DE GRUYTER Open Astronomy 2025; 34: 20250017

Research Article

Péter Futó* and Arnold Gucsik

The stellar Mg/Si, C/O, Ca/Si, Al/Si, Na/Si, and Fe/Si ratios and the mineral diversity of rocky exoplanets

https://doi.org/10.1515/astro-2025-0017
received August 21, 2024; accepted June 13, 2025

Abstract: The bulk planetary compositions are thought to be consistent with the chemical abundances of their host stars. The abundances of eight key rock-forming elements and the key planetary abundance ratios in G- and F-type main sequence stars located in the solar neighborhood within 50 pc were statistically analyzed. The averaged C/O, Mg/Si, and Fe/Si elemental ratios of the planetary systems play a crucial role in the chemical composition and mineralogy of a rocky planet's interior. We also investigated the variation of the calculated Ca/Si, Al/Si, Na/Si, and Fe/Si ratios in the samples of the examined stars utilizing the Ca, Al, Na, and Fe abundances from the catalog and then attempted to establish plausible occurrence trends of the analyzed abundance ratios for the rocky planet population at near-solar galactocentric distances. Considering these results, we provide simple predictions for the most likely bulk compositions of the potential rocky planets. We apply our results to compare them to the solar averaged abundance ratios, showing that the key elemental ratios for terrestrial planet composition in the Solar System are not typical among most of the studied stellar samples.

Keywords: stellar element abundance, elemental ratio, rocky planet, solar, mineralogy, G-type spectral star, F-type spectral star

1 Introduction

1.1 The chemical composition of the stars and their planets

The variability in stellar elemental ratios, such as Mg/Si, C/O, Ca/Si, Al/Si, and Na/Si, can lead to significant differences in the mineral assemblages of rocky exoplanets (Bond *et al.* 2010). This variation may ultimately restrict the formation of certain minerals, thereby influencing the geological and potentially biological evolution of these planets, as evidenced by the less diverse mineralogy on Mars compared to Earth, resulting from the absence of specific mineral-forming processes tied to elemental ratios and geodynamic activity (Ehlmann and Edwards 2014, Hazen *et al.* 2023, Russel and Ponce 2020).

Since host stars and their planets form within the same parts of the molecular cloud, there is a relationship between the chemical compositions of the stars and their orbiting planets. CI-chondrite abundances and the Earth's relative bulk composition of major rock-forming elements are close to that of the Sun (Lodders 2003, Wang *et al.* 2019). Space-based (Kepler, TESS) and ground-based exoplanet surveys (HARPS) have revealed many dependencies between the characteristics of exoplanets and the physical properties of their host stars (Cabral *et al.* 2019). Previous studies have demonstrated that giant planets are more frequent around high-metallicity stars (Gonzalez 1997, Santos *et al.* 2004, Fischer and Valenti 2005, Johnson *et al.* 2010). The iron abundance of host stars does not play a determining role in terrestrial planet formation; small planets could form even around metal-poor stars (Ida and Lin 2004). Adibekyan *et al.* (2015) found that low-mass planet host stars have higher Mg/Si ratios than giant planet hosts. This result indicates that the Mg/Si ratio plays an essential role in rocky planet formation. The mass abundances of refractory elements (Mg, Si, and Fe) are significant in the planet formation conditions (Adibekyan 2017). The Mg/Si mineralogical ratio is slightly higher

---

*** Corresponding author: Péter Futó,** Cosmochemistry Research Group, Department of Mineralogy and Geology, University of Debrecen, Egyetem tér 1, Debrecen, H-4032, Hungary, e-mail: orionp0077@gmail.com
Arnold Gucsik: Department of Physics, Eszterházy Károly Catholic University, Széchenyi tér 1, Eger, H-3300, Hungary

for host stars with detected low-mass planets than for non-host stars (Adibekyan *et al.* 2015, 2017). Other elements (Ca, Al, Na) are also important factors for the bulk compositions of terrestrial planets. As presented by Haywood (2008) and Adibekyan *et al.* (2012a, b), the iron-poor planet-hosting stars exhibit an enhancement of α-elements, and it can also be observed that low-mass planets can form at a wide range of metallicities (Buchhave *et al.* 2012). Previous studies in this area have focused mostly on the C/O, Mg/Si, and Fe/Si abundances of F-, G-, and K-type stars. In contrast, this study not only focuses on C/O, Mg/Si, and Fe/Si ratios, but it also statistically analyzes the mean values of Ca/Si, Al/Si, and Na/Si abundance ratios, which are also essential factors concerning the mantle and crustal mineralogy of rocky planets. An abundance analysis for the set of C/O, Mg/Si, Ca/Si, Al/Si, Na/Si, and Fe/Si ratios can provide not only more information on the chemical features of G- and F-type solar neighborhood stars but also an overall picture of the mineral diversity of their potential rocky planets. The study of the stellar abundance ratios of key rock-forming elements may bring us closer to an estimation of how typical the solar set of key elemental ratios is among the analyzed stellar patterns.

The most important mineralogical ratios are the C/O, Mg/Si, and Fe/Si, which determine the structural properties and bulk chemical compositions of rocky planets. The C/O ratio determines the distribution of silicon between carbide and oxide mineral constituents. The Mg/Si ratios determine the silicate mineralogy, and the relative sizes of planetary cores depend on the Fe/Si ratio. Putirka (2024) suggests that the (Mg + Fe)/Si ratio in the mantle provides a more precise classification than Mg/Si. The solar C/O and Mg/Si values are 0.54 and 1.05 (Asplund *et al.* 2005, 2009). Several extrasolar planetary host stars have been found to have relatively high C/O values above 0.8 (Fortney 2012, Brewer and Fisher 2016).

The terrestrial planets of these stars are different in composition from the Solar System bodies, and they have C-rich mineralogy with a large number of carbon-enriched mineral species (SiC, TiC, Fe_3C, graphite, *etc.*). The idea of the potential existence of carbon-rich planets has been derived from Kuchner and Seager (2005), who demonstrated that most C-rich planet-hosting stars can be found in the galactic bulge.

For an Mg/Si ratio ranging from 1 to 2, planetary building blocks are made from the combination of olivine and pyroxenes, which are distributed by the Mg/Si ratio. For Mg/Si values above 2, all Si is built into olivine (Mg_2SiO_4), and the excess Mg constitutes MgO or MgS (Bond *et al.* 2010). The transition zone of Mg-rich rocky planets may be dominated by olivine and ferropericlase (Fp). Inside the water ice line, the $Mg_2SiO_4/MgSiO_3$ in building rocks of rocky planets increases with increasing Mg/Si of host stars, which scales with [Fe/H] (Bitsch and Battistini 2020).

A broad range of metallicities and the variability of abundances of key rock-forming elements in planet-host stars are thought to yield a high mineralogical diversity in the rocky planet population of the Galaxy. Studying the distributions of the key elemental abundance ratios, the explored compositional diversity can provide information about how common the relevant Solar System abundances and the Earth's mineralogy are within our Galaxy.

More recently, Zhao *et al.* (2022), Rensen *et al.* (2023), and Sandora *et al.* (2023) described chemical evolution models using ion abundances for the Solar Wind, as well as planetary atmospheres such as Jupiter and the exoplanets.

1.2 Great mineralogical diversity for the rocky planet population

The composition of rocky exoplanets is a key factor in determining their mineral diversity and potential habitability. This mineral diversity is critical because it impacts not only the planet's surface geology but also its atmospheric and potential biochemical processes, akin to the mineral evolution observed on Mars, where differing elemental compositions lead to distinct mineral formation pathways and, consequently, diverse planet surfaces (Hazen *et al.* 2023).

The study of the spectroscopically determined elemental abundances of stellar photospheres provides insight into the bulk mineral composition of rocky planets. Bedell *et al.* (2018) found that the C/O and Mg/Si ratios of stars in the solar-metallicity range are homogeneous within 10% in the solar neighborhood. It may be implied that the terrestrial exoplanets have a low compositional diversity. At the same time, more studies show that there is a relatively high diversity in stellar Mg/Si and C/O elemental ratios (Fortney 2012, Delgado-Mena *et al.* 2010, Carter-Bond *et al.* 2012a). Bond *et al.* (2010) and Carter-Bond *et al.* (2012b) also suggest that a diverse range of terrestrial planetary compositions may exist within exoplanetary systems. Not only is the diversity of planetary bulk chemical composition relatively high, but also a moderately diverse range of mass-radius relations of solid exoplanets is also observable in the thin disk stellar populations of the Galaxy (Michel *et al.* 2020). The galactic chemical evolution (GCE) can considerably shape the resulting planet population (Nielsen *et al.* 2023). Previous studies highlight the importance of the planetary compositions for planet habitability, as known on Earth, since a planet's chemistry and mineralogy are crucial for the existence of plate tectonics (Stamenković and Seager 2016, Unterborn *et al.* 2017).

Many publications deal with the conditions of plate tectonics on massive rocky planets (O'Neill and Lenardic 2007, Valencia and O'Connell 2007, Korenaga 2010, Stein *et al.* 2011, Stamenković *et al.* 2012, Tackley *et al.* 2013). The planetary mass and composition, structural properties, adequate pressures, temperatures of rocky planet interiors, and plate mobility, as well as the characteristics of mantle convection, can be the essential conditions for plate tectonics on rocky exoplanets.

Note that the presence of light alloying elements such as sulfur strongly affects the melting temperature of iron (Fischer *et al.* 2013). In this manner, the number of light elements is an essential factor for the thermal evolution of terrestrial planetary cores, which is closely related to the existence of the magnetic field and the thermal evolution of the mantle. The view that plate tectonics might be a crucial factor for the formation and evolution of life on terrestrial exoplanets is widespread.

Studying the stellar abundances of key rock-forming elements can help to estimate the occurrence of plate tectonics in the Galaxy. We focus on the assumed optimal ranges of C/O, Mg/Si, and Fe/Si elemental abundance ratios, in which the likelihood of compositionally favorable conditions can be optimal for the tectonic processes on rocky planets.

The Martian mantle is likely composed of olivine and its higher-pressure phases, garnets, and pyroxenes. Similarly, the conditions of rocky planets can also be diverse in planetary systems and the Galaxy. It is necessary to consider that the bulk Mg/Si ratios of rocky planets in the planetary systems are not significantly different from the Mg/Si abundances of their host stars.

Carbon planets cannot be ideal candidates for sustaining efficient mantle convection over long periods, owing to the high thermal conductivity and viscosity of the carbon-rich mantle, which consists of various materials. Plate tectonics on carbon planets is less likely than on silicate planets, which can form under chemical conditions in a low-C/O regime (Stamenković and Seager 2016). Thus, we selected those G- and F-stars from the sample that have C/O values lower than 0.65. These relatively low-C/O stars have been further selected based on the Mg/Si values ranging from 1 to 2.

Experiments confirm that the viscosity of iron-rich ferropericlase (Fp) (Mg, Fe) O is reduced under the lowermost mantle conditions of Earth (Reali *et al.* 2019). Note that the rheological behavior of Fp may strongly influence the viscosity structure in the lower mantle zone of terrestrial planets, which are more massive than Earth and have a higher bulk Mg/Si ratio. Stamenković and Seager (2016) suggest that those terrestrial exoplanets that form in protoplanetary disks with a high concentration of Si and Na abundances are unlikely to sustain long-term, steady-state plate tectonics. Researchers find that the bulk planetary composition, with lower alkali and Si abundance, results in more mobile tectonic plates, which are most likely to sink into the asthenosphere. In contrast, the alkali and silica enrichment in the crustal material can yield an immobile top layer, which is unlikely to sink. The alkali- and Si-rich outermost solid layer of terrestrial planets is similar to the highly positively buoyant continental-type crust on Earth, which may not be able to subduct efficiently.

The solar C/O and Mg/Si ratios seem to be favorable for at least one planet for plate tectonics and habitability in the Solar System. The study also focuses on the solar-identical C/O and Mg/Si values in the dataset of the analyzed stellar elemental ratios.

1.3 The great compositional diversity of rocky planets and plate tectonics

We present our results for the examined chemical properties of the selected G- and F-stars located within 50 pc of the Sun. Several members of the analyzed sample are Sun-like stars, but all objects in the set of main-sequence stars have metallicities relatively close to the solar value.

