Identifying Features of Earth Like Exoplanets

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Abstract. Currently on a very small fraction of exoplanets are visible: those which are hot after formation or are classed as brown dwarves. Earth sized and Earth like exoplanets are not observable and even the newest telescopes such as JWST hasn't a hope of getting a picture with any useful detail. The interior structure and surface of such planets is invisible to us. I show some methods that have been used to estimate the interior dimensions of rocky exoplanets, now that radius of smaller planets can be measured more accurately. I also focus on behaviour of the mantles of such planets, and how their temperature could possibly affect the surface of the planet and hence its climate and conditions.

Keywords: exoplanets, terrestrial, topography, composition

1 Introduction

Since the discovery of the first exoplanet 51 Peg b in 1995, over 4000 have been found. The primary methods of discovery for exoplanets include radial velocity, transits, microlensing and direct imaging. Radial velocity and microlensing are dependent on gravity and distance; the higher mass the exoplanet, the more pronounced these effects. Transits are dependent on radius; a larger planet is more easily detected. Finally, direct imagine is currently on feasible with recently formed planets or brown dwarves; the hotter the exoplanet, the higher its magnitude will be. All this means that from the exoplanets known, more massive, larger planets close to their star are in the majority (around 65%) (https://exoplanetarchive.ipac.caltech.edu/). With their higher mass, these planets are structurally similar to Jupiter or Neptune. Planets with similar features (mass, diameter) to the Earth are more difficult to find requiring more sensitive equipment. In the 2000's a series of space missions geared specifically towards exoplanet discovery were launched. Without the vibrations of the Earth's atmosphere and with many different wavelengths of light now observable, discovering exoplanets became much easier and so the first rocky exoplanet was discovered by Kepler in 2011: Kepler 10b. Missions such as Kepler and Gaia provide us with accurate data about low mass exoplanets, including stellar distances, radius which ground based telescopes (those used for exoplanet discovery in the 1990's and early 2000's) couldn't. Ground based telescopes simultaneously improving their capabilities of measuring radial velocity. Knowing the radial velocity and stellar distance to a relatively high degree of accuracy provides us with information about diameter, mass and thus volume and density. From

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this it can be inferred what such a planet's composition might be by comparing its density to that of abundant elements and compounds. This, however, ignores the fact that planets do not have a uniform density and layers of different materials (metallic, iron/nickel core, silicate rock/sand, and atmosphere including hydrogen, helium, nitrogen and potential hydrocarbons). By disregarding the interior proportions of an exoplanet, our knowledge of its possible composition may be wrong entirely, including any idea of what its atmosphere is made up of.

It is possible to observe the spectrum of the host star in search for the most abundant materials making up rocky planets (in the Solar System) and assume that the proportions of such elements (Iron, Silicon, Magnesium, Aluminium etc) carry over to the planet [1]. These elements are somewhat resistant to high levels of heat and pressure such as those present in a forming star system and thus their proportions are unlikely to change during planet formation [2].

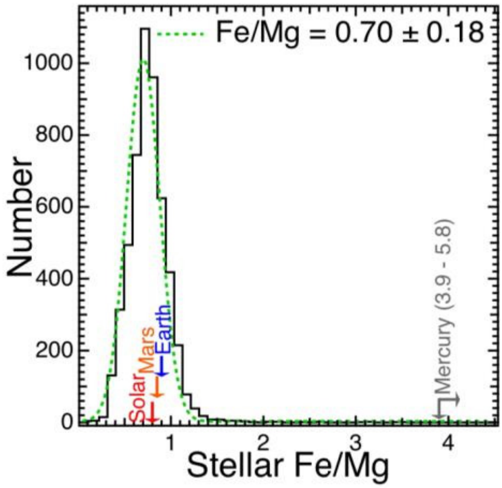

Fig. 1. histogram of the amount of Iron/Magnesium in the spectra of 5220 stars from [9]. Green line indicates the range of expected Iron/Magnesium values for planets orbiting stars part of the histogram. Values of Sun, Earth and Mars are shown to fall within margin of error (±0.18). Mercury is the anomalous result, with an estimate of 3.9-5.8 assume it has no Iron Sulphide. Data for the Sun, Earth and Mars [10],[11]. The data for the Earth and Mars prove that the method of consistent Fe/Mg ratio across the star and planets is feasible. However, inability to collect data from Venus and Mercury's irregularity shows some that there are some flaws. [1]

However, this can be disputed since these elements are not as refractory as some such as niobium and tungsten. Indeed, whilst the boiling points of these elements are similar (2800K +- 500K), their melting points differ by over 1000K for e.g., aluminium and iron. Some elements may indeed deplete more than others during planet formation. In our solar system, much of the semi volatile elements still found in the photosphere of the sun have chemically fractionated and are no longer found in the same ratios as in the Sun's photosphere [3]. Such elements include those with boiling points around and below 650-1350K, which notably includes elements such as magnesium, which are very abundant on Earth.

