Is the Sun a Random Star?

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Abstract: The properties of our star may be associated with special prerequisites for life. By comparing our Sun to other stars in our galaxy, we may be able to identify such prerequisites. If our star is typical, stellar conditions appropriate for life, and life itself may be common in the Universe. On the other hand, if the Sun is atypical, conditions appropriate for life may be uncommon. Here we describe a method to quantify how typical or atypical the Sun is compared with other stars

Keywords: Sun, Sun–like stars, Planetary Systems, Habitability, Exoplanets

Introduction

Looking for extrasolar terrestrial planets

Eleven years ago, the first extrasolar planet around a main sequence star was found (51Pegasi) [1]. That event unleashed a planet hunting fever, making searching for exoplanets one of the hottest topics of observational astronomy. More than 200 exoplanets have been found [2], most of them in large surveys using the radial velocity technique, (e.g. California and Carnegie Planet Search Project, [3]). The radial velocity or Doppler method involves measuring the variations an orbiting planet causes on the host star's line–of–sight velocity. These variations are derived from the displacement in the star's spectral lines. The radial velocity technique is, however, biased toward discovering high mass and short period planets [4] "hot jupiters", which are probably uninhabitable. The interest of planet searchers and the public has shifted to low mass terrestrial planets. This interest is driven by the desire to find habitable planets, and even life. Therefore, the next generation of planet searches will be focused on the detection of these terrestrial planets. We are thus most interested in those terrestrial planets orbiting within the Continuous Habitable Zone (CHZ), which is the range of orbital radii where liquid water on the surface of a planet can exist for several billion years [5]. Such planets are beyond the current detection sensitivity limits of planet finding techniques, hence none has yet been found.

Looking for another Sun

Conditions for habitability are not only determined by a planet's properties itself, they are given by the star–planet system characteristics (stellar type, planetary orbital parameters, and planetary masses). Hence, habitability is a function of both, planet and stellar properties. For example: Earth's habitability depends on a number of properties intrinsic to the Sun, or the molecular cloud that became the Sun e.g., a minimum abundance of heavy elements was needed to build it up, the solar carbon to oxygen ratio lower than one, resulted in an oxidizing rather than a reducing chemistry – allowing abundant water and silicate–rock to form. In the search for terrestrial planets around other stars, the simplest assumption is that the most Earth–like planets orbit Sun–like stars. The more a star resembles the Sun, the more solar system–like its planets might be. This idea motivated our search for solar twins – stars whose fundamental parameters (e.g. mass, effective temperature, chemical composition, luminosity and as many other observables as possible) are indistinguishable from solar values [6]. A few of these properties could be important initial conditions for the formation of stable habitable planets. To date, the two best solar twins found are 18–Sco [7] and HD 98618 [8]. They have no CHZ crossing hot jupiters around them (Marcy et al. 2005), and thus have been regarded as potential hosts to solar system like planetary systems and plausible candidates for hosting terrestrial planets in their habitable zones.

Previous Studies

Placing our Sun in context and identifying it as an anomalous or average star has proved to be a complex task. Gustafsson [9] and Gonzalez [10] have both looked at this issue. Their analyses attempted to answer the question by comparing the solar values of some observable parameters (e.g. chemical composition, mass, luminosity) to stellar values from particular samples of stars. While they agree on issues such as the Sun being moderately iron rich and more massive than most of the stars in the Galaxy, they suggest different explanations and their conclusions are somewhat incompatible.

After review of the solar mass, age, chemical composition, rotation rate, chromospheric activity and binarity, Gustafsson concludes that the Sun seems normal for its mass and age. He explains the mass and non–binarity of the Sun in anthropic terms: more massive stars would not allow the time needed for life to evolve, while a less massive star would have a lower probability of hosting planets in the habitable zone. An important suggestion drawn from this study is that since the Sun is normal, life does not need a very special environment to form [9].

After review of the solar mass, chemical composition, photometric variability, chemical composition and space motion (galactic velocities), Gonzalez found the Sun to be anomalous in most of the observed parameters: The Sun is more luminous than 88% of the stars within 10 parsecs. The Sun's photometric variability appears to be smaller than stars with a similar level of chromospheric activity. The Sun is oxygen–rich and carbon–poor and hence has a relatively small C/O ratio. The orbit of the Sun around the Galaxy has lower eccentricity and a smaller maximum distance from the galactic plane than most nearby F and G stars. Gonzalez proposes that these anomalies are explained by the anthropic principle; they were necessary for our existence [10]. Gonzalez argues that a G dwarf (such as the Sun) has better chances of being habitable than a K or M dwarf. Therefore, because stars more massive than the Sun do not live long enough to support the evolution of complex life and the Sun is among the 9% most massive stars in the neighbourhood, Gonzalez concludes that less than 9% of the nearby stars have masses within the habitable mass range.

Gustafsson [9] and Gonzalez [10] come to different conclusions regarding the Sun's typicality despite using a similar approach. While Gustafsson classifies the Sun as a normal star for its mass, Gonzalez finds the Sun to be anomalous and explains these anomalies as requirements for habitability. These studies have a black or white classification of the Sun for each parameter observed (i.e. either typical or atypical). Overall, Gustafsson suggests the Sun is a typical star while Gonzalez suggests the opposite. Here we describe a method to resolve this important issue by quantifying how atypical the Sun is, not whether it is or is not typical.

