128 baselines, each between 7.7 m - 3 km (Lenc et al. 2017), a frequency range of 75-300 MHz (i.e. transient signals), (Tingay et al. 2013, Feng et al. 2017) and an instantaneous 600 square degrees sky coverage (Kaplan et al. 2016).

SETI research at MWA in 2014 covered 400 square degrees of the sky, which contained 45 confirmed exoplanets, at a frequency in the range of 103-133 MHz. No narrowband signals were detected (Tingay et al. 2016).

3.4 Future projects

Despite the advances in technology and radio astronomy that have helped discover transient signals originating from pulsars or fast radio bursts, there has been no success in finding any confirmed SETI sources. This may be caused by the limitation of the area of the sky SETI research has been focused on so far (Tremblay et al. 2015). However, future telescopes on Earth, both in the southern and northern hemisphere, will have better sensitivity and sky coverage. In space, the plan is to send small satellites that would reach a potential civilisation within our lifetime. This section will detail these projects.
3.4.1 FAST

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is not only the largest radio telescope on Earth with a diameter of 500 m but also the most sensitive radio telescope. Opened in 2016, it will operate at a frequency of 70 MHz - 3 GHz \(\text{[Li & Pan 2016]}\), which includes both the 21 cm line and the waterhole frequency, interesting bands for SETI surveys.

3.4.2 Square Kilometre Array

MWA represents the low frequency part of the Square Kilometre Array (SKA), yet to be built, with a sensitivity 10 times higher than MWA \(\text{[Tingay et al. 2016]}\). Other arrays that are being built and will be part of the SKA include ASKAP (Australian Square Kilometre Array Pathfinder) with a collecting area of 4,000 m\(^2\) and a frequency range between 0.7-1.8 GHz, and MeerKAT, whose collecting area and frequency range are 9,000 m\(^2\) and 1-1.75 GHz, respectively \(\text{[Li & Pan 2016]}\).

3.4.3 Breakthrough Starshot

In the optical regime, where the waves are much narrower, a communication system would generate a low power signal that could be focused in one direction to cover large distances (thousands of light years). The Breakthrough Starshot Initiative aims to build a laser system that will focus a 1-km wide beam that will propel 1-gram (nano)probes to the nearest stars \(\text{[Worden et al. 2017]}\). This would travel at 0.25 c and it would reach Alpha Centauri and the newly discovered Proxima Centauri b in 20 years, which could be reached in 17,000 years by
probes such as Juno or 54,000 years by New Horizons. There are still engineering challenges that need to be surpassed for this project to come to life (Lubin 2016).

Other civilizations may already have a similar system in place used to propel small probes within their own stellar system or nearby stellar systems that would produce transient signals we could detect (Worden et al. 2017).

3.5 Messages from Extraterrestrial Intelligence (METI)

The scientific community’s realisation that radio waves can be used as a means of communication with civilisations other than the Earth (Cocconi & Morrison 1959) has not only prompted SETI searches, some of which are outlined in this dissertation, but it has also encouraged humankind to send messages out into space in the hope they will reach another intelligent civilisation. In 1974, a radio signal at a frequency of 2380 MHz was sent by Arecibo towards the globular cluster M13 in the form of a 1679-bit picture comprising of schemes representing counting, atoms associated with life i.e. H, C, O, N, and P, DNA bases, a human being, the Solar System and the Arecibo telescope (staff at the National Astronomy & Centre 1975). Messages were also put aboard the Pioneer spacecrafts (1971 and 1972) as plaques showing the hyperfine transition of neutral hydrogen, the location of the Sun within the Solar System, the Sun and the planets and a female and a male and Voyager spacecrafts (1977) in the form of 2 golden vinyl records consisting of images and sounds, both natural sounds e.g. thunderstorm and people speaking in different languages (Sagan et al. 1972). Radio messages were also sent from Evpatoria, Ukraine directed toward nearby stars (1999 and 2001) and toward the super-Earth exoplanet Gliese-581c 20 light years away from
In 2015, 28 scientists signed and released a statement concluding that before a future message is to be sent a “worldwide scientific, political and humanitarian discussion must occur”\[1\]. Hence these signals that we have sent into space letting potential civilisations know not only of our existence, but also our biology and culture have not been 100% applauded in the scientific community as it is believed we are putting ourself at risk by doing so. The argument is that in case a superior civilisation discovers the signals, it could choose to attack our planet \cite{shuch}. The counterargument is that humans have unintentionally let their presence in the Universe known by broadcasting radio signals via television, telecommunication and aviation for far longer \cite{garrett}.

In a more recent study, Heller \cite{heller} proposes that in case we are being contacted by an intelligent civilisation, we could use the world wide web as a wider way of collaboration to decrypt the message more effectively, which can be accessed by minds all over the world and not just a handful of people.

\footnote{See https://setiathome.berkeley.edu/meti_statement_0.html/}
Chapter 4

Detectability of Earth as a SETI strategy

Ever since humans started the space revolution 60 years ago, SETI projects have represented a significant part in the quest of understanding the Universe and life itself. Although there have been quite a number SETI surveys with a spread out sky coverage, that I outline in this thesis, there have been no ET detections so far. What if instead of looking out in all directions of the Galaxy, we establish which areas are worth exploring and concentrate on these? This project aims to find these ‘hotspots’ by investigating the Earth as an exoplanet and point out from which parts of the Galaxy Earth is the most detectable. In the context of measuring Earth’s detectability from outer space, the Earth’s SNR is computed.

This chapter will first give details on how the data used in my research project was obtained. Then the methods behind computing the individual and combined signal to noise ratios for the transit, radial velocity and astrometric measurement of the Earth as an exoplanet are outlined. In all cases, heatmaps are computed in
python which show which bits of the sky (hotspots) are more likely to have a good view of the Earth. The heatmaps feature the summed SNR from all stars at that location at each pixel in the image. The previous SETI surveys are summarised and the resolution of telescopes conducting SETI research is investigated and compared to the heatmaps produced in the project. New heatmaps are created that show which parts of the final SNR heatmap are best observed by radio telescopes with different diameters and at different observation wavelengths. A correlation between the two data sets and the confirmed exoplanet database from http://exoplanet.eu/ is made in the last part of the section.

4.1 Two catalogues: Tycho-2 and Hipparcos

While older catalogues such as Perryman (1989) and Perryman et al. (2001) only contained basic details about the stars e.g. the brightness of the stars, they were later amended with more essential measurements such as the temperatures of the stars e.g. Anderson & Francis (2012) and McDonald et al. (2012).

Two data sets were used in this project that contain details about 1,476,007 stars taken from the Tycho-2 catalogue and 117,112 stars from the Hipparcos catalogue. The distances to the stars were taken either from the original catalogues or from the Gaia Data Release 1 catalogue (the observations made in the first six months after the launch of the Gaia satellite), if available, and used to compute the luminosity of the stars (McDonald et al. 2017), while other photometry information of the stars was provided by Høg et al. (2000), van Leeuwen (2007) and McDonald et al. (2017).

