Towards a Classification System of Terrestrial Planets

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Abstract: The focus of extrasolar planet searches has become the detection of habitable terrestrial planets. Planetary mass and orbit have large and obvious effects on habitability. Since the chemical compositions of terrestrial planets also play an important role in habitability, we propose the creation of a classification system for Earth-like planets based on the abundances of elements most important for habitability. We describe the methodology for the creation of such a classification system based on the observed chemical abundances of stars.

Keywords: Terrestrial planet formation, Solar system, chemical composition

Introduction

Background for the Creation of a Planet Classification System

Scientific understanding of a group of new objects begins with a useful classification scheme. For a century astronomers have relied on the Hertzsprung-Russell diagram to classify stars according to their colour and magnitude. In the Hertzsprung-Russell diagram the Sun is seen to be part of the main sequence of hydrogen-burning stars. An analogous classification system for planets has yet to emerge. In our Solar System we have: small rocky planets close to the Sun (Mercury, Venus, Earth, Mars, asteroids), the gas giants (Jupiter and Saturn), then the ice giants (Uranus and Neptune) and finally a swarm of small dirty snow balls (Pluto and company). This rudimentary orbital-radius-dependent pattern of small refractory rocks, then large gas giants, then smaller ice giants, was taken as the standard model of planetary systems until the discovery of exoplanetary systems that did not conform to this pattern.

Detected Exoplanets and their Implications for Extrasolar Terrestrial Planets

More than 200 giant extrasolar planets have been found over the past 15 years [1]. Statistical distributions of the masses and orbital periods of the ~200 detected exoplanets are beginning to reveal the fraction of Sun-like stars that host planets. The current best estimate is that at least ~25% of Sun-like stars host currently observable planets [2]. Since our data is necessarily incomplete, this number is only a lower limit; the actual number could be ~100% [2]. The limited sensitivity of planet detection techniques and current observational durations of less than ~15 years heavily favours detections of the most massive short-period exoplanets. For example, it is still the case that if the Sun were among the targets being searched for planets, neither Jupiter nor any of the other planets is massive enough or has a short enough period to have been detected around the Sun [3]. Over the next few years this situation will change as the baseline of observation extends to periods longer than Jupiter's 12 year period and thus to distances beyond ~ 5 AU from the central star. Despite these limitations, we have a preliminary answer to the question: Is our Solar System typical of planetary systems? By examining the period and mass histograms of detected exoplanets and by correcting for known selection effects in the data, we found that the exoplanet data strongly suggest that Jupiter-like planets in Jupiter-like orbits are common [3,4], i.e., Jupiter may be a typical planet, not an outlier. More definitively, over the next few years, radial velocity searches will start to detect Jupiter-like planets at 5 AU and more, from their host stars, if they exist [3].

If the goal is to find planets that could harbour life, these detected exoplanets are not good candidates. Most are gas giants with no solid surfaces and no liquid water. They are not terrestrial planets in circumstellar habitable zones [5]. Finding terrestrial planets (not just planets) is the next big initiative in astronomy and the next big step towards understanding the Earth [6]. Although terrestrial planets are currently beyond detection limits, many are expected to be found over the next 20 years using half a dozen multi-million dollar ground- and space-based instruments designed specifically to detect them (e.g. SIM, COROT, Kepler, Terrestrial Planet Finder, Darwin). The determination of how common terrestrial planets are in the universe depends on how precisely one wants to define "terrestrial". Here we use "terrestrial" as a synonym for rocky. Terrestrial planets are those that resemble the Earth, and are thus composed of a silicate shell surrounding a metallic core, as opposed to Jupiter-like planets that are mostly composed of light elements such as H and He. Thus, Mercury, Venus, Earth and Mars are terrestrial planets. Detecting, characterizing and determining the habitability of nearby terrestrial planets is one of the highest priority areas in astronomy with far reaching implications for humanity.

The consensus picture of rocky planet formation by core accretion in a protoplanetary disk [7, 8] suggests that terrestrial planet formation is a common corollary of star formation. The concepts and observations upon which this picture is based include our understanding of i) the behaviour of volatile and refractory elements; volatile elements are swept out of the inner accretion disk leaving the more refractory elements to form the rocky planets (e.g. [9]) ii) the position of the snowline in a circumstellar disk; the snowline is the distance from the central star beyond which the temperature is low enough for water to condense into ice [10], iii) infrared spectroscopy of stars of different ages which yields the frequency of circumstellar disks as a function of stellar age; [11] and iv) the observed few million year time scale for the disappearance of the circumstellar disks, corresponds well with the time scales of the formation of terrestrial planets obtained from numerical simulations [12, 13, 14].