Another obstacle when deciphering the composition of exoplanets is compounds. Whilst Iron, Silicon and Magnesium are the most abundant elements on terrestrial planets in the solar system, they often do not exist in pure forms. Oxygen, which constitutes the most abundant element on Earth forms oxides with most metals that are also common on Earth. In fact, pure forms of more reactive elements e.g., magnesium, aluminium, sodium, calcium etc. are extremely rare and more often found as oxides or other compounds. Whilst it is possible to trace refractory elements from the star to the planet, metals often bond to non-metals and non-metals are very difficult to infer from the host star since they often have very low boiling points (e.g. oxygen 90K) and thus would not have had a good time in a hot newly formed star system. In the example of the Earth and Sun, oxygen makes up 0.97% of the Sun by mass, and iron 0.014%, whilst on the Earth, oxygen and iron are at almost a 1:1 ratio by mass.

2 method

I will be focusing on the interior structure and composition of rocky exoplanets. This not only provides us with crucial information about the possible chemistry (and its similarities and differences to Earth) as well as using thermodynamics and planet age to estimate its tectonic activity and hints at its surface topography

2.1 Interior composition

Planets that are well within the frost line and are in the region of rocky planet formation should have negligible amounts of hydrogen, helium and water since any substantial amount of these gases in the atmosphere would enlarge the planet's radius and thus place it into the category of sub-Neptune rather than rocky Earth like or super Earths [4]. For terrestrial or rocky planets in the solar system, their composition is relatively similar: a thin crust of silicate rock, followed by a semi molten mantle of the same silicate material then a metallic usually iron core. Assuming that the mantle has a constant 1:1 ratio of Silicon: Magnesium in moles, and assuming an iron core such as those found at the center of terrestrial planets in the solar system, the proportion of the planet's volume taken up by the core can be calculated [1]. This same study focuses on stars of magnitudes F K and G finding an average Iron/Magnesium of 0.7 ± 0.18 from which the percentage of the planet (by mass) taken up by both can be calculated and hence the extent of the planet which is part of core and mantle respectively can also be found. The study also used this method on the solar system, with the Sun, Earth and Mars turning out 0.8, 0.9, 0.85 Iron/Magnesium respectively. However, Mercury's unusually large core being an indicator that this method is still flawed; planets have plenty of time to change their composition either by a change in orbit, collision or otherwise. Using this method, it is not possible to predict the existence of Mercury-like exoplanets though given that we still don't know fully why Mercury has such a large core, it is reasonable to assume such planets are few and far between. It does mean however that this method is only capable of calculating a planet's structure at formation, and unable to account for any changes caused by cosmic events.

However, [4] uses the direct refractory ratio of planets including the aforementioned iron/magnesium and also iron/silicon to predict the existence of not only iron rich planets such as Mercury (large core:mantle ratio) but also Moon like planets which are predominantly made of rock with a small core. However, it should be noted that the Moon was likely not formed in the same way as the planets in the protoplanetary disc, instead the giant impact theory suggests that the Moon is made primarily of material from the crust of the Earth hence why it is so rich in silicate rock and iron poor; the high velocity collision of Earth and the proposed protoplanet as well as their impact angle of around 45 degrees caused much of the planet and Earth's crust and mantel to be sent into orbit where it formed the moon [5]. Other terrestrial planets in the solar system do not have a structure like the moon and the Sun's spectrum does not hint at the existence of such a silicate rich body.

2.2 Surface

The surface topography of an exoplanet is extremely important in determining its environment and potential habitability. For example, a planet with relatively uniform elevation i.e. a more or less flat planet likely to be an ocean world, if the temperature allows and water is present. It requires very little water to cover a flat world in a thin layer. However, a planet with significant elevation changes is more likely to experience continents as we do on Earth. All this plays a very important role in determining the climate of any Earth like planet and thus the conditions needed for extra-terrestrial life.

The elevation and landscape of planets are caused one of two ways. Tectonic processes cause plates to move towards, away or along one another creating trenches mountains and volcanos at their boundaries. This is the process behind most of the Earth's more notable geographical features namely the Himalayas, the Mariana Trench, Alps etc. In addition, high levels of tectonic activity allows for the fast moving liquid material in the outer core to transfer much more momentum to the mantle and thus the lithosphere. The higher amount of angular momentum transferred causes the shaping of the bottom of the lithosphere and by friction and pressure the surface of a planet as well [6]. For a planet without tectonic activity (likely due to cooling of the core) the main way the crust is shaped is by the contrasting pressure and density of the lithosphere (brittle, cooler upper part of the mantle which lies next to the crust) and the asthenosphere (hotter part of the mantle below the lithosphere). Whilst such a planet is not tectonically active and thus has no plates or convective currents in the mantle, warm and cool areas of the asthenosphere can still affect the lithosphere. When an area in the asthenosphere is warm, the material moves up pushing cooler material to the side, causing the lithosphere and crust on top to bulge upwards. When the asthenosphere is cool, the material sinks downwards and by traction and intermolecular forces pulls surrounding material downwards too. The downward motion of material in the asthenosphere drags parts of the lithosphere downwards too via friction causing the area of the crust to thicken. In situations of extreme heat from the mantle, a part of the crust can thin as cool material is pushed aside. Using the fact that the planet cools from outside to inside, estimates for temperatures of different parts of the mantel and core can be obtained and with that an idea of tectonic activity, and if the predicted temperature is too low potential endocrine sources of topography change.