The data sets based on Tycho-2 and Hipparcos contain 75 and 90 parameters, respectively, representing the stars’ properties. The parameters used in my
research project are: the distance to the stars, the right ascension (RA) and declination (Dec) of the stars, the luminosity of the stars (for computing signal to noise ratios) as well the effective temperature and the V magnitude of the stars (for the crossmatch with stars known to host exoplanets).

As the Tycho-2 dataset contains almost 1.5 million Milky Way stars, in theory it is meant to represent a full sky map of the Galaxy. However, due to the rotation mechanism and scanning procedure of the Gaia satellite, which is pictured in Figure 4.1, some parts of the Galaxy are less substantially surveyed than others, leaving gaps in the data set, given by the curved regions and dark stripes in Figure 4.2. These instrument-produced features are clearly visible in the maps that I got in my research.

There are more stars observed in the brighter regions of Figure 4.2 and less
stars at locations in which the map seems darker. In the middle of the map we can see the Galactic Plane of the Milky Way, which is 100,000 light years across and 1,000 light years thick. The closest stars to us and some of the brightest stars in the Galaxy are located in the Galactic Plane (Rix & Bovy 2013, Xu et al. 2015).

Figure 4.3 outlines how the Earth travels through the Milky Way. While the Sun orbits the galactic centre, which is 8,000 pc away, at 217.4 km/s (Gies & Helsel 2005) the Earth revolves around it on a tilted axis of 23.4° (Berger 1976) at 30 km/s.
CHAPTER 4. DETECTABILITY OF EARTH AS A SETI STRATEGY

4.2 Individual Earth signal to noise ratios

The first step is to read in and convert the RA and Dec of the two data sets from equatorial (positions are relative to the celestial equator in Figure 4.3) to ecliptic coordinates (positions relative to the ecliptic plane). A python conversion algorithm was used. The accuracy of the ecliptic coordinates were then verified using the NASA convertor\(^1\). Known values for the radius of the Sun, 695,700 km (Kosovichev & Rozelot 2018), the radius of the Earth, 6,378.1 km, Earth’s inclination, 23.4\(^\circ\), the distance between the Earth and the Sun, 149.6 million km, and Earth’s revolution period, 365 days,\(^2\) were used throughout the code, more specifically to compute the SNR of the transiting Earth.

The rest of this section describes how three individual SNRs of the Earth as an exoplanet observed from each of the stars from the two data sets based on the

\(^1\)https://lambda.gsfc.nasa.gov/toolbox/tb_coordconv.cfm/
\(^2\)https://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html/
transit, RV and astrometry detection methods are obtained. These three exo-
planet detection methods were chosen as they can be used to detect planets that
are relatively close to the observer and offer a good characterisation of the planet
i.e. mass, radius, inclination etc. By contrast, microlensing usually detects either
free floating or bound planets that are a few kpc away, while the directly imag-
ined planets are often hot young massive planets placed at large distances from
the host star (i.e. not habitable). All three SNRs are dependent on the distance
to the stars. In all instances, the SNRs are normalized and then heatmaps are
produced in python.

4.2.1 Transit SNR

Not all the stars in the Galaxy can observe the Earth transiting the Sun. The
condition for spotting an Earth transit is that the ecliptic latitude of the observer,
$\beta$, is in between 0 and 0.2664° (not including grazing i.e. the ingress/egress times
are ignored and the Earth is fully inside the Sun’s diameter). This figure was
obtained considering that the minimum ecliptic latitude, $\beta_{\text{min}}$, an observer could
have in order to capture an Earth transit is given by,

$$\beta_{\text{min}} = 90^\circ - \cos^{-1}\left(\frac{R_\odot}{\text{AU}}\right) \cdot \frac{180^\circ}{\pi},$$

(4.1)

where $R_\odot$ is the radius of the Sun. When going back to equatorial coordinates,
this translates into a declination range of $-23.36^\circ - 23.65^\circ$ for the stars in the data
sets. Figure 4.4 shows the transit time of the Earth as seen by 16 observers at
different ecliptic latitudes.

The first step when calculating the transit SNR is to compute the impact
parameter, $b$, of the Earth while transiting the Sun as seen by an observer (how
Figure 4.4: The time taken for the Earth to transit the Sun for a given ecliptic latitude of an observer.

\[ b = \text{AU} \cdot \cos \beta, \]  

(4.2)

where \( \beta \) is in radians and assuming that the Earth is on a circular orbit around the Sun.

The path length of the Earth across the Sun’s disc during transit, \( s \), is produced next, considering that \( M_\oplus \ll M_\odot \),

\[ s = \sqrt{(R_\odot + R_\oplus)^2 - b^2).} \]  

(4.3)

The impact parameter and Earth’s path length are represented in Figure 4.5, the latter being further used to compute the Earth’s transit duration, \( \tau \),

\[ \tau = \frac{s}{V_\oplus}, \]  

(4.4)
where $V_⊕$ is Earth’s velocity.

The more transits of the Earth are observed the higher the precision of the measurements, $\sigma_T$, is. Since the precision is dependent on the number of photons that enter the telescope’s aperture, which obey Poisson statistics, it is given by,

$$\sigma_T \propto N^{-1/2} \propto \tau^{1/2},$$

(4.5)

where $N$ is the number of photons.

The detectability or signal to noise ratio of the Earth for the transit method, $\text{SNR}_T$, is then computed, which depends both on the distance between the Earth and the observer, $d$ and the precision in the transit measurements,

$$\text{SNR}_T \propto \frac{\sqrt{\tau}}{d}.$$  \hspace{1cm} (4.6)

We can see from Equation 4.6 that the transit SNR depends on the distance between Earth and the observer and the location of the observer, all the other parameters are Sun/Earth constants.

Out of the 1,476,007 stars from the Tycho-2 data set, only 2,073 have a location which allows a potential observer to spot the Earth transiting the Sun. They form a thin strip along the ecliptic plane, as shown in Figure 4.6 and Figure 4.7, which depicts the locations of 50 stars with the highest transit SNR. There are hotspots around the top and bottom of the sinusoid distribution where it intersects with the Galactic plane.

On the other hand, there are 107,112 stars in the Hipparcos dataset. Out of these, 240 can spot the Earth’s transit. Their frequency per unit area map as well as the top 20 highest SNR stars are given by Figure 4.8. The large difference
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Figure 4.5: The geometry and physical parameters of the Earth while transiting the Sun: $b$, the impact parameter, $s$, the path length of Earth across the Sun and $R_\odot$, the radius of the Sun.

Figure 4.6: Heatmap of the SNRs of the Earth as it is seen transiting the Sun from 2,073 stars from the Tycho-2 dataset.
Figure 4.7: The 50 Tycho-2 stars that can best observe Earth’s transit.