Several sets of observations have important implications for the existence of extrasolar terrestrial planets. Observed exoplanets are too massive to have formed in the short-period close-orbits where we detect them. They must have migrated or been gravitationally scattered into their current orbits [15]. Since these planets must have formed beyond the snowline outside of the circumstellar habitable zone [2], it seems plausible that their transport inwards through the habitable zone would have destroyed any habitable terrestrial planets that may have been in the system. This is one factor that has been cited against the idea of terrestrial planets being common. However hot Jupiters that have migrated through the habitable zone make up a small (~ 5%) minority of systems. In addition, in systems where this transport has happened, it is possible that terrestrial planets can form after the passage of the giant [16].

The truncation of protoplanetary disks by close passages of nearby stars in the same stellar nursery has been hypothesized to play an important role in determining how common terrestrial planets are. However, Adams et. al. [25] find that most planetary systems with diameters less than 30 AU, would not be substantially disrupted by the passage of nearby stars or by far ultra violet flux, which can be seen ablating disks in the most dense star forming regions such as Orion.

Another factor that has been cited against the idea of terrestrial planets being common is that the gas giants in our Solar System seem to have unusually low eccentricities compared to the set of detected exoplanets. The low eccentricity of Jupiter may have played an important role in the formation of the terrestrial planets in stable orbits and the delivery of volatiles to the inner Solar System.

However, we do not know how frequent low eccentricities are. The broad range of eccentricities currently observed is probably correlated to the migration or gravitational scattering of these planets into observable orbits. Since these detected planets represent ~10-20% of the all systems, there is still room (80-90%) for most planetary systems to be much more like ours, i.e., with low eccentricity gas giants beyond the snowline and a few terrestrial planets nearer the host star.

Water and Habitability

All life on Earth depends on water. Therefore, it is reasonable to expect, on terrestrial planets elsewhere in the universe, the same close association between the presence of liquid water and the presence of life. Thus, we are most interested in terrestrial planets like the Earth that have liquid water on their surfaces. Although H_2O is the most common triatomic molecule in the universe, most of it is a solid or a gas. Therefore, an important potentially limiting factor on extraterrestrial life is not the presence of H_2O, but the presence of the pressure and temperature regimes to keep the H_2O liquid. Temperature and pressure regimes consistent with keeping H_2O a liquid are determined by planetary mass and planetary orbit, which are therefore the main constraints defining a circumstellar habitable zone [5]. The orbit should be the right size to keep the surface water between 0 and 100 C under the Earth's atmosphere - with higher temperature limits for denser atmospheres. Also, the mass of the planet must be sufficient to hold an atmosphere dense enough to maintain a pressure above the 6 millibar triple point pressure of H_2O and below the 220 bar critical point pressure of H_2O. Thus, habitability for water-based life is determined by a planet's mass [17], its proximity to the circumstellar habitable zone [5, 18], and by its bulk chemical composition.

Although H_2O is common in the universe, it is probably a universal feature of terrestrial planet formation that the inner 1 or 2 AU of a planetary system is relatively dehydrated due to its proximity to the host star. The water abundance in the asteroid belt places the snowline in our Solar System at ~2.7 AU [19] and we expect analogous snowlines in other planetary systems. The distance of these snowlines from their host stars depends on the luminosity of the host star. Since H_2O has to be delivered, the mechanisms that deliver volatiles into the inner planetary system are probably important prerequisites for volatile-based life on dry rocky planets. The Earth received its water from a combination of water-rich (~10% by mass) asteroid impacts from the outer asteroid belt, water-rich planetesimals from the Jupiter-Saturn region and to a lesser extent a late veneer of water from cometary nuclei [19, 20]. The delivery of water to the inner planetary system is controlled by the presence of gas giants with the right amount of eccentricity [21, 22]. These gas giants perturb water-rich bodies beyond the snowline and produce radial mixing of the material in the Solar System, much as the magnetic fields in the X-wind model [23] produce the radial mixing of components of meteorites that have undergone varying degrees of thermal processing.