We briefly discuss the collation of the abundance data and the methodology of calculating abundance ratios. We show that the variability of the abundance ratios of Mg/Si, C/O, Ca/Si, Al/Si, Na/Si, and Fe/Si may result in a relatively high diversity in the bulk mineralogy of rocky planets. In addition, more categories of the examined star samples need to be established on whether the distribution of analyzed key elementary ratios for rocky planets exhibits similar abundance trends in G- and F-stars for the full available range of C/O ratios, the low-C/O range (<0.65), and stars that are known to be orbited by planets. We compare the obtained trends in different ratio ranges to the solar relevant values for a better understanding of how rare the set of six solar elemental ratios is amongst the G- and F-type stars in the solar neighborhood within 50 pc. We discuss the implications of the likely atypical features of the Solar System's bulk chemistry in key planet-building elements.

The important purpose of this study is to investigate how the variability of stellar Mg/Si, C/O, Ca/Si, Al/Si, Na/Si, and Fe/Si ratios can affect the mineral diversity of rocky planets in the solar neighborhood. Another main goal is to analyze the distribution of relevant elementary ratios to reveal the extent of compositional diversity of rocky planets, and we attempt to estimate how unique the bulk mineralogical composition of the Earth can be.

2 Methods

2.1 Stellar elemental abundances and star samples

We utilize the sample of selected elemental abundances of main-sequence G- and F-spectral type stars located within 50 pc of the Sun, which have been derived from the stellar element abundance database of the Hypatia Catalog (Hinkel *et al.* 2014). The Hypatia Catalog is a compilation of spectroscopic abundance data derived from 294 literature sources for 102 elements for stars within 500 pc of the Sun. For the selection and the filtering of the data of G- and F-type stars from the catalog, we set constraints on the distance of stars from the Sun (within 50 pc), their spectral type (G1–G9 and F1–F9), and required that they belong to the Galactic thin disk.

This work provides chemical abundances and abundance ratios of six refractory elements (Mg, Si, Fe, Ca, Al, Na) and two volatile elements (C, O) for G- and F-spectral type main-sequence stars. After filtering the data, more selection criteria have been applied for the scheme of star lists, for instance, the distances of stars from the Sun, close-to-solar metallicity, and all stellar elemental abundances in the source database for the studied elemental ratios. The final stellar samples for analysis consist of 512 G-type and 258 F-type stars. The examined samples contain thin disc stars, which have been observed by high-resolution spectroscopic surveys. The G-dwarf stars ($4{,}900 < \mathrm{Teff} < 6{,}400$ K) can be found in the metallicity range of $-0.9 < [\mathrm{Fe/H}] < +0.6$. The F-type main-sequence stars ($5{,}700\ \mathrm{K} < \mathrm{Teff} < 7{,}200$ K) belong to the metallicity range of $-0.8 < [\mathrm{Fe/H}] < +0.6$.

Planet-hosting stars have also been collected in the samples, which have been discovered up to October 15, 2023 (NASA Exoplanet Archive). Seventy-nine host stars have been identified in the sample of G-stars, and 13 hosts have been found among F-stars.

2.2 Statistical modeling

Since the compositions of forming rocky planets depend on the chemical compositions of the galactic environment in which they formed, thus, the distribution trends and the mean values of the analyzed elemental ratios can only be used to explore the bulk chemical properties of the rocky planets. In this context, the results of the analyses will be applicable in the Galactic thin disk within about a few hundred parsecs from the Sun.

Both the known planet-host stars and the non-host stars were also examined in the same way, using the concerning data of elemental ratios in two analyzed C/O ranges ($0 < \mathrm{C/O} < 1.31$ and $\mathrm{C/O} < 0.65$). Bulk mineralogies richer in oxygen-bearing phases than those of Solar System terrestrial planets could form in planetary systems with an average C/O ratio lower than solar ($\mathrm{C/O} < 0.54$). Accordingly, a value of $\mathrm{C/O} = 0.5$ was selected for the analysis, and the distributions of C/O ratios below 0.5 have also been examined in both stellar samples. Oxygen-rich bulk mineralogy could be formed in low C/O planetary systems; thus, the distributions of C/O ratios below 0.5 have also been analyzed in both star samples. It is necessary to compare the mean value of six abundance ratios of known planet-host stars with the ratios of non-host G- and F-type stars. Additionally, it needs to give a comprehensive image of the common, the rare, and the exotic bulk mineralogy of the potential rocky planet population. It is also examined how the demonstrated compositional diversity affects the frequency of plate tectonics on low–mass rocky planets.

We study plausible linkages between the distributions of stellar abundance ratios of the analyzed major rock-forming elements. Distances, properties of the galactic disk and the spectral types of the sample stars have been obtained by using the stellar properties option in the database of the Hypatia catalog. Eight elemental ratios of the stars have been collected and indexed to compute the six key planetary elemental ratios. The Sun (C, O, Mg, Si, Ca, Al, Na, and Fe = 0.00 dex) is the reference star for elemental abundances. $N_1/N_2 = SVN_1/N_2\{\log_{10}[X_1/H]/\log_{10}[X_2/H]\}$ with units in mol, where SVN_1/N_2 is the solar value of the given elemental ratio, $[X_1/H]$ and $[X_2/H]$ are the abundances for the given elements index.

After computing the Mg/Si, C/O, Ca/Si, Al/Si, Na/Si, and Fe/Si molar ratios, we calculated the mean values for all in the sample. Furthermore, we have plotted the supersolar (higher-than-solar), solar identical, and subsolar (lower-than-solar) values, comparing with each the Mg/Si ratio, the carbon-to-oxygen ratio, Ca/Si, Al/Si, Na/Si, and Fe/Si ratios for analyzing their distribution. Based on the data of Asplund *et al.* (2005, 2009), the molar values of the solar Ca/Si, Al/Si, Na/Si, and Fe/Si ratios are 0.0631, 0.0724, 0.0457, and 0.87, respectively.

To describe the plausible bulk chemical and mineralogical composition of the potential planets of the sample stars, we focus on the obtained mean values of the six elemental ratios. For simplicity, we mainly focus only on those constituents, which may be the characteristic mineral components in the mantle and crust of rocky planets, while several minor accessory minerals have also been considered.

Moreover, we focus on solid planetary building blocks that formed around the potential host stars in the region of terrestrial planet formation inside the water ice line.

In the statistical modeling, the variability of elemental ratios is being considered in the metal-poor and metal-rich regimes of the studied metallicity range. Since elemental abundances vary with the overall metallicity of stars, this also implies that, for example, the Mg/Si and Al/Si ratios are expected to be correlated. After determining the elemental abundance ratios, a simple linear regression analysis was conducted for the Mg/Si and Al/Si ratios within the sample of G-type stars, potentially indicating a correlation between these two ratios.

2.3 Effect of the errors and uncertainties

Differences can arise between data sets from abundance measurements and determinations, which may have been caused by the following factors: resolution of the spectra, LTE- or non-LTE analysis, instrumental limitations, and errors in specific optical systems. The LTE (Local thermodynamic equilibrium) and non-LTE (non-local thermodynamic equilibrium) abundance analyses are different approaches for determining the composition of stars. The variation of the source stellar abundance catalogs has a mean of 0.14 dex and a median of 0.11 dex for all elements in all stars in the Hypatia catalog (Hinkel *et al.* 2014). Moreover, the calculations of elemental ratios have ±0.005 uncertainties in molar values.

All of the results of abundance analyses in this study are based only on statistical approaches. However, the revealed trends and relations can be used to make reasonable predictions for the expected occurrence of the different bulk chemical compositions of planetary systems.

2.4 Favorable stellar abundances for plate tectonics

To investigate the favorable range of stellar C/O and Mg/Si abundance for plate tectonics, we focus on the influence of the characteristic mineral components in the mantles of rocky planets on the viscosity regime, which is a key factor controlling the efficiency of mantle convection.

Carbon planets are unable to sustain long-term plate tectonics, unlike silicate planets, due to the high viscosity of their carbon-dominated mantles (Stamenković and Seager 2016). Therefore, the stellar C/O values favorable for active geodynamics are expected to be lower than 0.65, below which silicate-dominated planets may form in protoplanetary disks.

A low Mg/Si ratio (<1) may lead to a more viscous mantle due to the dominance of pyroxenes (Spaargaren *et al.* 2020), while a high stellar Mg/Si ratio (>2) resulting in a high bulk planetary Mg/Si ratio can produce a thick lithosphere that resists subduction (Bond *et al.* 2010). Accordingly, the estimated favorable range of stellar Mg/Si values for plate tectonics is approximately between 1 and 2.

For a more accurate assessment, other parameters – primarily planetary mass – must also be considered. The efficiency of plate motions and subduction is expected to increase with planetary mass (Valencia and O'Connell 2007). However, previous modeling studies (Miyagoshi *et al.* 2015, 2018) suggest that rocky planets more massive than ~4 Earth masses are unlikely to exhibit plate tectonics due to a large viscosity contrast throughout the mantle and the formation of a thick, stagnant lithosphere.

Based on Earth's example, it is known that an Earth-mass planet can sustain plate tectonics over geological timescales, provided that the necessary conditions are met. It implies that the favorable planetary mass range for plate tectonics is likely between approximately 1 and 4 Earth masses.

Taking into account the ranges of C/O and Mg/Si elemental ratios considered most suitable, we attempt to estimate the expected proportion of planetary systems in our galactic environment that may host rocky planets with conditions sufficient for the operation of plate tectonics, based on the distribution of the studied elemental ratios.

3 Results and discussion

We find that the variability of Mg/Si, C/O, Ca/Si, Al/Si, Na/Si, and Fe/Si ratios results in moderately high diversity in terms of the bulk elemental composition and mineralogy in potential rocky planets for both G- and F-type stars.

3.1 Distribution of the key elemental ratios in the fully examined C/O range

The number of G-stars and F-stars with calculated Mg/Si, Ca/Si, Al/Si, and Na/Si ratios in the sample of the full examined C/O range (0–1.31 for G-stars, 0–1.18 for F-stars) is 512 and 258, respectively. The calculated Fe/Si ratios are 501 and 258 for G- and F-stars.

Figure 1a and b presents the mean values of six key abundance ratios for G-and F-stars, while Figure 2a and b shows the number of super-solar, solar identical, and subsolar values for six analyzed ratios in the G- and F-star samples. The obtained distributions indicate that most G- and F-type stars with subsolar C/O and super-solar Mg/Si ratios exhibit Ca/Si, Al/Si, and Na/Si ratios that are higher than the relevant solar values. The solar set of the six analyzed elemental ratios does not belong to the common patterns of the analyzed stellar elemental ratios; accordingly, the solar pattern of six elemental ratios seems to be atypical for the population of G- and F-type stars within 50 pc in the solar neighborhood.