(more than 20%) in SNR in between a limited number of stars and the rest of the stars is noted by the green colour. The majority of the bright stars lie in the first half of the sinusoidal ecliptic plane.

4.2.2 Radial velocity SNR

All the stars in the Galaxy can receive a specific RV signal coming from Earth. If this signal is detectable or not depends on the precision of the RV signal, $\sigma_{RV}$, which has a limited sensitivity, $\sigma_{RV} \propto K$. As the amplitude of the signal, $K \propto \sin i$, the precision in the RV signal scales as $\sin i$.

The RV signal to noise ratio is derived next, which depends on the distance between the Earth and the star as well as on the precision in the RV signal, which is proportional to the latitude of the star, as given by the projection of the
Figure 4.8: The transit heatmap of 240 Hipparcos stars (top) and the locations of 20 of these that have the highest SNR (bottom). The green arrow on top of the colourbar points to the stars whose SNR is larger than 1.
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spherical coordinates of the Galaxy into a 2D Cartesian plane,

\[ \text{SNR}_{RV} = \frac{\sin(\pi/2 - \beta)}{d}, \]

where SNR\(_{RV}\) is the RV signal to noise. Therefore, observers that are closer to us can detect us more easily.

While all stars from both Tycho-2 and Hipparcos datasets have a certain non-zero RV, the RV heatmap of the Tycho-2 stars shows gaps in the data i.e. parts of the sky that were left unsurveyed due to Gaia satellite’s scanning technique. These features are not visible in the Hipparcos dataset due to the lack of stars needed for emphasizing the specific pattern in the data.

In the Tycho-2 dataset, there is an abundance of high SNR stars situated in the Galactic plane, as shown by Figure 4.9 as these stars are brighter and closer to us (Bensby & Feltzing 2010, Gallagher & Sparke 2007). There are also two areas that are significantly brighter than the rest of the heatmap i.e. hotspots, which can be found approximately between 75° – 135° and 285° – 335° in RA and -40° – 40° in declination. Most stars with the highest RV SNR can be found roughly at declinations -40° – 40° and a wide range of RA but predominantly around the two bright regions and in the centre of the RV heatmap.

Figure 4.10 outlines the first 100 stars with the largest RV SNR from the Hipparcos dataset plotted on top of the Hipparcos RV heatmap. While no specific pattern can be differentiated, given the small number of stars i.e. just over 100,000, it can be concluded that stars have a tendency to lie at all RA but only between -60° – 60° in declination. The 100 highest SNR stars follow this pattern, with a significant gap between 75° – 175° in RA and -60° – 0° in declination and a gap between 150° – 325° in RA and 0° – 60° in declination.
Figure 4.9: RV heatmap of the Earth from 1,476,007 stars from the Tycho-2 dataset (top) and the 100 highest SNR stars (bottom).
Figure 4.10: The locations of 100 of the 107,112 Hipparcos stars that have the highest SNR.

4.2.3 Astrometry SNR

As with RV, Earth’s astronomical shift could be detected from all the parts of the Galaxy. The astrometry signal to noise, SNR\text{ast}, is given by the ratio of the astrometric shift, $\theta$, over the precision in the astrometric measurement, $\sigma_{\text{AST}}$, parameters which are given by Equation 2.4 and Equation 2.5 respectively. As $F \propto d^{-2}$ (Gabrielli 2004), Equation 2.5 becomes

$$\sigma_{\text{AST}} \propto d.$$  \hspace{1cm} (4.8)

In the final step, considering that $a \ll d$ and $M_\oplus \ll M_\odot$ (which is a constant), SNR\text{ast} is given by,

$$\text{SNR}_{\text{ast}} \propto \frac{1}{d^2}.$$  \hspace{1cm} (4.9)

It can therefore be concluded that stars that are closer to Earth are more likely
to detect us via the astrometry method.

Similar to the RV heatmap in Figure 4.9, the astrometry heatmap computed using the Tycho-2 stars in Figure 4.11 has two main hotspots, the first between $80^\circ - 175^\circ$ in RA and $-60^\circ - 0^\circ$ in declination, and the second between $275^\circ - 350^\circ$ RA and $0^\circ - 60^\circ$ declination. While the 100 stars with the highest SNR are more spread out, the heatmap still contains a higher concentration of high SNR stars around the bright areas.

While less bright than the RV heatmap in Figure 4.10, the Hipparcos astrometry heatmap shown in Figure 4.12 contains stars distributed across all RA and $-80^\circ - 80^\circ$ in declination. However, the brightest of these can be found in two regions only, one separated by an RA between $25^\circ - 125^\circ$ and declination between $-60^\circ - 20^\circ$ and another with $225^\circ - 350^\circ$ in RA and $-60^\circ - 60^\circ$ in declination. The majority of the top 100 SNR stars are within these two regions.

4.3 Combined SNR

While the vast majority of confirmed exoplanets have been discovered so far either via the RV or the transit method, some have both an RV signal and a transit associated with them. In this section I aim to find a way to analyse how having measurements from two or three detection methods can influence the detectability of the Earth. By combining the SNR of different detection methods that have the same weighting it is possible to account for how the Earth looks like from all the stars in the Galaxy, not just those that have a good view using only one detection method. Producing a combined SNR assures that all the stars are considered equally and that they can detect the Earth, regardless of the method they use.
Figure 4.11: Astrometry heatmap of the Earth from 1,476,007 stars from the Tycho-2 dataset (top) and the 100 highest astrometry SNR stars. The grey colour denotes stars with a much larger SNR than the majority of stars.
As not all the target stars observe Earth transiting the Sun (only 0.1% do), the challenge here is to produce a combined SNR that had the same weighting. The astrometry method was chosen as the reference weighting for the RV and transit as the sum of all its SNRs, \( \Sigma_{as} \), was the smallest out of the three, with the mention that the transit method required an extra weighting to account for the significant difference in numbers.

The combined SNR, \( W_i \) is given by,

\[
W_i = \sum_i S_i \cdot \alpha_i, \tag{4.10}
\]

where \( S_i \) is the SNR of each of the three detection methods, \( i \), \( \alpha \) is the weighting.
and $\alpha = 1$ for astrometry. The transit and RV weightings, $\alpha_{tr}$ and $\alpha_{rv}$, respectively, are obtained using,

$$
\alpha_{tr} = \frac{\Sigma_{as}}{\Sigma_{tr}} \times \frac{N_{tr}}{N_{st}}
$$

$$
\alpha_{rv} = \frac{\Sigma_{as}}{\Sigma_{rv}} \times \frac{N_{st}}{N_{st}}, \tag{4.11}
$$

where $\Sigma_{tr}$ and $\Sigma_{rv}$ are the sums of all transit and RV SNRs, respectively, $N_{st}$ is the number of all stars and $N_{tr}$ is the number of stars that can observe the Earth’s transit.