Methodology for creating a classification system: the chemical composition and the habitability of terrestrial planets

The collapse of molecular clouds into stars, proto-planetary disks and eventually terrestrial planets is a process that involves a series of fractionation events. Hydrogen, helium and other volatiles are removed leaving the more refractory elements. The refractory elements are then further fractionated as a result of cooling, condensation sequences, chemical affinity and the magnetically modulated bipolar outflows seen as a normal feature of star formation. The resultant fractionation (at least in one example) can be constrained by measurements of the elemental abundances in the terrestrial planets and meteorites of our Solar System. The Earth is made of an iron core, a silicate mantle and a volatile-rich crust/ocean/atmosphere that harbours life. This composition was determined by the elemental abundances of the primordial Sun and the fractionation processes that occurred in the accretion disk at ~ 1 AU from the Sun. The other terrestrial planets (Mercury, Venus and Mars) have bulk compositions similar to the Earth.

We propose that the bulk compositions of terrestrial planets orbiting other stars can be extracted from measurements of stellar elemental abundances. These bulk compositions will provide the basis for the first chemical-composition-based classification system of terrestrial planets. With the initial framework of such a classification system, we will begin to be able to answer the question: How does the chemical composition of the Earth and biosphere compare to the composition of other terrestrial planets and other biospheres that may exist in the Universe? Our classification system of terrestrial planets will inform our searches for other earths, and constrain our speculations about extraterrestrial life [27, 28].

Existing ways to obtain information on the composition of an extrasolar planet are limited. In rare cases when the planetary orbit is seen edge on from the Earth, transit photometry and radial velocity measurements yield the radius, mass and hence the density of the planet, from which rough estimates of the composition are made. Another way is to identify minerals in protoplanetary disks by absorption and emission features in infrared spectra. Limited angular resolution prevents this approach from probing the parts of the disks in circumstellar habitable zones [29].

The elemental abundances of the Sun provided the raw material for the terrestrial planets. The most obvious pattern is the extreme depletion in the terrestrial planets of the most volatile elements: hydrogen (H) and the noble gases (He, Ne, Ar). The abundances of the most refractory elements, (Mg, Si, Fe Al, Ca, Ni, Cr, Ti and Co) are virtually identical in the Sun and terrestrial planets [30, 31]. The distribution of elemental abundances in Mercury, Venus, Earth and Mars is a measure of how different terrestrial objects can be, starting from the same solar material. [32, 8, 33, 34]. The observed range then gives us preliminary estimates of the range of elemental depletion in the terrestrial planets orbiting nearby stars.

An increasingly large body of observations of circumstellar accretion disks, including infra-red spectroscopy sensitive to mineralogy (e.g. [29]), suggests that the fundamental aspects of the accretion and fractionation processes that led to the depletion pattern in our Solar System are universal. Elemental volatility is universal within the range of temperatures and pressures expected in protoplanetary disks. That is, terrestrial planets around other stars will have refractory elemental abundances that match their host stars. Also, terrestrial planets will be severely depleted in the noble gases compared to their host stars. These simple plausible examples have major implications for the composition of terrestrial planets orbiting other stars – stars whose relative abundances of refractory elements can vary by factors of at least two compared to the Sun.

A planetary classification system must be informed by how the composition of the Sun compares to the compositions of other stars [35] and by how these compositional differences propagate into compositional differences in the terrestrial planets that orbit them. Based on the plausible assumption that the basic features of the elemental depletion patterns seen in our Solar System are universal, the elemental abundances from comprehensive stellar spectral surveys can be used to estimate the bulk chemical composition of the terrestrial planets that orbit these stars. Thus, elemental abundances of other stars give us an estimate of the bulk compositions of other earths.

It is important to note that these estimates can be done in a statistical way or on a star-by-star basis. The statistical analysis will yield a classification scheme for terrestrial planets enabling us to place the composition of the Earth in context and begin to answer the question: How typical is the Earth? The star-by-star analysis will enable us to predict what kind of terrestrial planet will be orbiting each star – information that will help interpret the anticipated infrared spectra of terrestrial planet atmospheres and help us locate the nearest habitable terrestrial planets.