Methodology

To estimate how typical or atypical the Sun is compared other stars, solar values should be compared to a representative sample of stars. That is, for each parameter, how many standard deviations the Sun is from the mean of this stellar sample needs to be determined. By doing this comparison with a dozen or so parameters, a χ^2 analysis can quantify the degree of anomaly that the Sun displays. For example, imagine that life on Earth were uranium based, and that the Sun was anomalously rich in uranium compared to other stars. We would then expect a high abundance of uranium in a stars to be a prerequisite for life.

Here we list a few stellar parameters with a brief description of their possible implications for habitability. Some stellar parameters are intrinsically dependent on others. Identifying this is needed to know the number of independent degrees of freedom.

• Mass, Luminosity and Temperature: The luminosity and effective temperature of star are two of the easiest stellar properties to derive. They determine its spectral class and therefore its position in the Hertzsprung–Russell diagram. However, they both depend on how massive the star is. Mass and age determine the luminosity and effective temperature at any given moment throughout the star's lifetime. The initial mass alone will dictate how long the star shines with roughly constant luminosity (main sequence phase).

• Age: The age determination method introduces inherent uncertainties: well–determined stellar ages can only be deduced for old stars [11; 12]. Therefore, in samples of stars with well–determined ages, there is a clear over–representation of old stars. This prevents correct estimates of how much older or younger the Sun is with respect to an unbiased sample of stars.

• Orbital Parameters and Galactic Velocities: The Galactic velocity components of a star (U,V and W), eccentricity, minimum galactic radius and maximum distance from the galactic plane are related to each other. Gustafsson [9] and Gonzalez [10; 13] suggest that eccentricity and distance to the galactic plane could be related to habitability – large eccentricities being responsible for allowing a star to orbit closer to the galactic centre, where the danger of supernovae blast waves and cosmic, gamma and X–ray radiation increases considerably (see [14] and references therein for a quantification of the danger posed by supernovae). Also, the periodicity of the passage of the Sun through the thin disk, could be associated with perturbations of Oort cloud objects that can hit Earth and cause mass extinction of varying severity [15].

• Chemical Composition: The amount of heavier–than–helium elements in a star is one of the most important factors for planet formation. The solar system's terrestrial planets are depleted in volatile elements while their refractory abundances closely resemble the solar refractory abundances. Likewise, the abundance patterns in extrasolar terrestrial planets will match those of their host stars [16]. When comparing stellar to solar abundances, abundances derived in a differential approach cancel out basic deficiencies of the analysis. For example, the assumption of Local Thermodynamic Equilibrium LTE (when corrections for non–LTE effects are not available) cause an equal offset in the elemental abundance determinations for both, the Sun and stars. This offset is cancelled out in F, G and K dwarfs when the stellar abundances are expressed relative to solar [17]:

$$[X/H] = log(X/H)_{star} - log(X/H)_{sun} \qquad (1)$$

• Elemental Abundance Ratios: The composition and chemistry of the planets determined by the initial elemental composition of the protoplanetary disk can be expressed as elemental abundance ratios. Different elemental ratios of a host star produce different compositions and chemistries of its terrestrial planets. The carbon to oxygen ratio (C/O) is the most significant; if the C/O ratio is larger than one, oxygen will pair up with carbon, forming carbon monoxide, which will be driven away by the stellar wind. In this oxygen–depleted scenario, planets will be mostly composed of carbon compounds, e.g. silicon carbide [18]. Despite the importance of the C/O ratio, the available stellar oxygen and carbon abundance data is limited. This is due to the thermal sensitivity of the OI infrared triplet line at 7775Å and the CI line at 6587Å which make these abundances amongst the hardest to determine accurately [19; 12; 20].

• Stellar Activity: Radick [21] and Gustafsson [9] find that the Sun's photometric variability is relatively low for its level of chromospheric activity. Gustafsson reported that the chromospheric activity seems typical for stars with solar age and rotation. Leitzinger et al. [23] stress the relevance of stellar activity and its possible connection to habitability. They propose levels of coronal mass ejections as another determinant of habitability.

• UV Radiation Environment: Early UV radiation from young stars is more intense, and thus can play an important part in the formation of early atmospheres and the evolution of life [23]. Stellar rotation and/or activity may be a currently observable proxy for the Sun's early solar system UV environment [23].

Ideally, all the observable properties of the Sun should be compared to an unbiased sample of stars. However, limited observational capabilities and resources make the selection of datasets and parameters a non–trivial process. To allow a consistent comparison between the results obtained by different studies (e.g. metallicities reported by Nördstrom [11] and Valenti [24]), special attention must be paid to the details of sample selection effects, systematic errors and calibration methods.

Conclusion

In our search for extrasolar worlds, we want to know how special stars with habitable planets are. Whether the Sun is or is not a random star, might reveal which stellar properties are related to habitability. Previous studies have addressed the issue and come to somewhat contradictory results. Here we present the idea of how to quantify how typical or atypical the Sun is compared to a representative sample of stars in the Galaxy.

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