The rest of this section is split in two parts, the first one dealing with the Tycho-2 stars and the second one with the Hipparcos stars. For each dataset, the combined SNR equations are applied to all the stars and heatmaps are obtained. Then the stars that cannot detect the Earth via the transit method i.e. the majority of stars are analysed by computing their combined RV-astrometry SNR. The last analysis involves the minority of stars that can spot the Earth’s transit i.e. the stars that lie on the ecliptic plane.

### 4.3.1 Tycho-2 stars

**All stars**

The transit, RV, and astrometry SNRs of all 1,476,007 stars are combined using [Equation 4.10] and [Figure 4.13] was produced that shows the Earth’s detectability from these stars. The gaps in data can be seen as well as the three areas that contain a higher percentage of stars with high SNR, one ranging from $75^\circ-175^\circ$ in RA and $-60^\circ-40^\circ$ in declination, one from $150^\circ-250^\circ$ in RA and $-60^\circ-40^\circ$. 
Figure 4.13: Heatmap combining the transit, RV, and astrometry SNRs of the Earth for the Tycho-2 stars (top) and the 100 stars that have the highest combined SNR (bottom). The green areas represent stars whose combined SNR is larger than 1.
in declination, and another from $275^\circ - 350^\circ$ in RA and $-20^\circ - 60^\circ$ in declination. Most of the 100 stars with the highest combined SNR occupy the regions around the three hotspots, while some of them are in the central part of the heatmap.

Compared with Figure 4.9, the hotspots in Figure 4.13 are not as bright and not as large, a direct influence of Figure 4.11 which contains stars whose SNR is slightly lower.

**RV and astrometry stars**

The 1,473,934 stars that cannot observe the Earth’s transit and have a combined SNR determined by Earth’s RV signal and astrometry shift are plotted. The RV-astrometry combined heatmap as well as the 100 highest SNR stars are given by Figure 4.14. Figure 4.13 and Figure 4.14 present very similar features, proving that the dominant SNRs in the combined heatmap come from the RV and astrometry SNRs. This is not surprising, considering that these two SNRs are available for the vast majority of stars. The same observation holds true for the 100 stars with the highest SNR. In fact the same 100 stars are featured in the two heatmaps.

**Stars that see Earth’s transit**

The 2,073 stars that can see Earth transiting the Sun lie on the ecliptic plane of the Galaxy. Their combined (RV, transit and astrometry) SNRs as well as the 50 stars with the highest combined SNR can be seen in Figure 4.15. The regions between $25^\circ - 150^\circ$ and $225^\circ - 325^\circ$ in RA are brighter than the rest of the
Figure 4.14: Heatmap combining the RV and astrometry SNRs of the Earth for the Tycho-2 stars (top) and the 100 stars that have the highest RV-astrometry combined SNR (bottom). Stars with an SNR bigger than 1 are represented in green.
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heatmap (hotspots). Most of the 50 highest combined SNR stars are comprised by these two regions and the majority of the others are located in between.

Figure 4.16 and Figure 4.17 outline the combined RV-transit and the astrometry-transit SNRs of the 2,073 stars as well as the 50 highest SNR stars from each set, respectively. The hotspots in Figure 4.16 are much brighter than in Figure 4.15, proving that the RV signal of the Earth is stronger than its astrometric one. This is further shown in Figure 4.17, which doesn’t have any significantly large hotspots. The 50 highest RV-transit and astrometry-transit SNR stars are distributed along the ecliptic, similarly to Figure 4.16.

4.3.2 Hipparcos stars

Figure 4.18 shows the highest SNR stars from the transit-astrometry-RV combined heatmap, the RV-astrometry combined heatmap, the astrometry-transit and RV-transit for the 240 out of 107,112 Hipparcos stars that could detect Earth’s transit due to their position. Using all the Hipparcos stars, the combined heatmaps follow a pattern similar to the individual RV/astrometry heatmap, while the astrometry-transit and transit-RV heatmaps are similar to the individual transit heatmap.

4.4 Previous SETI surveys and the combined heatmap

Once the final combined heatmap for the Tycho-2 dataset, which contained enough stars to feature a pattern, was obtained and the hotspots were identified, a range of interesting RA and declination coordinates was set. This was then further compared with the sky coverage areas of four telescopes previously/currently
Figure 4.15: Heatmap combining RV, transit and astrometry SNRs for 2,073 of the Thyco-2 stars (top) and the 50 stars that have the highest combined SNR.
Figure 4.16: Heatmap combining RV and transit SNRs for 2,073 of the Tycho-2 stars (top) and the 50 highest TV-transit SNR stars.
Figure 4.17: Heatmap combining astrometry and transit SNRs for 2,073 of the Thyco-2 stars (top) and the 50 highest astrometry-transit SNR stars.
Figure 4.18: From top to bottom: the 100 highest combined SNR stars, the 100 highest RV-astrometry combined SNR stars, the 20 highest RV-transit combined SNR stars that can observe Earth’s transit, and the top 20 highest astrometry-transit combined SNR stars.
working on SETI surveys.

While four of the telescopes cover the entire sky in RA, the range of declinations is different for each of them. GBT can observe at declinations between -45°−90° (the project Serendip VI) \cite{korpela2015}, Arecibo works at -2°−38° in declination (project Serendip V) \cite{korpela2011}, Parkes observes at declinations above 20° \cite{stootman2000}, ATA focused on a declination strip between 53°−56° \cite{siemion2012}.

As shown in Figure 4.19, most of the final heatmap has been covered by a previous SETI survey. Most of the heatmap falls in the declination range of GBT (i.e. declinations over -45°). The ATA survey of a narrow strip of the sky intersects with both GBT and Parkes surveys. The declination range 20°−38° has been covered by three surveys i.e. GBT, Parkes and Arecibo, while GBT and Arecibo only intersect in the area -2°−20°, and GBT and Parkes only intersect
in areas delimited by $38^\circ$–$55^\circ$ and $55^\circ$–$90^\circ$ in declination. The declination range $-45^\circ$–$2^\circ$ has only been covered by GBT.

Most of the bright region on the left hand side of the heatmap can be detected with GBT, while certain portions of it are covered by both Arecibo and Parkes, while the bright region on the right hand side of the heatmap can be covered by GBT (most of it), Arecibo and Parkes (roughly half of it) and ATA (some bits).

It is worth noting that my comparison does not take into account that, while the combined heatmap features the whole sky, the SETI telescopes can only observe either the northern or the southern hemisphere, depending on their location (in other words half of the sky). Three out of the four telescopes are located in the northern hemisphere i.e. Arecibo, GBT, and ATA, while the Parkes telescope is in the southern hemisphere.