The translation of stellar chemical abundances into meaningful robust conclusions about the "geology" and thus the habitability of terrestrial planets is a difficult challenge. However, it promises to extend the concept of a circumstellar habitable zone to include the idea of a chemical habitable zone based on the chemical abundances of extrasolar terrestrial planets. This chemical habitable zone, or terrestrial planet classification system, will be a multi-dimensional scheme that will locate terrestrial planets within estimated abundance ranges of particularly important elements. The most important of these elements will be carbon, oxygen, magnesium, silicon, sulfur and the radioactive isotopes responsible for keeping planets convectively active.

Important information about terrestrial planets can be extracted from the observed stellar ratio of two elements: carbon and oxygen. These two elements are the most important "metals" making up ~ 2/3 of the non-hydrogen/non-helium mass of the Sun (i.e. 2/3 of ~1.4%). The C/O ratio determines the type of chemical environment in which the other elements condense and therefore the mineral and bulk composition of the terrestrial planets that form around the star. The minerals that elements condense into, depend on the C/O ratio of the host star. To first order, C and O pair up to form CO, a volatile gas that is swept out of the inner parts of the planetary system. The remaining atoms (either C or O, depending respectively on whether C/O >1 or < 1) dominate disk chemistry. For example in our Solar System (C/O ~ ½), after most of the C was swept away as volatile CO or CH_4, the remaining surplus of oxygen combined with the next most abundant elements iron, magnesium and silicon to form the predominant minerals in the Earth: the iron magnesium silicates olivine and pyroxene.

In an oxygen rich, "oxidizing" protoplanetary disk, with C/O < 1, silicates and oxides form, as happened 4.5 billion years ago in the case of the Earth. If C/O > 1, instead of a rocky silicate planet, the carbon-rich reducing environment produces a carbon planet [36] made of reduced condensate - predominantly graphite and silicon and titanium carbides. This would be a terrestrial planet drastically different from Earth. Thus, surveys of stellar C/O ratios [37] will be one of the most important data sets in classifying terrestrial planets [38].

Quantifying Radioactivity and the Heat Budget

The role of temperature in the origin of life is a topic of active research (see [39] and references therein). We have discussed how temperature at the surface is controlled by orbital radius and planetary mass which gravitationally binds an atmosphere. But heat generated by radioactivity (and possibly by gravitational accretion, gravitational settling and the latent heat of the phase transition of the cooling core) plays an important role in resupplying the surface with material out of chemical equilibrium. One of the first steps towards estimating the habitability of a terrestrial planet will be to determine whether chemical disequilibria are maintained by the resurfacing of the planet, either through plate tectonics or some other mode of resurfacing. This in turn is determined by the heat budget. The abundances of radioactive isotopes play the dominant role in setting the heat budget of a terrestrial planet.

The thermal budget of the earth is determined by mantle heat production from radioactive decay of a small number of isotopes. The abundances of the radioactive isotopes ^{40}K, ^{235}U, ^{238}U and ^{232}Th dominate the heat production of terrestrial planets. To estimate the abundance of these radioactive isotopes in other earths we will determine the best proxy elements whose abundances track most closely the abundance of the element for which little or no data is available. Estimates of the relative abundances of potassium, uranium and thorium can be made in this way when direct observations are not available. To convert elemental abundances to isotopic abundances, we assume solar relative abundances for the isotopes [40]. With the resulting isotopic abundances we can model the heat budgets of other earths as a function of time and make rough estimates of whether terrestrial planets of a given mass will still be undergoing convectively driven resurfacing (see [41, 42, 43]).

Summary

Estimating the habitability of nearby planets is one of the most important priorities in astronomy. Small variations in the abundances of critical elements (e.g. C, O, Mg, Si, S and radioactive isotopes) strongly affect habitability. In our preliminary efforts to make quantitative estimates of the characteristics of Earth-like planets orbiting nearby stars and determine their habitability, we will proceed as follows:

1. determine the elemental fractionation depletion patterns that produced the terrestrial planets of our Solar System starting from solar composition material
2. determine the range of stellar elemental abundances from comprehensive new stellar spectroscopic surveys and compare the abundances to solar values
3. estimate the chemical composition of terrestrial planets around nearby stars based on the depletion pattern of 1. and the stellar abundances of 2. above
4. classify terrestrial planets based on the estimates of the ranges over which the most important elemental abundances of terrestrial planets can vary
5. develop tighter links between bulk composition and habitability by studying these links on Earth.

This proposed research will provide the basis for the first classification system of terrestrial planets and help focus subsequent studies of the habitability of nearby earth-like planets.

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