The abundance variations of essential rock-forming elements can yield many mineral species, increasing the diversity of crustal and mantle mineralogy in the galactic rocky planet population. Not only do the physical and

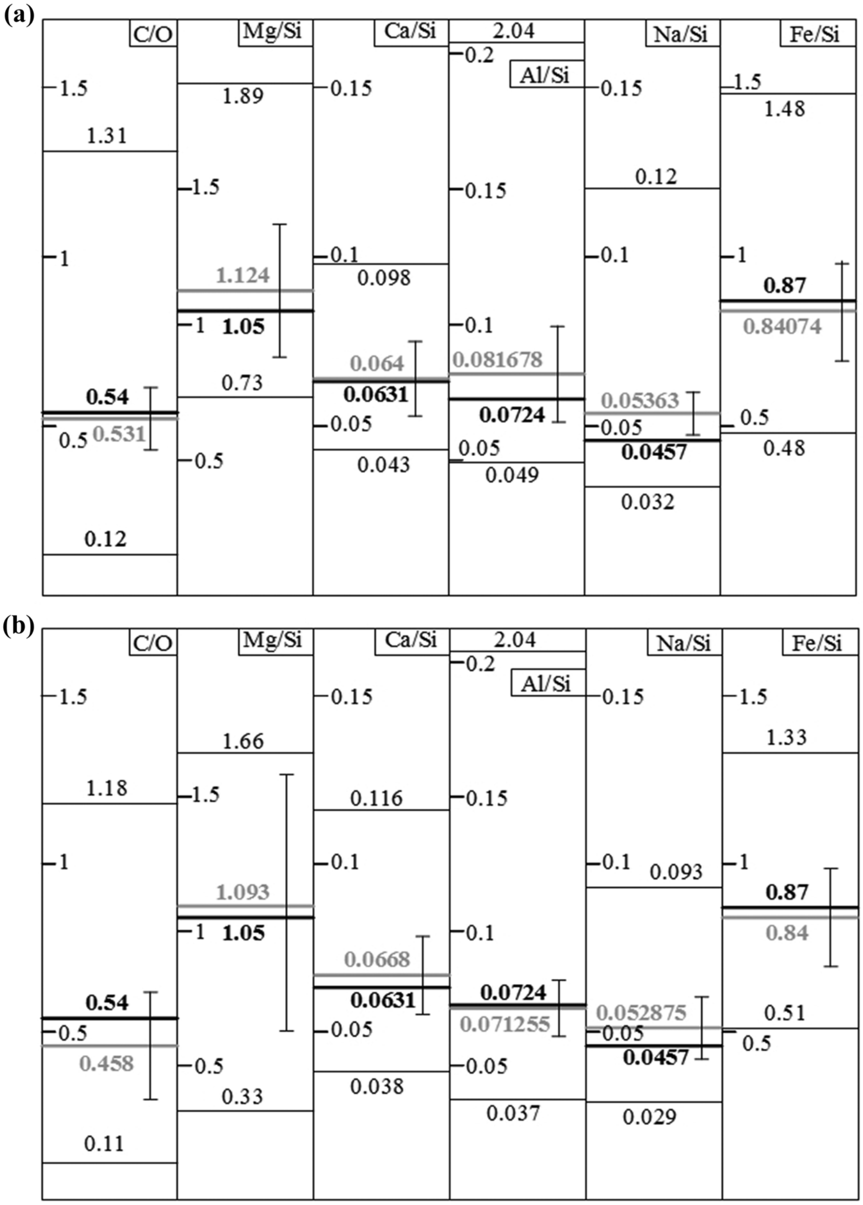

Figure 1: (a) Mean values for the abundance ratios of C/O, Mg/Si, Ca/Si, Al/Si, Na/Si, and Fe/Si (denoted by gray lines) in G-type stars for fully analyzed sample, relative to the relevant solar average values (denoted by black lines). Standard deviations are shown in the figure. (b) Calculated mean values for C/O, Mg/Si, Ca/Si, Al/Si, Na/Si, and Fe/Si abundance ratios (denoted by gray lines) in F-type stars for a fully analyzed sample. Reference values of the relevant solar abundance ratios are indicated by black lines. Standard deviations are shown in the figure.

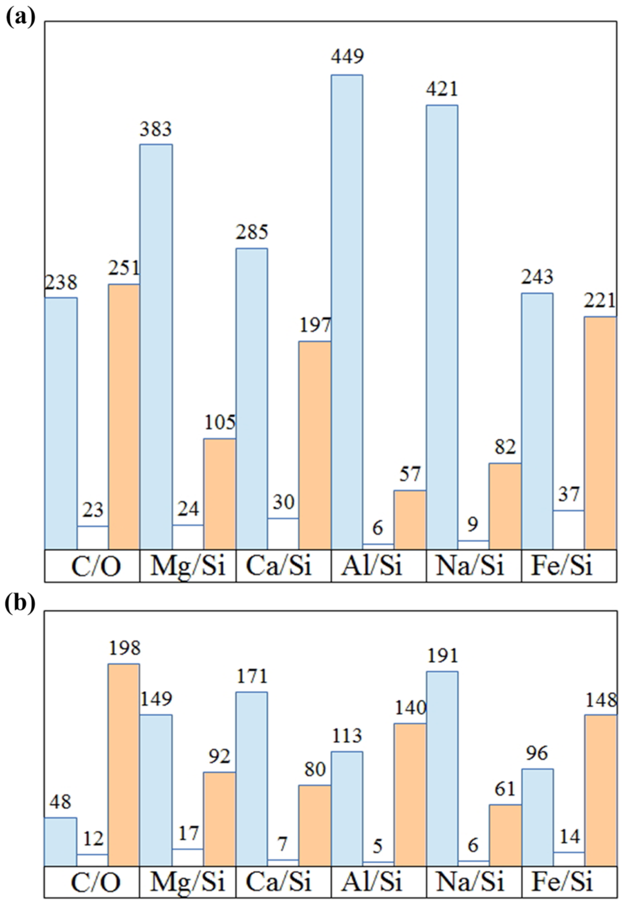

Figure 2: (a) The number of G-type stars for the full analyzed sample in the supersolar (blue column), the solar identical (empty column), and the subsolar (orange column) ranges of six analyzed elemental ratios. (b) The number of F-type stars for the full analyzed sample in the supersolar (blue column), the solar identical (empty column), and the subsolar (orange column) ranges of six analyzed elemental ratios.

chemical processes, but also the biological processes, play an important role in the origin and evolution of minerals on Earth. Biological processes can increase mineral diversity, as known on Earth. Note that Hazen and his colleagues (Hazen *et al.* 2015) concluded that Earth is unique in its mineralogical composition. The C/O ratios of host stars do not exhibit in all cases a strong correlation with the bulk C/O ratios of their rocky planets (Thiabaud *et al.* 2015). However, the bulk refractory element ratios of rocky exoplanets directly correlate with the host star refractory ratios (Mg/Si, Fe/Si) (Valencia *et al.* 2010). A previous study found that Mg-depleted and Ca-, Al-enriched silicate planets can frequently be formed around low-Mg/Si stars.

As shown in Figure 1a and b, most G- and F-stars with higher Mg/Si values than solar exhibit higher-than-solar mean Ca/Si, Al/Si, and Na/Si values, and they can be characterized by super-solar Ca/Si, Al/Si, and Na/Si ratios, respectively. Super-solar, solar identical, and sub-solar values of Ca/Si, Al/Si, and Na/Si ratios for 375 stars with super-solar Mg/Si ratios have been plotted in Figure 3.

As seen in this plot, most relatively high Mg/Si G-stars also exhibit super-solar Ca/Si, Al/Si, and Na/Si abundance ratios, indicating that the potential rocky planets in high-Mg/Si systems around G-stars are expected to be enhanced in calcium, aluminum, and sodium-bearing minerals compared to planets in lower Mg/Si planetary systems.

Most previous compositional models describe simplified mineralogy for terrestrial exoplanets with pure or Fe-dominated metallic cores and magnesium-silicate mantles (Seager *et al.* 2007, Zeng and Sasselov 2013). The bulk Mg/Si ratio with molar values ranging from 1 to 2 for an approximately Earth-mass rocky planet results in a forsterite-pyroxene upper mantle and bridgmanite-periclase lower mantle. The planetary Mg/Si ratio provides constraints on the relative proportion of main mantle-building minerals (Unterborn *et al.* 2016).

Most Mg-depleted silicate planets are expected to form in low-Mg/Si planetary systems. The Mg-depletion could lead to the formation of planets enriched in orthopyroxene ($MgSiO_3$) and feldspars (Carter-Bond *et al.* 2012b, Suárez-Andrés *et al.* 2018). The remainder of the silicon produces the coexistence of $MgSiO_3$ and SiO_2 in the interior of Earth-mass or more massive terrestrial planets (Umemoto *et al.* 2017). The lower mantle of the largest fraction of Mg-depleted silicate planets is expected to be composed mostly

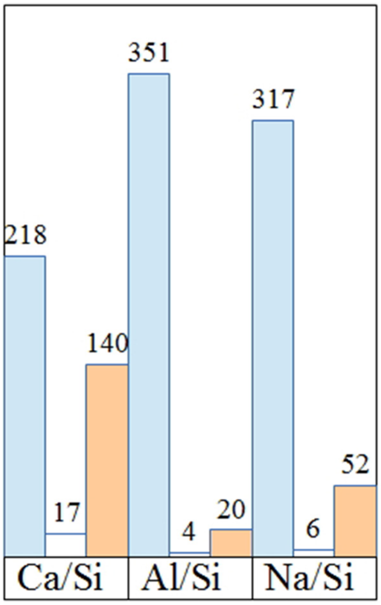

Figure 3: The number of supersolar, solar identical, and subsolar Ca/Si, Al/Si, and Na/Si ratios for higher than solar Mg/Si G-stars in the full sample.

of $MgSiO_3$ pv/ppv plus SiO_2, depending on the Mg/Si ratio. At the same time, the amount of Ca-perovskite in the lower mantle of Mg-depleted planets may be smaller than in the case of the most Mg-rich rocky planets, owing to the slightly higher-than-solar mean Ca/Si ratio of G- (0.064) and F-stars (0.0668) with higher Mg/Si ratios.

It should be noted that the possible upper mantle composition of the lowest-Mg/Si planets is dominated by garnets, diopside, and their high-pressure phases. Pyroxenes in the Earth's upper mantle are composed of three major constituents: enstatite ($Mg_2Si_2O_6$) (en), diopside ($CaMgSi_2O_6$) (di), and jadeite ($NaAlSi_2O_6$) (jd) (Gasparik 1989). The amount of enstatite is expected to decrease in a Mg-poor bulk mineralogy. Therefore, the pyroxene budget in the upper mantle of Mg-depleted rocky planets is thought to be represented by a diopside-dominated di-jd system (Futó 2022).

As shown in Figure 1a, a higher-than-solar mean Al/Si ratio (0.081678) indicates that the mineral assemblage in the upper mantle zone of the potential planets around G stars is unlikely to have a relatively large amount of Al-rich minerals compared to that of the Solar System terrestrial planets. The upper mantle of silicate planets formed in high-Mg/Si systems consists mainly of Mg- and Al-rich mineral phases (olivine, ferropericlase, spinel), and the lower mantle may contain relatively larger amounts of ferropericlase and Ca-perovskite than solar ones compared to the $MgSiO_3$ pv and ppv. The most analyzed G- and F-type stars can be characterized by subsolar C/O and supersolar Mg/Si ratios.

Figures 4 and 5 show the relative number fractions of Ca/Si, Al/Si, Na/Si, and Fe/Si values that are higher than, equal to, or lower than solar values for the studied G- and F-type stars, grouped into four categories defined by their C/O and Mg/Si ratios relative to solar averages.

For example, in the first row of the figures, the combination –C/O and +Mg/Si refers to stars with sub-solar C/O and super-solar Mg/Si ratios. Most G-type stars in this C/O–Mg/Si category exhibit super-solar Ca/Si, Al/Si, and Na/Si abundance ratios.

Figure 4 shows that Al/Si values are the largest super-solar elemental ratios for G stars; the most significant values are shown in the −C/O; +Mg/Si range and the +C/O; and +Mg/Si range. In contrast to G stars, the most super-solar ratios related to subsolar ratios in the pattern of F stars are found in the case of the Ca/Si and Na/Si values, which have also appeared in the −C/O; +Mg/Si and the +C/O; and +Mg/Si ranges (Figure 5). The proportion of the subsolar and super-solar Fe/Si ratios of G- and F-type stars is moderately variable in the different C/O-Mg/Si ranges.

Among the stellar abundance ratios of G-type stars, a strong positive correlation is observed between Mg/Si and other element ratios relevant to rocky planet formation, such as Al/Si (Figure 6c). The analysis yielded a correlation coefficient of 0.5332 (the standard error is 0.0101). This implies that silicate planets forming around Mg-rich stars are also likely to have a higher proportion of aluminum-bearing minerals in their mineralogical composition. The C/O–Mg/Si (Figure 6a) and the Mg/Si–Fe/Si (Figure 6b) regressions indicate moderately positive correlations.

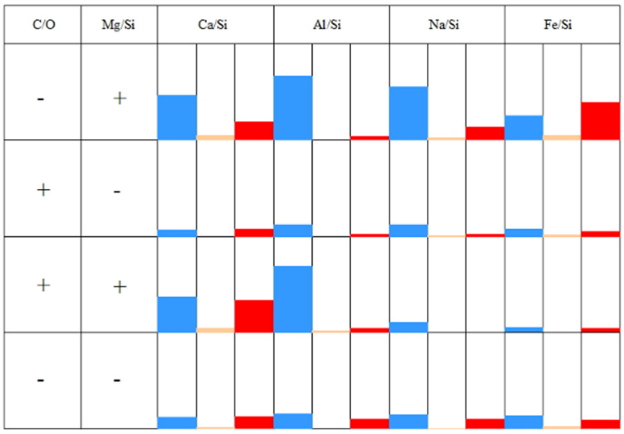

Figure 4: The averages of G-type stellar Ca/Si, Al/Si, Na/Si, and Fe/Si ratios for the cases of −C/O, +Mg/Si; +C/O; −Mg/Si; +C/O; +Mg/Si and −C/O; and −Mg/Si ranges. − and + denote the sub- and super-solar values of C/O and Mg/Si ratios. The columns of the plot: the blue color denotes the super-solar, the pink color denotes the solar-identical, and the red color indicates the sub-solar average values of the elemental ratios.