### 4.5 Telescope resolution

Once I obtained the final combined heatmap i.e. Figure 4.13, I want to see what parts of the heatmap can be detected using a telescope that is used to conduct SETI searches. This is dependent on two factors, the sky coverage of the telescope, and the wavelength range of the telescope. Given the wavelength range and the diameter of the telescope, I can to establish a set of resolutions of the telescope that I use as a standard deviation to replot the combined heatmap. This new heatmap will show me which areas of the combined map are best observed at a certain wavelength. I will also be able to tell if any of the hotspots in the combined heatmap are covered by the telescope and, if so, which is the best wavelength at which observations should be made.
The resolution of a telescope, \( \sigma \), is given by the equality between the diffraction limit, \( \theta \), in radians, of the aperture of the telescope, \( D \), which is \( \theta = \frac{1.22\lambda}{D} \) and the full width half maximum (FWHM) i.e. \( 2.355 \sigma \) (Born & Wolf 1999). When turned into arcmin, this becomes

\[
\sigma = 1753.25 \cdot \frac{\lambda}{D} \text{ arcmin}, \tag{4.12}
\]

where \( \lambda \) is the wavelength of observation.

Table 4.1: The diameters and the frequency ranges of the GBT, Arecibo and Parkes radio telescopes which were used for SETI surveys.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Diameter (m)</th>
<th>Frequency range (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBT</td>
<td>100</td>
<td>0.1 - 116</td>
</tr>
<tr>
<td>Arecibo Telescope</td>
<td>305</td>
<td>0.4 - 10</td>
</tr>
<tr>
<td>Parkes Telescope</td>
<td>64</td>
<td>0.4 - 23</td>
</tr>
</tbody>
</table>

To determine the relationship between the resolution of the telescope and the heatmap I obtained, I focused on 3 telescopes and one array of telescopes that have conducted SETI searches. For the individual telescope dishes, I chose three wavelengths, the minimum and maximum they could resolve at as well as the 21 cm line which was within the wavelength range of all of them. For the array I analysed the minimum, the maximum and the mid-frequencies of observation. I next used Equation 4.12 to compute the corresponding resolutions along with a python astropy function and the sky coverage of the telescopes i.e. the RA and declination range discussed in section 4.4 to produce graphs that show what part of the Galaxy these telescopes/array are most sensitive to. This depends on the
diameter of the telescope or the baseline of the array as well as the wavelength of observation. The diameters and the frequency range of the 3 single dish radio telescopes that I chose, GBT, Arecibo, and Parkes are shown in Table 4.1.

As Arecibo can observe at all RAs and declinations in between $-2^\circ-38^\circ$, the graphs that I produced in python have all the other declinations obscured by two blue rectangles so that the relevant part of the sky is emphasized. The resolution of Arecibo is used to smooth the combined heatmap in Figure 4.20 for three wavelengths, the minimum and maximum Arecibo can observe as well as the 21 cm line. Arecibo can observe the parts of two bright regions that are within its declination range. As the wavelength is increased, it becomes clearer that the bright region on the right hand side of the heatmap contains the majority of the hotspots.

The portion of the sky that GBT cannot cover i.e. declinations $-90^\circ-45^\circ$ was masked out in Figure 4.21. The rest of the combined heatmap as seen by GBT at the chosen wavelenths is then outlined along with the corresponding resolution. Most of the two big bright regions are visible by GBT at wavelengths smaller than its maximum wavelength, while it can observe half of the third small bright region.

---

Figure 4.21: The regions of the combined heatmap that GBT is most sensitive to at a wavelength of 2.58 mm (left), 0.21 m (middle) and 2.99 m (right).

Figure 4.22: The zones of the combined heatmap that the Parkes telescope is most sensitive to at a wavelength of 0.01 m (left), 0.21 m (middle) and 0.75 m (right).

Because the Parkes telescope can observe the sky at declinations above 20°, this area is emphasized in Figure 4.22 in 3 cases of different wavelengths. The top bit of the bright region on the left side of the combined heatmap as well as half of the bright region on the right hand side of the heatmap are visible with Parkes. As the wavelength is increased, the bright regions shrink and get blurrier.

Since GBT and Parkes have both been used as part of the Breakthrough Listen project to conduct SETI observations, a map can be produced to show how the two telescopes can be used together to see parts of the combined heatmap. The telescopes, with a combined diameter of 164 m, can observe an overlapping area of the map i.e. declinations higher than 20°, while GBT can also observe declinations between -45° – 20°, as shown in Figure 4.23 (the purple band). Compared to Figure 4.21 by combining the two telescopes, a better resolution at a greater wavelength is achieved.

The MWA was the array of telescopes that I plotted, which has 8,128 baselines.
Figure 4.23: The area of the combined heatmap that the Green Bank and Parkes telescopes together are most sensitive to at a wavelength of 2.58 mm (left), 0.21 m (middle) and 2.99 m (right).

Figure 4.24: The area of the combined heatmap that the MWA is most sensitive to at a wavelength of 1 m (left), 2.5 m (middle) and 4 m (right).

Its shortest baseline is 7.7 m and longest one is over 3 km. Baselines that are less than 120 m have a high sensitivity up to a degree (Lenc et al. 2017). The MWA can observe at frequencies between 75-300 MHz (Tingay et al. 2013). The resolution calculations were based on the case when the baseline ($D$ in Equation 4.12) is 1.5 km (maximum).

The MWA conducted a SETI survey with a limited focused RA and declination range, i.e. RA between $255^\circ-277^\circ$ and $-18^\circ-38^\circ$ in declination (Tingay et al. 2016), which is shown in Figure 4.24 overplotted on the combined heatmap. A baseline of 1.5 km was chosen for this comparison as well as the minimum, midway and maximum wavelengths that can be observed by MWA. As well as the single dish telescopes, the resolution of the array decreases as the wavelength is increased. A small portion pertaining to the bright region on the right side of the heatmap has been examined by the SETI study.
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4.6 Cross matching with known exoplanets

At the time of the writing of this thesis there were 3,767 confirmed exoplanets. As some of these are part of a multiple planet system, the first step is to remove the duplicate host stars from the exoplanet coordinates database downloaded from http://exoplanet.eu/, though binary stars are kept.

The crossmatch algorithm involves, in the first phase, comparing all the stars from the two datasets with the exoplanet database in the search for RA, α, and declination, δ, close matches. Four search radii are chosen, \( c = 1.08 \) arcsec (0.0003 degrees), 2.16 arcsec, 3.24 arcsec, and 4.32 arcsec, such that

\[
\sqrt{(\alpha_d - \alpha_e)^2 \cos(\delta_e)} + (\delta_d - \delta_e)^2 \leq c,
\]

where indices \( d \) and \( e \) refer to the dataset (Tycho-2 or Hipparcos) and the exoplanet database, respectively.