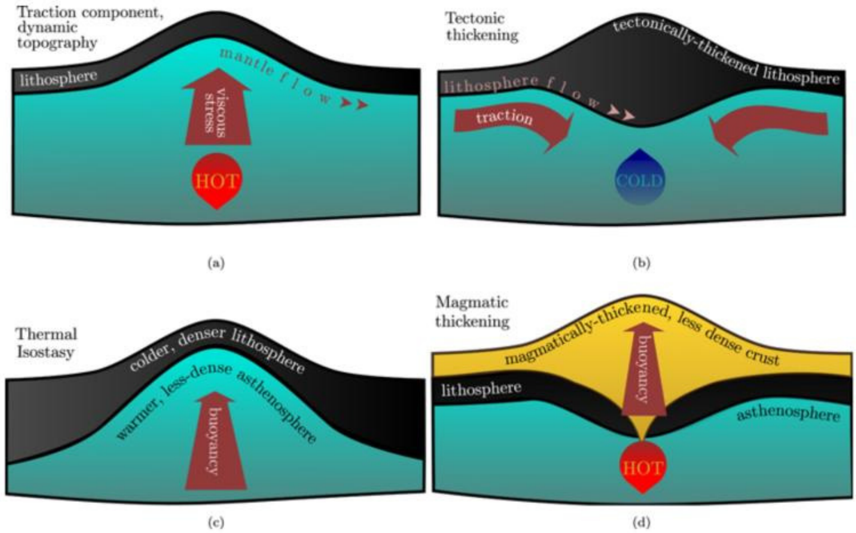

Fig. 2. Illustrating the main ways the crust and topography is shaped for planets which are not tectonically active. A) rising warm material pushes cooler rock to the sides, creating a bulge. B) cool rock sinks dragging lithosphere downwards from both sides, making it thicker. C) difference in pressure causes the less dense material to 'float' upwards. D) hot material moves upwards through the lithosphere forming a new surface [7].

Knowing the brightness of the host star, it is possible to infer the approximate age of the star. The assumption is made that it is nearly impossible for an FGK star to capture an Earth sized rocky planet and for it to entire into a stable near circular orbit near to the star. Therefore, it is also assumed that the planet formed around the same time as the star. With current planet formation models, the temperature of the protoplanetary disc as well as the radius (and hence volume and surface area) of the planet, it is possible to predict a potential internal temperature (heat is contained in the planet's interior or volume and lost via its surface area into space). After the surface of the planet freezes and ceases to be molten, cosmic events such as meteorite impacts, cosmic rays, or even protoplanetary collisions and gamma ray bursts have little effect on the core temperature. Knowing the core temperature, an estimate of the core: mantle ratio (part 2.1) and radius it is possible to calculate the temperature at the asthenosphere (just below the surface i.e. very near the top of our silicate mantle, iron core two part planetary model) and therefore the level of tectonic activity, and if none is calculated, endogenic effects on topography.

An important point worth noting is that a tectonically inactive planets lack the ability for transport of material between the mantle and the lithosphere/surface. On Earth, the only known example of confirmed activity in the lithosphere, elements which are not found in the crust which are more abundant lower down in the mantle can be transported upwards and many of these elements are key in organic molecules involved in the synthesis of proteins and nucleic acid [8]. The Earth's crust is dominated by oxygen, silicon and handful of other metals and such volcanos, geysers and hydrothermal vents are often responsible for bringing material from the mantle to the surface. For an exoplanet with no lithospheric tectonically activity and such a much weaker and smaller convective cycle in the mantle, it is unclear if it has sufficient resources needed for the chemistry for life.

3 Conclusion

With the launching of the space telescopes specifically designed to observe exoplanet transits and with the ever improving radial velocity technology on the ground, measuring the radius of exoplanets has become much easier and more precise, from a margin of error of up to 20% using only ground based telescopes to close enough to zero that some calculations may be carried out without problems. Mass radius models of planets now allow us to identify Earth like planets and Super Earths from sub Neptunes. Such a model makes it possible to distinguish a rocky planet such as the Earth from planets that have a significant gaseous envelope, though both may have similar masses at first glance. As accuracy of measuring exoplanet radius passes 1% margin of error, exact proportions of a planets interior can be calculated, however currently we are limited to educated guesses from the spectrum of the parent star. It remains difficult to distinguish planets with a thick gas atmosphere from rocky planets if the rocky planet is abundant in less dense material such as most forms of iron oxide, which tend to form in a flaky structure. This low-density solid can interfere with mass radius models to mimic a hydrogen helium atmosphere. As more powerful space telescopes are launched especially infrared ones such as the JWST (launched Dec 25 2021), data and subsequently the math involved and ultimately the results will become more precise and accurate.

4 References

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