The most analyzed G- and F-type stars belong to the –C/O; +Mg/Si range, in which the number of supersolar values related to the subsolar Ca/Si, Al/Si, Na/Si, and Fe/Si ratios

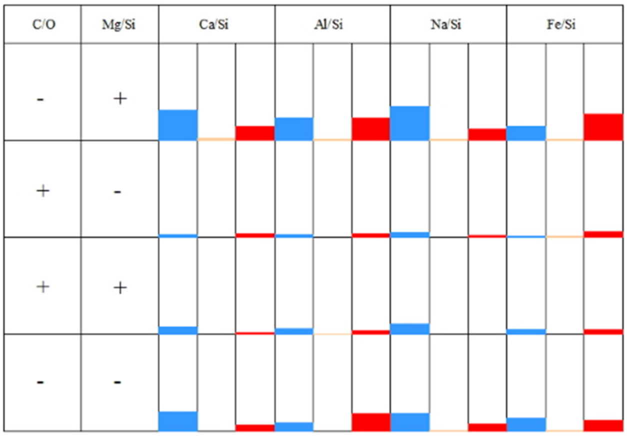

Figure 5: The averages of F-type stellar Ca/Si, Al/Si, Na/Si, and Fe/Si ratios for the cases of −C/O, +Mg/Si; +C/O; −Mg/Si; +C/O; +Mg/Si and −C/O; and −Mg/Si ranges. − and + denote the sub- and super-solar values of C/O and Mg/Si ratios. The columns of the plot: the blue color is the super-solar, the pink color is solar-identical, and the red color is the subsolar average values of elemental ratios.

exhibit similar variability for both spectral types. Based on the obtained distributions of abundance ratios, we apply a simple three-layer planetary interior model in our study. For simplicity, the three-layer models of approximately Earth-mass rocky planets (Figure 7a–d) are constructed using bulk mineralogies representing the core, upper/lower mantle, and crust, based on C/O and Mg/Si ratios as well as astrochemical considerations. In terms of the mass–radius relationship, rocky exoplanets that are close in mass and size to Earth can exhibit a strong compositional correlation (Zheng *et al.* 2016). These planets resemble Earth in bulk composition and may have similar interior structures. The most likely major mineral constituents for rocky planetary mantles across the main C/O and Mg/Si ranges are summarized in Figure 8. Several predictions for plausible bulk mineral compositions have been adopted in this study from the literature. Specifically, the results of Seager *et al.* (2007) and Zeng and Sasselov (2013) are used to model mantle mineralogy for bulk Mg/Si ratios ranging from 1 to 2 and above 2, while studies by Carter-Bond *et al.* (2012b), Futó (2022), and Suárez-Andrés *et al.* (2018) provide relevant data for the mantle mineralogy of Mg-depleted silicate planets under carbon-poor conditions. Mainly basaltic crust, forsterite-pyroxene upper mantle, and bridgmanite-dominated and ferropericlase-rich lower mantle have been predicted in most cases for the Earth-sized or slightly smaller potential rocky exoplanets in the solar neighborhood. The proportion of the subsolar and supersolar Fe/Si ratios of G- and F-type stars is moderately variable in the different C/O–Mg/Si ranges. The mean stellar Fe/Si values are lower than the Solar System averaged iron-to-silicon ratio (as seen in Figure 1a and b). Mg/Si, Fe/Si, and C/O ratios can be used to constrain the planetary internal structure and chemical composition of terrestrial planets (Bond *et al.* 2010, Dorn *et al.* 2015). Iron mass fractions of rocky planets are in good agreement with the iron abundance of host stars; the relative Fe-abundance of the Sun can be used to infer the iron mass fraction of Venus, Earth, and Mars (Santos *et al.* 2015). The Fe/Si distributions of stars can be used as a proxy for predicting the iron mass fractions of potential planets around solar-like stars. As Fe is the main elemental building block of the metallic core and Si is one of the most abundant elements in the mantle of silicate-dominated planets, the planetary Fe/Si ratio provides constraints on the mass ratio of the mantle to the core (Unterborn *et al.* 2016). As shown in Figure 1a and b, the mean values of the Fe/Si ratio are found to be smaller than solar around G- and F-stars, providing information about the iron mass fractions of their potential rocky planets. Most terrestrial exoplanets may have an Earth-like or smaller

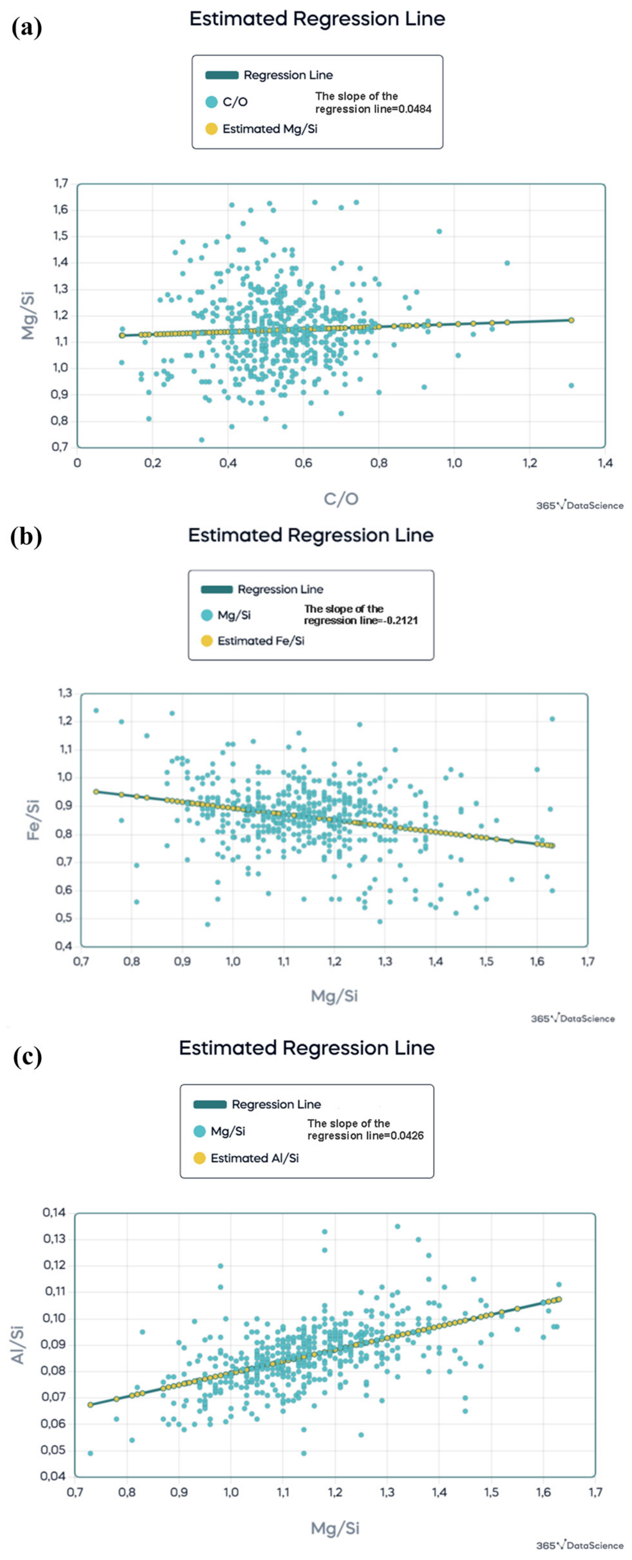

Figure 6: (a) Correlation between C/O and Mg/Si elemental abundance ratios in G-type stars. The correlation coefficient is 0.0493, and the standard error is 0.1460. (b) Correlation between Mg/Si and Fe/Si elemental abundance ratios in G-type stars. The correlation coefficient is 0.2653, with a standard error of 0.1127. (c) Correlation between Mg/Si and Al/Si elemental abundance ratios in G-type stars. The correlation coefficient is 0.5332, and the standard error is 0.0101.

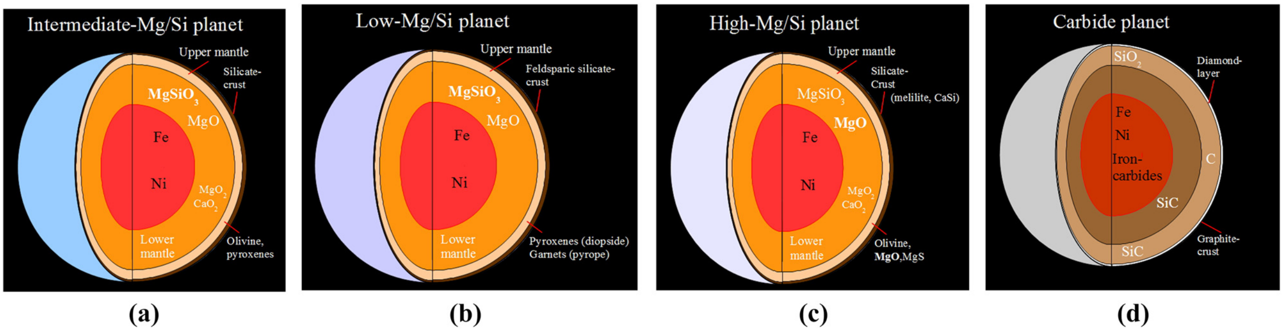

Figure 7: (a) Interior structure model of an Earth-sized rocky planet with an intermediate Mg/Si ratio, representing a mantle dominated by silicate minerals similar to those found in Earth's interior. (b) Interior structure model of an Earth-sized rocky planet with a low Mg/Si ratio, leading to a mantle composition enriched in silica-rich minerals. (c) Interior structure model of an Earth-sized rocky planet with a high Mg/Si ratio, characterized by a mantle dominated by magnesium-rich minerals. (d) Interior structure model of an Earth-sized rocky planet with a carbon-rich mineralogical composition.

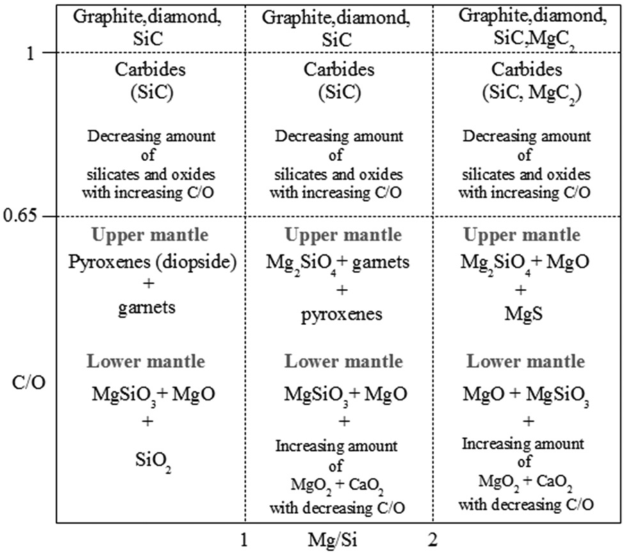

Figure 8: The potential mineralogy of planetary mantles represented as contour plots on C/O and Mg/Si axes, with nine distinct mineralogical regimes indicated.

core mass fraction as constrained by the observed Fe/Si distributions.

3.2 Distribution of the key elemental ratios in the C/O range <0.65

In this study, the relative abundances of those planet-building elements are examined, which determine the mineralogy of silicate-dominated rocky planets. In the low-C/O regime, the Mg/Si ratio controls the silicate mineralogy, and the Ca/Si, Al/Si, and Na/Si ratios can also contribute to the formation of the bulk composition of the rocky planetary bodies. Moriarty *et al.* (2014) found that a region of the protoplanetary disk can contain a significant amount of solid carbon in the terrestrial planet formation zone if the initial C/O ratio of the disk is expected to be at least 0.65. Moriarty *et al.* (2014) also found that carbon-rich planets can form throughout a large radial range of the protoplanetary disk if the C/O ratio is greater than 0.8. The chemical conditions in the systems with C/O values higher than 0.65 can lead to the formation of carbon-rich planets. Therefore, a C/O range below 0.65 can be used to achieve a more accurate approach to the elemental abundances of G- and F-type stars.