The relationship between the number of matches and the allowed arcsec range is produced. The star matches within 1.08 arcsec were then chosen for further investigation, which consists of running two checks on the selected stars, if the effective temperatures of the two stars are within 30% of each other, and if the difference in the apparent V magnitudes of the two stars is less than 0.5.

The stars that have passed the two checks are then tested on their potential habitability. Firstly, Equation 2.10 and Equation 2.11 are used to calculate the HZ limits of the selected stars. Secondly, the already known exoplanets of the stars are studied to check if their semi-major axes are within the calculated HZ limits. Thirdly, their radii and masses are investigated to check if the exoplanets might have a rocky composition. Finally, the stars are linked to their Earth detectability.
values and a list of the stars that can best see the Earth is produced.

There are no matches within the chosen aperture range in between the Hipparcos dataset and the exoplanet.eu catalogue.

The Tycho-2 dataset had different numbers of matches depending on the size of aperture chosen, i.e. 117 matches within 1 arcsec, 148 within 2 arcsec, 168 within 3 arcsec, and 186 within 4 arcsec, as shown in Figure 4.25. Although the crossmatch algorithm’s scope was to determine all the stars with known exoplanets that might have more than 1 Tycho-2 crossmatches, no such examples were found. Of all 186 matches, all of them had only one Tycho-2 equivalent. This can be explained by having a look at the Tycho-2 dataset, which contains stars whose RAs and declinations, when considered separately, may be similar to other stars’ but there is a lack of stars that are very similar in both their RA and declination coordinates.

94% of the exoplanets around the crossmatched stars (within 1 arcsec) were
Figure 4.26: The 20 stars with known exoplanets obtained via the crossmatch algorithm that have the best Earth detectability. Representations were made according to the detection method i.e. imaging, transit or RV and the exoplanet mass i.e. small ($<25 \, M_\oplus$), medium ($25-300 \, M_\oplus$) or big ($> 300 \, M_\oplus$). The exoplanet of the star at 14hr20min2s, -20° has an unknown mass, considered as 0 on the map.

66 out of the 117 stars within 1 arcsec passed the two checks, on the effective temperature and the V magnitude. Two interesting cases are represented by a Sun-like star, HD 10442, orbited by a massive HZ transiting planet once every 3 years (which might be orbited by exomoons) and CD-35 2722, which ranks as the 20th star by highest Earth detectability from the Tycho-2 dataset. This is a young M-dwarf 20 pc away with a known massive exoplanet discovered via imaging orbiting at a distance of 67 AU. Both exoplanets discovered via the transit method, 3% via RV, 1% via imaging, 1% via TTV and 1% via other detection methods. It is worth noting that none of these 66 stars have been looked at before in previous studies (Heller & Pudritz 2016, Wells et al. 2018).
The 20 crossmatches with the highest Earth detectability figures are plotted in Figure 4.26 on top of the combined heatmap which had a kernel smoothness of 0.4 armin applied for the purpose of enhancing the hotspots of the map. 65% of these top 20 stars lie between declinations of -40° – 0°, whereas most of them are placed just outside the bright regions of the heatmap. From the stars’ exoplanets, one exoplanet has an unknown mass, 20% have a mass < 1 $M_{\oplus}$, 35% have a mass between 25-300 $M_{\oplus}$ and the mass of 40% of them is bigger than 300 $M_{\oplus}$. Four exoplanets have an unknown radius, 3 have a radius less than 2 $R_{\oplus}$, 5 have a radius between 2-10 $R_{\oplus}$, and the radius of the other 8 is more than 10 $R_{\oplus}$. The hosts of these exoplanets have a mass between 0.4–1.65 $M_\odot$.

Table 4.2: Details regarding the rocky exoplanets found in the crossmatch between the exoplanet.eu catalogue and the Tycho-2 dataset. The name, semi-major axis, mass, radius and orbital period of the exoplanets are included.

<table>
<thead>
<tr>
<th>Name</th>
<th>Semi-major axis (AU)</th>
<th>Mass ($M_{\oplus}$)</th>
<th>Radius ($R_{\oplus}$)</th>
<th>Orbital period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler-19 b</td>
<td>0.09</td>
<td>8.26</td>
<td>2.17</td>
<td>unknown</td>
</tr>
<tr>
<td>Kepler-78 b</td>
<td>0.01</td>
<td>1.68</td>
<td>1.17</td>
<td>0.36</td>
</tr>
<tr>
<td>Kepler-36 b</td>
<td>0.12</td>
<td>4.46</td>
<td>1.45</td>
<td>13.84</td>
</tr>
</tbody>
</table>

Out of the 66 stars with known exoplanets there are 3 that are orbited by exoplanets that are considered rocky, which can be found in Table 4.2, and 3 that are orbited by potentially rocky exoplanets i.e. their masses are not known, one of which is host to 2 exoplanets. The potentially rocky exoplanets are detailed in Table 4.3. All of these 7 exoplanets are outside of the HZ of their hosts (which are Sun-like stars) and have been discovered via transit.
Table 4.3: Details regarding potentially rocky exoplanets found in the crossmatch between the exoplanet.eu catalogue and the Tycho-2 dataset. As the masses of these exoplanets are unknown, figures regarding their name, semi-major axis, radius and orbital period are included.

<table>
<thead>
<tr>
<th>Name</th>
<th>Semi-major axis (AU)</th>
<th>Mass ((M_\oplus))</th>
<th>Radius ((R_\oplus))</th>
<th>Orbital period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPIC 249622103 b</td>
<td>0.03</td>
<td>unknown</td>
<td>1.37</td>
<td>2.47</td>
</tr>
<tr>
<td>EPIC 249622103 c</td>
<td>0.07</td>
<td>unknown</td>
<td>1.31</td>
<td>unknown</td>
</tr>
<tr>
<td>Kepler-450 d</td>
<td>unknown</td>
<td>unknown</td>
<td>0.82</td>
<td>7.51</td>
</tr>
<tr>
<td>EPIC 204221263 b</td>
<td>unknown</td>
<td>unknown</td>
<td>1.51</td>
<td>4.02</td>
</tr>
</tbody>
</table>
Chapter 5

Conclusion and further work

I set out to investigate the detectability of Earth from 1.6 million stars in the Milky Way to find what areas of the Galaxy have the best view of us. In my analysis, I used three detection methods, transit, radial velocity, and astrometry, which an observer a few pc away could use to detect the Earth. Signal-to-noise ratios of each detection method as well as combined signal-to-noise ratios for the Earth were employed to produce heatmaps that show the hotspots in the Galaxy i.e. zones full of stars that can best detect us.

5.1 Improvement to analysis

This research project included stars from the Gaia catalogue data release 1. However, the 1.6 million dataset stars represent only a small fraction of the total current Gaia catalogue, which includes 2 billion stars. It would be interesting to see how the combined heatmap would change with the addition of more stars. The number of close matches between the Gaia stars and the exoplanet.eu catalogue of confirmed exoplanet hosts is also expected to increase. However, increasing
the number of stars would also increase the computation process time; hence illustrating the need for fast computers running on multiple cores.