Mg/Si, Ca/Si, Al/Si, and Na/Si ratios of 403 G-type and 244 F-type stars have been calculated in the regime of C/O <0.65. The number of calculated Fe/Si ratios is 391 for G-type stars and 244 for F-type stars. In the Mg/Si range of 1–1.1, there are 91 G-type stars and 55 F-type stars. The majority of G-type (187) and F-type stars (83) in the sample belong to the Mg/Si range of 1.11–1.3. Forty-two G-type stars and 22 F-type stars lie between 1.31 and 1.5 Mg/Si values, while 13 G-type stars and 4 F-type stars can be characterized by Mg/Si values above 1.5. It has been found that in the C/O range containing values lower than 0.65, G-type and F-type stars have a similar distribution in Mg/Si, which implies that the chemical composition of the protoplanetary disks in key rock-forming elements can be similar around different spectral-type young stars in the solar neighborhood. This observed distribution of Mg/Si values suggests that the probability of the formation of rocky-type planets with bulk Mg/Si ranging from 1.1 to 1.3 is much higher than that of Mg-poor (Mg/Si < 1.1) and Mg-rich (Mg/Si > 1.5) planets. The mean values of stellar Mg/Si ratios for G-type and F-type stars are higher not only in the full examined range of C/O ratios but also in the C/O range below 0.65 than the solar averaged Mg/Si (Figure 6a and b), which confirms that the solar chemical composition is not typical among the values of sample stars with respect to the relative abundance of key planet-building elements (Figure 9).

3.3 Distribution of C/O ratios below 0.5

The chemical conditions in systems with C/O values lower than solar can lead to the formation of rocky planets with a higher abundance of oxygen-rich mineral phases compared to those found in Solar System terrestrial planets. Accordingly, a low-C/O range with an upper limit of 0.5 was selected in this study to enable a more detailed analysis of elemental abundances.

The distribution of the stellar C/O values below a carbon-to-oxygen ratio of 0.5 is shown in Table 1. The number of C/O values gradually decreases from the C/O range of 0.41–0.50 to the range of 0–0.10 for G-type and F-type stars, too. The number of C/O ratios for G-type stars below 0.5 (203) represents 39.6% of the sample of examined G-type stars in the full C/O range (512). In contrast, the number of C/O ratios for F-type stars below 0.5 (180) is 69.7% of the full C/O range in the sample for F-type stars (258). These results show that more terrestrial planets could have formed in oxygen- and water-rich environments within extrasolar planetary systems around F-type stars than G-type stars. In low-C/O protoplanetary disks, more oxygen is incorporated into water molecules

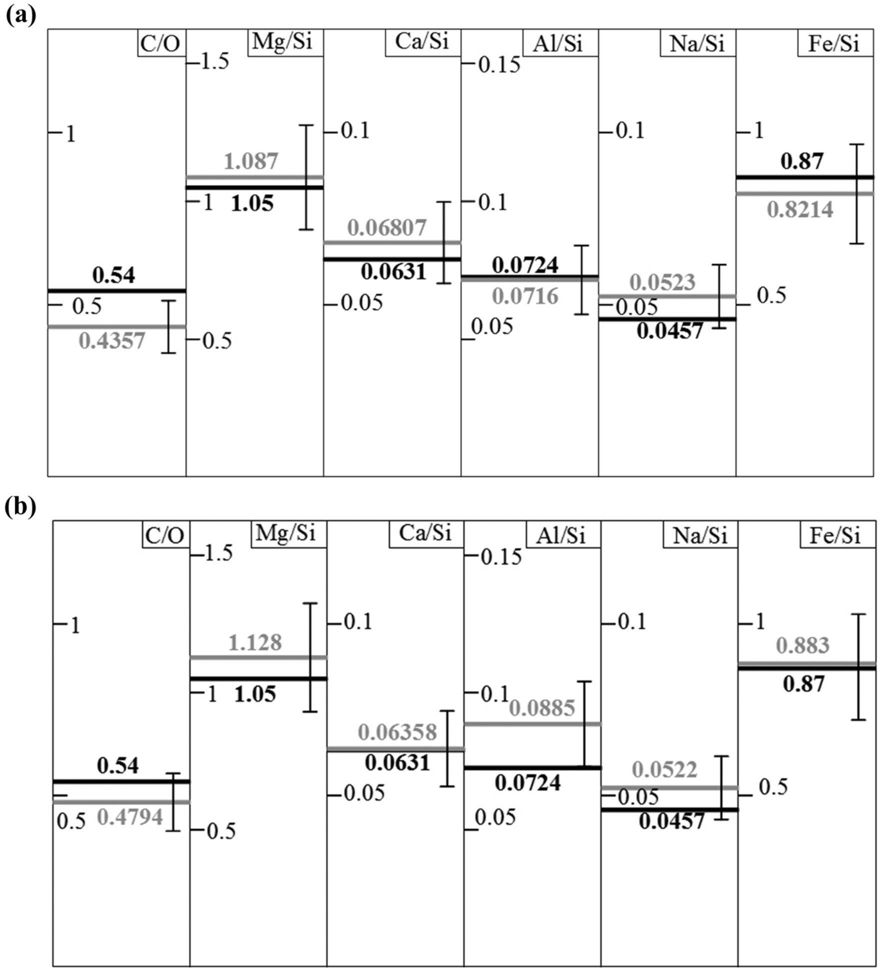

Figure 9: (a) Mean values of the six analyzed elemental ratios in G-stars in the case of the C/O ratios ranging from 0 to 0.65. Mean values of the stellar abundance ratios are indicated by gray lines, and the black lines denote the relevant solar values for reference. Standard deviations are shown in the figure. (b) Mean values of the six examined elemental ratios (fray lines) in F-stars for the case of C/O range 0–0.65. The relevant solar abundance ratios are denoted by black lines. Standard deviations are shown in the figure.

Table 1: The distribution of the stellar C/O values (C/O < 0.5)

C/O	0.41–0.50	0.31–0.40	0.21–0.30	0.11–0.20	0–0.10
G-stars	132	46	20	5	0
F-stars	91	65	19	5	0

compared to high-C/O disks, in which a larger fraction of oxygen forms CO molecules rather than water molecules. Therefore, water will be present in greater amounts in the planetary materials (ices, atmospheres) of the outer regions of low-C/O planetary systems. Additionally, a larger fraction of rocky planets with water- and oxygen-rich mineralogy of the bulk silicate planet (BSP) is predicted to form in the terrestrial planet formation zone for cases of oxygen-rich PPD chemistry. The O-rich conditions can yield such an olivine-dominated upper mantle composition and MgO-bearing lower mantle composition for rocky planets containing accessory mineral assemblages with O-rich species, the composition of which depends on the stellar and bulk planetary C/O, Mg/Si, and Ca/Si ratios. MgO, magnesium peroxide (MgO_2), and CaO_2 may be present in the deep mantle conditions of high-Mg/Si rocky Earth-mass planets and super-Earths, depending on the elevated oxygen abundances of the planet-harboring stars and the conditions of the O-rich environments in rocky planetary interiors (Lobanov *et al.* 2015, Nelson *et al.* 2015, Futó 2021). In conclusion, most of the potential rocky exoplanets around G-type and F-type stars are found to have magnesium-rich mineralogy with an enhancement of O-rich

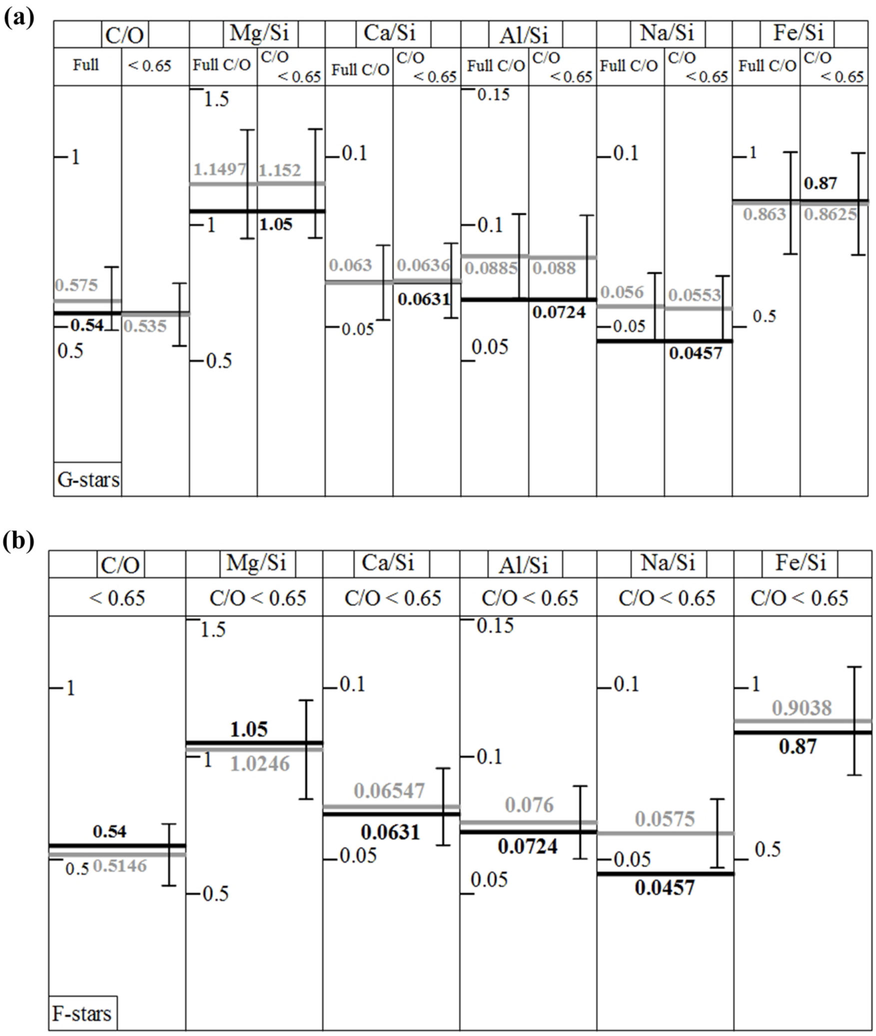

Figure 10: (a) Gray lines show the mean of the analyzed ratios in the planet-hosting G-stars for the range of full C/O spectrum and for C/O values ranging from 0 to 0.65. Black lines show the solar averages of the ratios of key planet-building elements. Standard deviations are shown in the figure. (b) The mean values of the six ratios in the planet-harboring F-stars of the C/O range 0–0.65. Solar ratios are also shown by black lines. Standard deviations are shown in the figure.

mineral species compared to the rocky planet compositions of the Solar System.

The chemical conditions in the low-C/O planetary systems can also contribute to the great diversity of rocky planet compositions. This factor determines the mineralogical characteristics of rocky planets in most planetary systems in the solar neighborhood. The elemental abundance analyses show that the major fractions of the thin disc G-type and F-type stars are likely to harbor rocky planets, most of which have relatively high bulk Mg/Si ratios and are formed under low C/O chemical conditions in PPDs. Therefore, we conclude that most of the higher Mg/Si planets are likely to have higher water content compared to planets that formed in low-Mg/Si planetary systems.

3.4 Distribution of the key elemental ratios in planet-host stars

More than 6,000 exoplanets have been confirmed to date. Our sample of known planet-host stars contains 79 G-stars (C/O = 0.17–0.80), with 60 low-C/O (<0.65) members and 13 F-stars. Each of these F-stars has a C/O ratio ranging from 0.35 to 0.58. We also examine the distribution of key abundance ratios for both G- and F-stars with known planetary companions, finding that the most analyzed elemental ratios (except for the values of C/O and Fe/Si ratios) show similar distribution trends in the samples of G-stars (full examined C/O range, range of C/O < 0.65, and planet-host stars). The mean value of the C/O ratio (0.575) is found to be higher than solar in the sample of planet-hosting stars examined in the full C/O range (Figure 10a). Interestingly, the mean Fe/Si ratio is calculated to be similar in the G-star samples of the full C/O range and the planet-harboring stars, while its value is slightly higher than solar in the sample of C/O <0.65.

In Figure 10a and b, F-stars with known planets exhibit similar abundance trends to the samples of G- and F-stars with and without planets in the case of the C/O, Ca/Si, Al/Si, and Na/Si ratios, but the mean Mg/Si is slightly lower, and the mean Fe/Si is slightly higher than solar (Figure 10b). The reason for this may be that the known planet-hosting stars of the F-star sample are very few (13), which is insufficient for exact and reliable abundance analyses. Figure 11a and b shows the number of supersolar, solar-identical, and subsolar values of six analyzed ratios for known planet-host stars in G- and F-star samples. G-type planet-host stars have a similar distribution trend to G-type stars in the full C/O regime. F-type planet hosts and F-type stars in full C/O regimes have different distribution trends.

In Figure 11a and b, nine G-stars host super-Earths (Mp < 10 MEarth), 12 G-stars host Neptune-like planets (Mp < 30 MEarth), and 58 G-stars have Jovian planets (Mp ≥ 30 MEarth). Thirteen F-stars host gas giant planets (Mp ≥ 30 MEarth). G-host stars with different types of planets exhibit similar distribution trends to those of the entire G-sample, except for the Neptune-like planet and Jovian hosts, which have mean C/O values higher than solar. The sample of G-type super-Earth hosts includes lower C/O and Fe/Si, slightly higher Ca/Si, Al/Si, and Na/Si values than solar, which distribution trend also reflects the characteristic trend for the total sample of G-stars (Table 2).

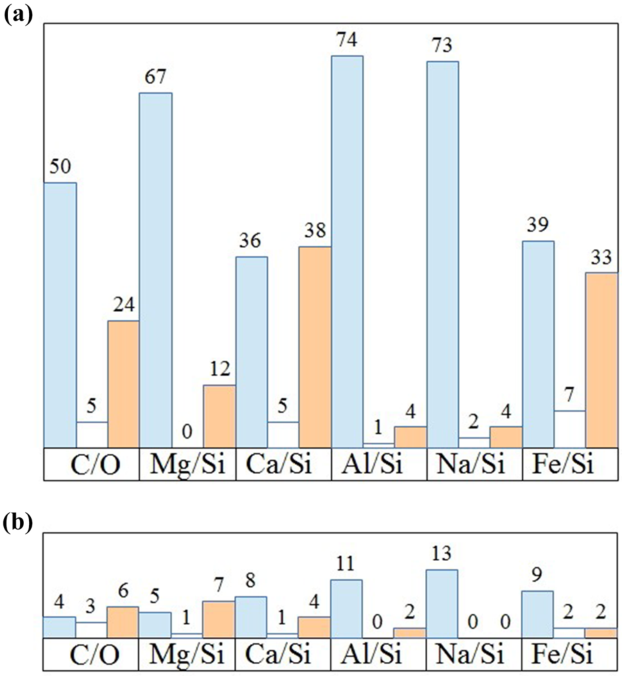

Figure 11: (a) The number of known G-type planet host stars in the supersolar, the solar identical, and the subsolar ranges of six analyzed elemental ratios. (b) The number of known F-type planet host stars in the supersolar, the solar identical, and the subsolar ranges of six analyzed elemental ratios.

Interestingly, the mean Mg/Si ratio of G-type super-Earth hosts is higher than the average Mg/Si ratio for both G- and F-stars without known planetary companions, highlighting that low-mass planets are more frequent around stars with a high Mg/Si ratio (Adibekyan *et al.* 2015). As shown in Figure 11, stars hosting super-Earths tend to exhibit not only relatively high Mg/Si ratios but also elevated Al/Si ratios – both in comparison to the average values for G-type stars and to stars hosting other types of planets.

3.5 The common mineralogical compositions for rocky planets

We demonstrated that the greatest fraction of G- and F-type stars are characterized by an increased Mg/Si ratio and a

Table 2: Mean C/O, Mg/Si, Ca/Si, Al/Si, Na/Si, and Fe/Si ratios for G- and F-type super-Earth, Neptune- and Jovian-planet host stars. Standard deviations are indicated in the table

		C/O	Mg/Si	Ca/Si	Al/Si	Na/Si	Fe/Si
Super-Earths	G-star	0.52 0.611/0.443	1.184 1.39/1.01	0.06412 0.075/0.055	0.090 0.106/0.077	0.0544 0.064/0.046	0.8177 0.96/0.70
	F-star	—	—	—	—	—	—
Neptune like	G-star	0.5866 0.689/0.50	1.1458 1.346/0.975	0.06535 0.077/ 0.0556	0.0889 0.104/0.077	0.06117 0.072/0.052	0.869 1.021/0.74
	F-star	—	—	—	—	—	—
Jovian	G-star	0.58 0.68/0.49	1.1855 1.39/1.01	0.06235 0.073/0.053	0.0881 0.104/0.075	0.05727 0.067/0.049	0.8688 1.021/0.74
	F-star	0.5146 0.60/0.438	1.0246 1.204/0.872	0.06547 0.077/0.056	0.076 0.089/0.065	0.0575 0.068/0.049	0.90 1.057/0.766

decreased C/O ratio compared to the solar-relevant values. The most common composition for the potential terrestrial planets of these stars can be characterized by Mg-rich crustal plus mantle mineralogy and possibly a greater water budget compared to the Solar System terrestrial planets. The Fe/Si ratios are lower than solar for both G- and F-stars, plausibly linked to the formation of smaller core mass fractions. Moreover, the most common compositions for the rocky planetary mantles in the solar neighborhood can be described by mineral assemblages that are slightly richer in Ca-bearing minerals (Ca-pv, ppv) in the lower mantles and Ca-, Al-, and Na-bearing minerals (pyroxenes, garnets) in the upper mantles.

As shown in Figure 12, approximately two-thirds (65.23 and 68.99%) of the studied G- and F-type stars located within 50 parsecs of the Sun fall into the category characterized by a C/O ratio below 0.65 and an Mg/Si ratio between 1 and 2. This compositional range is considered the most favorable in terms of mantle viscosity, which affects the efficiency of mantle convection, and thus it represents the mineralogical conditions most conducive to plate tectonics. When also considering the previously identified optimal planetary mass range of 1–4 Earth masses, it follows that at most roughly one-sixth of rocky exoplanets may undergo tectonic activity during their evolution. Based on the results of the analysis, most rocky

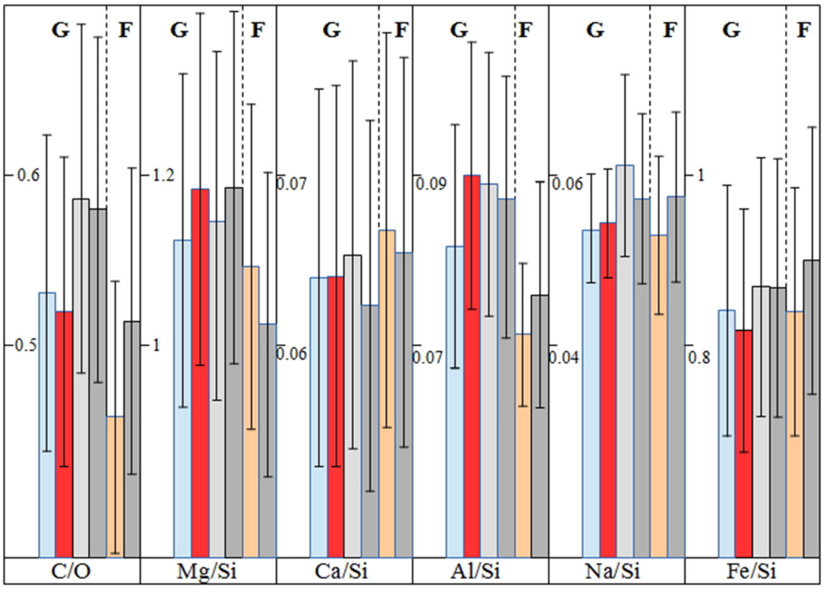

Figure 12: The mean values of the C/O, Mg/Si, Ca/Si, Al/Si, Na/Si, and Fe/Si elemental ratios for the full sample of G-type (light blue) and F-type (pink) stars, as well as for those stars within the sample that host super-Earth (red), Neptune-like (light grey), and Jupiter-like (dark grey) planets. The left column corresponds to data for G-type stars, and the right column refers to F-type stars. Standard deviations are indicated in the figure.

exoplanets in our galactic neighborhood are likely to possess upper mantles rich in olivine and containing pyroxenes in substantial mass fractions, as well as lower mantles predominantly composed of $MgSiO_3$ perovskite/post-perovskite and a relatively significant amount of ferropericlase. Their crustal compositions may range from felsic – rich in silicon and feldspars – to basaltic, depending on the dominant geological and geodynamic processes. Approximately one-fifth (20.12%) of G-type stars fall within the C/O range of 0.65–1 and the Mg/Si range of 1–2. Rocky planets potentially formed around these stars may exhibit carbon-rich mineralogies, including both dominantly silicate-based compositions and those primarily composed of carbon-bearing minerals.

Among G- and F-type stars with Mg/Si ratios below 1, the proportion remains significant (11.72 and 25.58%, respectively) when the C/O ratio is below 0.65, but above this threshold, the number of stars in any mineralogical regime does not exceed 2%. These findings suggest that rocky planets with magnesium-poor mineralogies formed under low C/O conditions (<0.65) are not uncommon, whereas carbon-rich planets – similar to magnesium-rich ones – are relatively rare. No stars with Mg/Si ratios greater than 2 were found among the analyzed G- and F-type stars, indicating that such stars are likely very rare in the local galactic environment near the Sun.

The most common rocky planets fall into the mineralogical category defined by C/O ratios below 0.65 and Mg/Si ratios between 1 and 2. However, variability within the 1–2 Mg/Si range can already exert a significant influence on a planet's geology and geodynamic processes. For instance, substantial differences in geological activity may arise between two planets of similar mass and internal structure if one formed in a protoplanetary disk with an Mg/Si ratio close to 1, and the other in a disk with a ratio approaching 2 (Figure 13).

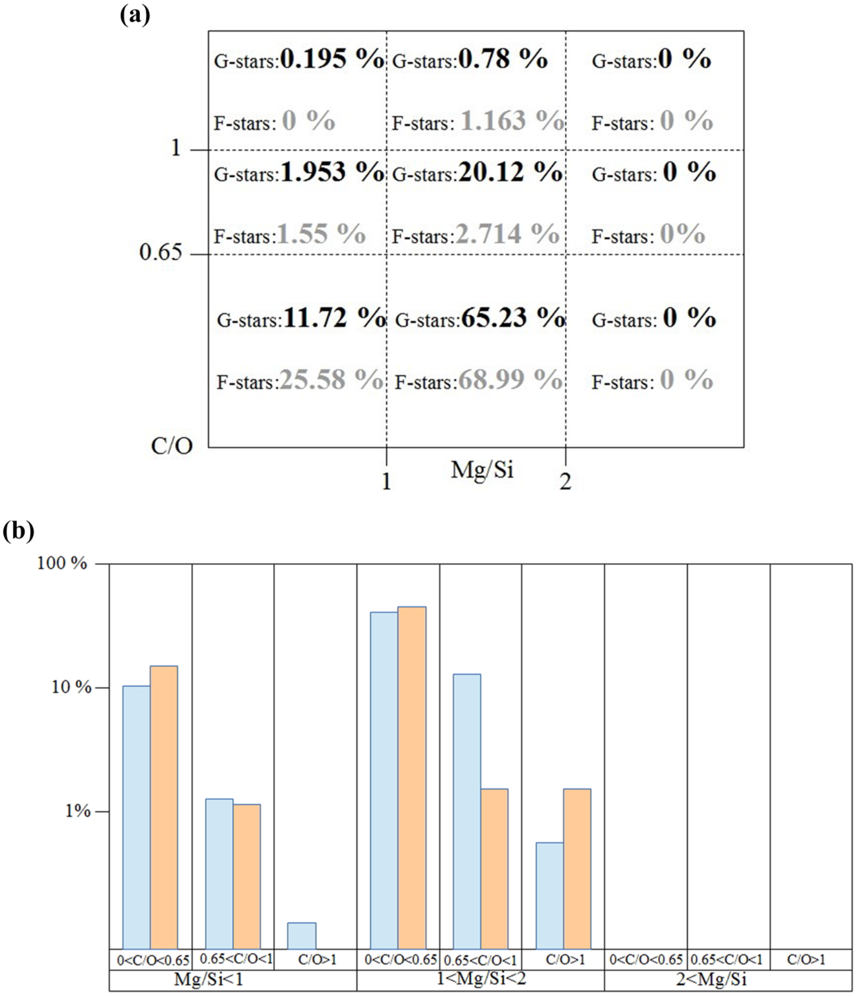

Figure 13: Quantification of the mineralogical results for the full sample of G- and F-type stars across nine defined mineralogical regimes (a). (b) visualization of the mineralogical results for the full sample of G- and F-type stars across nine defined mineralogical regimes. It shows the data in addition to the labels.