Coverage of SETI surveys could be improved if the southern hemisphere had greater coverage in addition to MWA and Parkes. The southern part of the sky is less explored and surveyed by radio telescopes than its northern counterpart.

Considering the recent start of the FAST telescope in China as well as the SKA in the coming years, new SETI surveys from both hemispheres will be produced. Combined with a more accurate heatmap of the Galaxy, that would contain more stars, the suitable sky coverage ranges (RA and declination) that the new telescopes could focus on would mean an easier more direct way to identify potentially interesting signals.

My heatmap suggests that it may be more efficient to analyse the identified hotspot regions initially. As a single radio telescope can produce over 100 terabytes of data per day, the cost of storing all these data online would be several million pounds (Worden et al. 2017). If instead a specific area of the Galaxy would be chosen, compressing the data and making it easily accessible by storing it online would be more affordable.

5.2 Conclusion

A lot of emphasis has been put in recent years in discovering exoplanets. The sensitivity of the detection methods has improved year by year, along with developments in spectroscopy, engineering, and technology in general. Someday it is possible an equivalent of Earth will be discovered. But today, we also have the
opportunity to decide which stars have the highest potential of detecting Earth and knowing we are here.

The detectability or SNR of Earth as seen by an alien observer via the transit, RV and astrometry methods were successfully computed knowing the coordinates, distances and luminosities of 1.6 million stars from 2 datasets. These were then further combined into aggregated SNRs that take into account contributions of 2 or 3 detection methods. The final heatmap represents the combination of all three detection methods SNR for all stars from the Tycho-2 catalogue. This map was then compared to current SETI surveys and confirmed exoplanets.

A comparison between the final heatmap and the main SETI surveys led by Arecibo, ATA, GBT and Parkes was done the plotting the sky coverage of the surveys over the heatmap. The resolution of radio telescopes was also investigated for three different wavelengths within the observation range of each telescope to determine which parts of the heatmaps the telescopes were most sensitive to. The final heatmap was also used to compute a scatter plot of 20 exoplanets whose hosts matched with the dataset stars and had a high Earth detectability.

In conclusion, the detectability of the Earth is determined by the SNR of the detection methods used. For all methods analysed, RV, astrometry, and transit, the distance between the Earth and the target star plays a significant role. Regarding the transit method, only stars that lie on the ecliptic plane are able to spot Earth’s transit around the Sun and account for a small minority (< 1%) of all stars in the two datasets. Establishing a relationship between the Earth detectability heatmap, previous SETI surveys as well as the resolution of the SETI radio telescopes, may be helpful in making searches for SETI signals more efficient. Knowing of potential crossmatches between stars in the Galaxy and stars that host exoplanets may come helpful to future exoplanet projects like
TESS and the James Webb telescope, whose mission is to look deeper into the characteristics of exoplanets.
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Appendices
# Appendix A

## List of parameters

Table A.1 provides a list of the parameters used in this dissertation.

Table A.1: List of parameters used in this dissertation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_\oplus$</td>
<td>Earth mass</td>
</tr>
<tr>
<td>$M_J$</td>
<td>Jupiter mass</td>
</tr>
<tr>
<td>$R_\oplus$</td>
<td>Earth radius</td>
</tr>
<tr>
<td>$P$</td>
<td>orbital period of a planet</td>
</tr>
<tr>
<td>$e$</td>
<td>eccentricity of the orbit of a planet</td>
</tr>
<tr>
<td>$\omega_*$</td>
<td>argument of periapsis</td>
</tr>
<tr>
<td>$K$</td>
<td>semi-amplitude of the RV shifts</td>
</tr>
<tr>
<td>$a$</td>
<td>semi-major axis</td>
</tr>
<tr>
<td>$\nu$</td>
<td>true anomaly</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>longitude of ascending node</td>
</tr>
<tr>
<td>$i$</td>
<td>inclination of the orbit of the planet</td>
</tr>
</tbody>
</table>
### APPENDIX A. LIST OF PARAMETERS

Continued from previous page

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(\omega)$</td>
<td>position of periapsis</td>
</tr>
<tr>
<td>$M_p$</td>
<td>planet mass</td>
</tr>
<tr>
<td>$M_\star$</td>
<td>star mass</td>
</tr>
<tr>
<td>$\sigma_{RV}$</td>
<td>uncertainty in RV measurements</td>
</tr>
<tr>
<td>$d$</td>
<td>distance from the Earth</td>
</tr>
<tr>
<td>$R_J$</td>
<td>Jupiter radius</td>
</tr>
<tr>
<td>$a_{HZ}$</td>
<td>habitable zone semi-major axis</td>
</tr>
<tr>
<td>$L$</td>
<td>star luminosity</td>
</tr>
<tr>
<td>$L_\odot$</td>
<td>Sun’s luminosity</td>
</tr>
<tr>
<td>$T_{\text{eff}}$</td>
<td>star effective temperature</td>
</tr>
<tr>
<td>$\langle S \rangle$</td>
<td>average stellar flux</td>
</tr>
<tr>
<td>$R$</td>
<td>resolution</td>
</tr>
<tr>
<td>$R_\odot$</td>
<td>Sun radius</td>
</tr>
<tr>
<td>$M_\odot$</td>
<td>Sun mass</td>
</tr>
<tr>
<td>$b$</td>
<td>impact parameter</td>
</tr>
<tr>
<td>$\beta$</td>
<td>ecliptic latitude</td>
</tr>
<tr>
<td>$V_\oplus$</td>
<td>Earth’s velocity</td>
</tr>
<tr>
<td>$F$</td>
<td>flux of the star</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Earth’s transit duration</td>
</tr>
<tr>
<td>$\sigma_T$</td>
<td>precision of the transit method</td>
</tr>
</tbody>
</table>

Continued on next page
Continued from previous page

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>telescope diameter</td>
</tr>
<tr>
<td>$\sigma_{AST}$</td>
<td>uncertainty in the astrometric measurement</td>
</tr>
<tr>
<td>$N_{photons}$</td>
<td>number of photons</td>
</tr>
<tr>
<td>$P_{tr}$</td>
<td>transit probability</td>
</tr>
<tr>
<td>$\rho_*$</td>
<td>star mean density</td>
</tr>
<tr>
<td>$\delta$</td>
<td>transit depth</td>
</tr>
<tr>
<td>$T_*$</td>
<td>star temperature</td>
</tr>
<tr>
<td>$l_{in}$</td>
<td>inner HZ limit</td>
</tr>
<tr>
<td>$l_{out}$</td>
<td>outer HZ limit</td>
</tr>
<tr>
<td>$s$</td>
<td>path length difference</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>telescope resolution</td>
</tr>
<tr>
<td>$A$</td>
<td>signal amplitude</td>
</tr>
</tbody>
</table>
Appendix B