3.6 Rare and exotic bulk mineralogy for rocky planets

At the same time, we suggest that the variable stellar Mg/Si and C/O ratios, in some cases, may result in rare BSP compositions yielding unique crustal and mantle mineral assemblages for rocky planets. It has also been found that a large fraction of low-Mg/Si stars have a variable degree of carbon enrichment compared to that of the higher-Mg/Si stars. Fourteen stars among the G-stars (2.73%) have C/O ratios above 0.8, and five stars have C/O ratios higher than 1. The sample of F-stars contains seven stars with C/O ratios above 0.8 (2.71%); four of them have a C/O ratio larger than 1. These results highlight that C-rich planetary systems are not only frequent in globular clusters but may also exist in the galactic thin disk. Note that the number of carbon-rich planets in the solar neighborhood is likely significantly higher than just a few percent. It is considered likely that carbon–silicate planets could form around moderately carbon-rich stars with C/O ratios between 0.8 and 1.0 (Futó 2014) or between 0.65 and 0.8 (Futó and Gucsik 2025), depending on the semi-major axes of planet formation. Sixty (G) and 65 (F) stars exhibit Mg/Si values lower than 1. If they have rocky planets, those may have a very different mantle and crustal mineralogy from those of the terrestrial planetary bodies of the Solar System. Fifty-nine stars present Mg/Si values ranging between 0.80 and 0.99 for both the G and F star samples. The forming terrestrial planets in the low-Mg/Si planetary systems are expected to be Si-rich, having upper mantles consisting mainly of olivine, diopside phases, pyrope, and SiO_2. Their lower mantles are likely composed of MgSiO3 pv/ppv and relatively small amounts of MgO. Considering the observed stellar Mg/Si abundances and GCE models, the extremely low Mg/Si planetary systems are likely to be very rare in spiral galaxies. Mg/Si values lower than 0.5 are 0 and 1 in the G-star and F-star samples, respectively. In very low-Mg/Si systems, the upper mantle of an Mg-depleted planet is made of diopside phases, Fe-rich garnets, and SiO_2, and the lower mantle builds up from $MgSiO_3$ pv/ppv and high-pressure SiO_2. The SiO_2-rich magmas produce andesite/rhyolite igneous rocks, and the granitic crust contains a great number of feldspars, mostly building up from felsic igneous rocks. If the bulk Mg/Si ratio of BSP is lower than 0.5, the Mg is in $MgSiO_3$ pv/ppv in the lower mantle, while the excess Si constitutes high-pressure SiO_2 phases, which present as the dominant mineral in the greatest mass fraction of the mantle. In extremely rare cases, the bulk Mg/Si ratio of a solid planet may be close to zero, yielding a “silica planet” with crustal and mantle composition made mostly from SiO_2. In summary, the largest fraction of analyzed G- and F-stars, having subsolar C/O and supersolar Mg/Si, Ca/Si, Al/Si, and Na/Si ratios, can harbor rocky planets with different bulk mineralogy from those of solar terrestrial planets. The similar or solar identical sets of the six examined abundance ratios can rarely be found in the stars of the thin disc within 50 pc of the Sun in terms of the obtained results (Table 3).

3.7 The set of the examined stellar abundance ratios and the Earth's atypical bulk mineralogy

As seen in the analysis of the sets of the six examined stellar abundance ratios, the set of solar values is different from most of the sets of stellar abundances. The regimes from 0.52 to 0.56 for C/O and from 1.03 to 1.07 for Mg/Si ratios have been investigated to have identical solar compositions for G- and F-stars. Twelve stars were identified in this range, among which eight are G-type and four are F-type stars (Table 3). The number of fractions of G-stars that have identical solar sets of C/O and Mg/Si ratios is found to be 1.56% of the sample of 512 G-stars. Interestingly, the set of these elemental ratios is obtained to be 1.55% of the sample of 258 F-stars.

As seen in Table 3, the Ca/Si, Al/Si, and Na/Si ratios of G- and F-stars with solar identical C/O and Mg/Si values exhibit similar values to the relevant mean values in the full C/O regime (Figure 1a and b). The datasets of HIP 35145 (G-star) and HIP14954 and HIP81662 (F-stars), which

Table 3: Closely solar identical sets of C/O and Mg/Si stellar ratios in the examined sample for G-type and F-type stars

G-type star	C/O	Mg/Si
HIP 116937/HD 222595	0.56	1.06
HIP 35145/HD 55647	0.52	1.03
HIP 100963/HD 195034	0.53	1.05
HIP 27417/HD 38949	0.55	1.05
HIP 45859/HD 80355	0.53	1.03
HIP 36129/HD 57813	0.56	1.03
HIP 68162/ HD 121504*	0.55	1.03
HIP 102018/HD 196800	0.55	1.07
F-type star	**C/O**	**Mg/Si**
HIP 14954/HD 22.52	0.56	1.03
HIP 75379/HD 31.09	0.54	1.05
HIP 81662/ HD 47.20	0.56	1.05
HIP 21158/HD 39.02	0.54	1.06

*Planet host.

constitute 0.2 and 0.77% of the entire examined sample of G- and F-stars. Previous models show that 22% of solar-type stars host Earth-mass planets in the habitable zone (HZ) (Petigura *et al.* 2013), at the distance from the star where the conditions of condensation chemistry are expected to be similar to those conditions under which Earth could form. Considering the occurrence of HZ Earth-mass planets in terms of the model of Petigura *et al.* (2013) and the obtained solar-identical elemental ratio (0.2%) for the sample of G-stars, the occurrence of rocky planets with approximately Earth-analog bulk elemental compositions is estimated to be less than 0.04% per solar-like star.

The set of the six analyzed key elemental abundance ratios for 32 G2V spectral-type stars (Figure 14) exhibits a similar abundance trend to that of G-stars in the fully examined C/O regime (512 G-stars). The set of six key elemental ratios of the Sun does not seem to be typical among the sets of analyzed 32 G2V stars. The number of solar analog stars with very similar abundance ratios of key rock-forming elements to that of the Sun may not only be low near the galactic midplane, but their numbers may also possibly be low farther from the midplane, where stars are enriched to a greater extent in Mg, Si, and Ca, suggesting a slightly supersolar trend for most stellar Mg/Si and Ca/Si ratios.

4 Discussion

On that basis, the set of solar abundance ratios and the Earth's bulk mineralogy is thought to be rare and linked to G- and F-type stars in the solar neighborhood. The events of special post-accretion evolution have also contributed to the formation of Earth's unique mineralogy.

It is known that specific elemental ratios in stars with planets are very important for the formation of geologically active rocky planets. Adequate values of C/O, Mg/Si, Fe/Si, and even several key elemental ratios (Ca/Si, Al/Si, Na/Si) in bulk planet composition might considerably contribute to the conditions of long-term geodynamics and the evolution of complex life. In addition, the solar-identical or closely solar sets of these specific elemental ratios in planet-host stars likely increase the likelihood of the formation of their rocky exoplanets being Earth-like. For the Sun, slightly higher C/O and Fe/Si, slightly lower Ca/Si, Al/Si, Na/Si, and lower Mg/Si ratios have been identified compared to most stars, and thus the set of the six solar analyzed abundance ratios is found to be different from the majority of abundance sets in the examined G- and F-star samples.

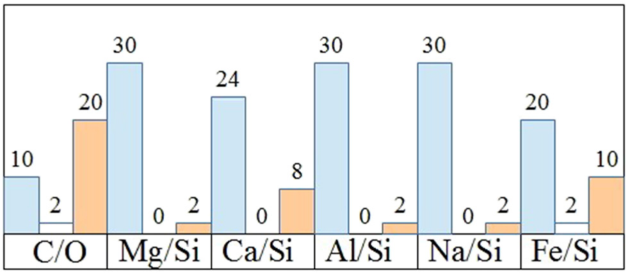

Figure 14: The number of super solar, solar identical, and subsolar values of six analyzed elemental ratios for solar G2V-type stars.

The most common rock-forming minerals are likely to dominate on most Earth-like planets. However, Hystad *et al.* (2015) argued that considering the number of rare minerals, the probability of Earth's mineralogy on other Earth-like planets is remarkably low. They conclude that Earth's mineralogy is unique in the cosmos since the likelihood is extremely low that two planets are identical in all aspects of their initial chemical and physical conditions during the formation processes. Moreover, the biological factor also contributes to Earth's mineral diversity.

One of the initial chemical conditions for rocky planet formation is the set of key planetary abundance ratios having a high variability, which also affects the occurrence of rare minerals.

It has been thought that highly siderophile elements (HSE, gold, platinum, *etc.*) are delivered by large impacts during the early-stage evolution of Earth. Korenaga and Marchi (2022) showed that the metals in the core of impactors with their HSE budget could be retained in the mantle. These metals could be transported toward the Earth's crust on billion-year timescales due to mixing by mantle convection. This process could contribute to the enrichment of the crustal gold and platinum budget. Accordingly, the mode of convection (sluggish, stagnant, or mobile lid) plays a crucial role not only in geological activity but also in the evolution of crustal mineralogy and petrology of a terrestrial planet. Active geodynamics and mantle convection have been working in the Earth's interior for several billion years.

We estimate the expected number of planets that can sustain plate tectonics. They could have formed in the case of one-sixth of the rocky exoplanets, considering the favorable range of stellar C/O and Mg/Si abundance ratios. However, only a small fraction of these planets can likely sustain long-term plate movements over billion-year timescales owing to other required conditions.The set of the six stellar analyzed abundance ratios, compared to the relevant solar values in this study, shows lower than solar Be abundances in the most examined stellar samples adopted from the literature. The large impact events of Earth's post-accretion evolution and tectonic activity indicate that Earth is not unique in the essential abundance ratios for bulk mineralogy, but it can also be rare or unique with respect to crustal mineralogy in the near-solar galactic population of rocky planets.

5 Conclusion

The set of key elemental abundance ratios in the Solar System, the chemical features of the condensation of planet-building minerals, and the special processes in the evolutionary history of our planet were the determining factors for the formation of the Earth's atypical bulk mineralogy. Among them, the set of analyzed elemental ratios is the most fundamental factor that determines the chemical conditions for the formation of rocky planetary bodies in a planetary system. In this paper, we have, therefore, analyzed the abundances of five key elements (O, C, Fe, Mg, Si) plus metallic elements (Ca, Al, Na) in G- and F-type stars, which can be located in the solar galactic neighborhood by using the relevant data from the Hypatia Catalog. We have examined the most important effect of the variability of C/O and Mg/Si elemental ratios on the bulk mineralogical composition of rocky planets.