Program

#Author: Andreea Dogaru (andreea.dogaru@postgrad.manchester.ac.uk)
#Project: A new strategy for SETI: Earth as an exoplanet
#University: The University of Manchester
#Degree: MSc Astronomy and Astrophysics by research
#Programming Language: Python 3.6.4 on Linux

from math import cos,sin,acos,pi,sqrt
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from astropy.convolution import convolve_fft,Gaussian2DKernel

#Coordinate transformation with open('table2.dat','r') as f:
    df = pd.DataFrame(l.rstrip().split() for l in f)
    ra=df[1] #longitude
    dec=df[2] #latitude
    luminosity=df[11]
    distance=df[5]
```python
count = len(dec)
long = np.empty([0, 0])
lat = np.empty([0, 0])
dis = np.empty([0, 0])
a = np.empty([0, 0])
lum = np.empty([0, 0])
C = np.empty([0, 0])
D = np.empty([0, 0])
eclon = np.empty([0, 0])
eclat = np.empty([0, 0])
eqlongdeg = np.empty([0, 0])
eqlatdeg = np.empty([0, 0])
eclatdeg = np.empty([0, 0])
eclondeg = np.empty([0, 0])
for i in range(count):
    long = np.append(long, float(ra[i]) * pi / 180)
eqlongdeg = np.append(eqlongdeg, float(ra[i]))
lat = np.append(lat, float(dec[i]) * pi / 180)
eqlatdeg = np.append(eqlatdeg, float(dec[i]))
dis = np.append(dis, float(distance[i]))
lum = np.append(lum, float(luminosity[i]))
a = np.append(a, acos(cos(inc) * sin(lat[i]) - sin(inc) * cos(lat[i]) * sin(long[i])))
eclat = np.append(eclat, pi / 2 - a[i])
eclatdeg = np.append(eclatdeg, float(eclat[i] * 180 / pi))
D = np.append(D, sin(a[i]) * sin(inc))
C = np.append(C, acos((sin(lat[i]) - cos(a[i]) * cos(inc)) / D[i]))
if pi / 2 >= long[i] >= 0 or 2 * pi >= long[i] >= 3 * pi / 2:
    if C[i] > pi / 2:
        eclon = np.append(eclon, 5 * pi / 2 - C[i])
```

else:
    eclon=np.append(eclon,pi/2-C[i])
elif pi >= long[i] >= pi/2 or 3*pi/2>=long[i]>=pi:
    eclon=np.append(eclon,pi/2+C[i])
    eclondeg=np.append(eclondeg,eclon[i]*180/pi)

# Transit SNR computation
imin=acos(Rsun/au)
imindeg=imin*180/pi
ecmindeg=90-imindeg
inc=23.436928*pi/180  # Earth’s inclination
T=365*24*3600  # Earth’s period
tmax=T*Rsun/(pi*au)  # only when inclination is 90 i.e. max
Vearth=2*Rsun/tmax
masssun=1.99*10**30  # Sun’s mass

def transnr(i,d):
    b=au*cos(i*pi/180)
    s=sqrt((Rsun+Rearth)**2-b*b)
    t14=sqrt(2*s/Vearth/3600)/d
    return t14
snrt=np.empty([0,0])  # snr for transit
if 0 <= eclatdeg[i] <= ecmindeg:
    snrt=np.append(snrt,transnr(90-eclatdeg[i],dis[i]))
elif eclatdeg[i] <0 or eclatdeg[i] >ecmindeg:
    snrt=np.append(snrt,0)

# Astrometry SNR computation

def astsnr(d):
    snr=1/(d*d)
    return snr
snras=np.empty([0,0])  # snr for astrometry
snras=np.append(snras,astsnr(lum[i],dis[i]))
#RV SNR computation

def rvsnr(i,d):
    snr=(sin(pi/2-i))/d
    return snr

snrv=np.empty([0,0]) #snr for rv
snrv=np.append(snrv,rvsnr(eclat[i],dis[i]))

#Transit time calculation

contor=(math.pi/2-imin)/16
F,Q = [],[] #initializing zero arrays to have inclinations and t14 appended to

def timeall(i):
    b=au*math.cos(i)
    s=math.sqrt((Rsun+Rearth)**2-b*b)
    t14=(2*s/Vearth)/3600
    return t14 for i in range(16):
        print(i,(imin+i*contor)*180/math.pi,timeall(imin+i*contor)) #print table of values
        F.append(90-(imin+i*contor)*180/math.pi)
        Q.append(timeall(imin+i*contor)) #16 t14s

#Producing a heatmap

with open('all','r') as f:
    df = pd.DataFrame(l.rstrip().split() for l in f)
ra=df[0] #ra
dec=df[1] #declination
snrt=df[2] #SNR
count=len(dec)
lon=np.empty([0,0])
lat=np.empty([0,0])
sn=np.empty([0,0])
for i in range(count):
lon = np.append(lon, float(ra[i]))
lat = np.append(lat, float(dec[i]))
sn = np.append(sn, float(snr[i]))
heatmap, xedges, yedges = np.histogram2d(lon, lat, weights=sn, bins=(512, 384))
extent = [xedges[0], xedges[-1], yedges[0], yedges[-1]]
axis_font = 'size':'22'
plt.clf()
im1 = plt.imshow(heatmap.T, extent=extent, origin='lower', vmin=sn.min(), vmax=1, aspect="auto", cmap='hot_r')
im1.cmap.set_over('g')
plt.colorbar(extend='max').set_label('SNR', **axis_font)
plt.xlabel("Right Ascension (degrees)", **axis_font)
plt.ylabel("Declination (degrees)", **axis_font)
axes = plt.gca()
plt.show()

# Cross-match between datasets and exoplanet database
n = 0
for i in range(count2):
    for j in range(count):
        if sqrt((raa[i]-raexa[j])*(raa[i]-raexa[j])*cos(decexa[j])*cos(decexa[j]) + (deca[i]-decexa[j])*(deca[i]-decexa[j])) <= 0.0012:
            one = np.append(one, raa[i])
            two = np.append(two, deca[i])
            n += 1
            print("n")
            three = np.append(three, raexa[j])
            four = np.append(four, decexa[j])

# Resolution of the telescope
kernel = Gaussian2DKernel(stddev=4.31)
scipy_conv = convolve_fft(heatmap.T, kernel)
im1=plt.imshow(scipy_conv, extent=extent, origin='lower', vmin=min, vmax=1, aspect="auto", cmap='nipy_spectral_r')
im1.cmap.set_over('g')
t = np.linspace(0.361,360)
plt.fill_between(t, -89.88, -2, color='blue', alpha='0.7', interpolate=True)
plt.fill_between(t, 38, 89.832, color='blue', alpha='0.7', interpolate=True) # Arecibo