The distribution analyses show that the primary mineralogy of potentially rocky planets in the solar neighborhood is likely similar to that of the Solar System terrestrial planets, but the mantle mineralogy of the rockiest planets around the systems of G- and F-stars may be more enriched in Mg-rich species, such as olivine and magnesiowüstite. The obtained distributions and calculated mean values for the prime elemental abundance ratios C/O and Mg/Si indicate that the Solar System averages of these ratios differ from the most stellar values in both examined C/O ranges; solar C/O is slightly higher, while solar Mg/Si is lower than the stellar averages. Solar Ca/Si, Al/Si, and Na/Si ratios also deviate from the mean stellar values; they are lower than the majority of stellar ratios of G- and F-stars, except for Al/Si values in the F-star samples. In conclusion, the set of examined solar abundance ratios in this type of pattern is not common, implying that the composition of solar-terrestrial planet-building materials and thus the Earth's bulk mineralogy cannot be typical in the rocky planet population of the solar neighborhood within 50 pc of the Sun. The obtained results indicate that the mineral diversity of rocky planets in the Galaxy may be greater than previously thought. The variation of the C/O ratio can lead to a more diverse range of bulk mineral compositions for Mg-depleted and more highly Mg-rich planets, too. Stellar variations in the abundances of Mg, Si, C, and O by determining the mantle mineral composition greatly affect the efficiency of mantle convection, plate tectonics, and geological activity of rocky planets. The solar Mg/Si ratio and Na abundance are slightly lower than in the case of the most analyzed G- and F-stars, which can be favorable for mantle dynamics and plate movement on Earth. The abundance of Al and Ca in the most Mg-depleted planets is too low to constitute larger amounts of Al- and Ca-mineral phases. At the same time, high-Mg/Si rocky planets can anomalously exist with relatively high Al- and Ca-abundance in their BSP compositions. Most of the high-Mg/Si rocky planets are likely to be richer in Al and Ca, and they have silicate mantles with larger amounts of Al- and Ca-bearing minerals than found on Earth. The revealed trends in the variations of examined elemental ratios are valid only for the case of the thin disk population within 50 pc. Still, they are thought to be reflected in the changes in the alpha element distribution between different stellar populations. The predictions of the statistical analysis cannot be generalized to the total fraction of thin disk stars at near-solar galactocentric distances since 50 pc is small on galactic scales. However, future research and the further evolution of GCE models can reveal that our results may not only be valid for the solar neighborhood, but their validity can be extended to a larger fraction of the thin disk population at solar galactocentric distances in a farther region of the Milky Way Galaxy. More comparative analyses of all-important stellar abundance ratios in the future can help better understand the formation and evolutionary history of the Solar System and own planet: Earth.

Acknowledgments: This research is based on the use of the Hypatia Catalog Database, an online compilation of stellar abundance data as described in Hinkel *et al.* (2014, AJ, 148, 54), which was supported by NASA's Nexus for Exoplanet System Science (NExSS) research coordination network and the Vanderbilt Initiative in Data-Intensive Astrophysics (VIDA). This work has made use of data from the NASA Exoplanet Archive (https://exoplanetarchive.ipac.caltech.edu), which is operated by the California Institute of Technology under contract with the NASA Exoplanet Exploration Program.

Funding information: The funding has been approved by Hungarian Electronic Information Service National Programme based on an agreement between Hungarian

Electronic Information Service National Programme and De Gruyter.

Author contributions: Conceptualization, P.F. and A.G.; methodology, P.F.; validation, P.F. and A.G.; data curation, P.F.; writing – original draft preparation, P.F. and A.G.; project administration, A.G.; All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors state no conflict of interest.

References

Adibekyan VZ, Delgado-Mena E, Sousa SG, Santos NC, Israelian G, Gonzalez Hernandez JI, et al. 2012a. Exploring the α-enhancement of metal-poor planet-hosting stars. The Kepler and HARPS samples. Astron Astrophys. 547:A36.

Adibekyan VZ, Santos NC, Sousa SG, Israelian G, Delgado Mena E, Gonzalez Hernandez JI, et al. 2012b. Overabundance of α-elements in exoplanet-hosting stars. Astron Astrophys. 54:A89.

Adibekyan V, Santos NC, Figueira P, Dorn C, Sousa SG, Delgado Mena E, et al. 2015. From stellar to planetary composition: Galactic chemical evolution of Mg/Si mineralogical ratio. Astron Astrophys. 581:L2.

Adibekyan V. 2017. Formation and evolution of exoplanets in different environments. Non-stable universe: Energetic resources, activity phenomena, and evolutionary processes. ASP Conference Series. Byurakan, Armenia, Vol. 511, p. 70.

Adibekyan V, Gonçalves da Silva HM, Sousa SG, Santos NC, Delgado Mena E, Hakobyan AA. 2017. Mg/Si mineralogical ratio of low-mass planet hosts. Correction for the NLTE effects. Astrophysics. 60:325–332.

Asplund M, Grevesse N, Sauval J. 2005. The solar chemical composition. Cosmic Abundances Rec Stellar Evolution Nucleosynthesis. 336:25.

Asplund M, Grevesse N, Sauval AJ, Scott P. 2009. The chemical composition of the Sun. Annu Rev Astron Astrophys. 47:481–522.

Bedell M, Bean JL, Meléndez J, Spina L, Ramírez I, Asplund M. 2018. The chemical homogeneity of Sun-like stars in the solar neighborhood. Astrophys J. 865:68.

Bond JC, O'Brien DP, Lauretta DS. 2010. The compositional diversity of extrasolar terrestrial planets. I. In situ simulations. Astrophys J. 715:1050–1070.

Bitsch B, Battistini C. 2020. Influence of sub- and super-solar metallicities on the composition of solid planetary building blocks. Astron Astrophys. 633:A10.

Brewer JM, Fisher DA. 2016. C/O and Mg/Si ratios of stars in the solar neighborhood. Astrophys J. 831:20.

Buchhave LA, Latham DW, Johansen A, Bizzarro M, Torres G, Rowe JF, et al. 2012. An abundance of small exoplanets around stars with a wide range of metallicities. Nature. 486:375–377.

Cabral N, Lagarde N, Reylé C, Guilbert-Lepoutre A, Robin AC. 2019. Chemical composition of planet building blocks as predicted by stellar population synthesis. Astron Astrophys. 622:A49.

Carter-Bond JC, O'Brien DP, Mena E, Israelian G, Santos NC, González-Hernández JI. 2012a. Low-Mg/Si planetary host stars and their Mg-depleted terrestrial planets. Astrophys J. 747:L2.

Carter-Bond JC, O'Brien DP, Raymond S. 2012b. The compositional diversity of extrasolar terrestrial planets. II. Migration simulations. Astrophys J. 760:44.

Delgado-Mena E, Israelian G, González-Hernández JI, Bond JC, Santos NC, Udry S, et al. 2010. Chemical clues on the formation of planetary systems: C/O versus Mg/Si for HARPS GTO sample. Astrophys J. 725:2349–2358.

Dorn C, Khan A, Heng K, Connolly JAD, Alibert Y, Benz W, et al. 2015. Can we constrain the interior structure of rocky exoplanets from mass and radius measurements?. Astron Astrophys. 577:A83.

Ehlmann BL, Edwards CS. 2014. Mineralogy of the Martian surface. Annu Rev. 42:291–315.

Fischer DA, Valenti J. 2005. The planet-metallicity correlation. Astrophys J. 622:1102–1117.

Fischer RA, Campbell AJ, Reaman DM, Miller NA, Heinz DL, Dera P. 2013. Phase relations in the Fe–FeSi system at high pressures and temperatures. Earth Planet Sci Lett. 373:54–64.

Fortney JJ. 2012. On the carbon-to-oxygen ratio measurement in nearby Sun-like stars. Implications for planet formation and the determination of stellar abundances. Astrophys J Lett. 747:L27.

Futó P. 2014. A new planet-class: carbon-silicate planets. XLV. Lunar and Planetary Science Conference, March 17–21; Houston, USA. Abstract:1046.

Futó P. 2022. The rocky planets with magnesium- depleted mantle composition. LIII. Lunar and Planetary Science Conference, Virtual Conference. Houston, USA. p. 1036.

Futó P, Gucsik A. 2025. Carbon-rich mineral composition of silicate-dominated rocky planets in a large fraction of low-Mg/Si planetary systems. LVI. Lunar and Planetary Science Conference. Houston, USA. p. 1074.

Gasparik T. 1989. Contributions to Mineralogy and Petrology. Vol. 102. Heidelberg: Springer; p. 389–405.

Futó P. 2021. The rocky planets with magnesium-rich mantle composition. LII. Lunar and Planetary Science Conference, Virtual Conference. Houston, USA. p. 1017.

Gonzalez G. 1997. The stellar metallicity-giant planet connection. Mon Not R Astron Soc. 285:403–412.

Haywood. M. 2008. A peculiarity of metal-poor stars with planets? Astron Astrophys. 482:673–676.

Hazen RM, Grew ES, Downs RT, Golden J, Hystad G. 2015. Mineral ecology: chance and necessity in the mineral diversity of terrestrial planets. Can Mineral. 53:295–324.

Hazen RM, Downs RT, Morrison SM, Tutolo BM, Blake DF, Bristow TF. 2023. On the diversity and formation modes of martian minerals. J Geophys Res. 128(9):e2023JE007865.

Hinkel NR, Timmes FX, Young PA, Pagano MD, Turnbull MC. 2014. Stellar abundances in the solar neighborhood: the Hypatia Catalog. Astron J. 148:54.

Hystad G, Downs RT, Grew ES, Hazen RM. 2015. Statistical analysis of mineral diversity and distribution: Earth's mineralogy is unique. Earth Planet Sci Lett. 426:154–157.

Ida S, Lin DNC. 2004. Toward a deterministic model of planetary formation. II. The formation and retention of gas giant planets around stars with a range of metallicities. Astrophys J. 616:567–572.

Johnson JA, Aller KM, Howard AW, Crepp JR. 2010. Giant planet occurrence in the stellar mass-metallicity plane. Publ Astron Soc Pac. 122:905–915.

Korenaga J. 2010. On the likelihood of plate tectonics on super-Earths: does size matter? Astrophys J Lett. 725:L43–L46.

Korenaga J, Marchi S. 2022. Vestiges of impact-driven three-phase mixing in the chemistry and structure of Earth's mantle. Proc Natl Acad Sci. 120:e2309181120.

Kuchner MJ, Seager S, 2005. Extrasolar carbon planets. arXiv:0504214v2.

Lobanov SS, Zhu O, Holtgrewe N, Prescher C, Prakapenka VB, Oganov AR. 2015. Stable magnesium peroxide at high pressure. Sci Rep. 5:13582.

Lodders K. 2003. Solar system abundances and condensation temperatures of the elements. Astrophys J. 591:1220–1247.

Michel A, Haldemann J, Mordasini C, Alibert Y. 2020. Planetary mass-radius relations across the galaxy. Astron Astrophys. 639:A66.

Miyagoshi T, Kameyama M, Ogawa M. 2015. Thermal convection and convective regime diagram in super-Earths. J Geophys Res: Planets. 120:1267–1278.

Miyagoshi T, Kameyama M, Ogawa M. 2018. Effects of adiabatic compression on thermal convection in super-Earths of various sizes. Earth Planets Space. 70:200.

Moriarty J, Madhusudhan N, Fischer D. 2014. Chemistry in an evolving protoplanetary disk: effects on terrestrial planet composition. Astrophys J. 787:81.

NASA Exoplanet Archive: Planetary Systems Table. Doi: 10.26133/NEA22.

Nelson JR, Needs RJ, Pickard CJ. 2015. Calcium peroxide from ambient to high pressures. Phys Chem Chem Phys. 17:6889–6895.

O'Neill C, Lenardic A. 2007. Geological consequences of super-sized Earths. Geophys Res Lett. 34:L19204.

Nielsen J, Gent MR, Bergemann N, Eitner P, Johansen A. 2023. Planet formation throughout the Milky Way. Planet populations in the context of Galactic chemical evolution. Astron Astrophys. 678:A74.

Petigura EA, Howard AW, Marcy GW. 2013. Prevalence of Earth-size planets orbiting Sun-like stars. Proc Natl Acad Sci. 110:19273–19278.

Putirka KD. 2024. Exoplanet mineralogy. Rev Mineral Geochem. 90:199–257.

Reali R, Jackson JM, Van Orman J, Bower DJ, Carrez P, Cordier P. 2019. Modeling viscosity of (Mg, Fe) O at lowermost mantle conditions. Phys Earth Planet Inter. 187:65–75.

Rensen F, Miguel Y, Zilinskas M, Louca A, Woitke P, Helling C. 2023. The deep atmospheric composition of jupiter from thermochemical calculations based on Galileo and Juno data. Remote Sens. 15:841.

Russell, MJ, Ponce A. 2020. Six 'must-have' minerals for life's emergence: Olivine, pyrrhotite, bridgmanite, serpentine, fougerite and mackinawite. Life. 10(11):291.

Santos NC, Israelian G, Mayor M. 2004. Spectroscopic [Fe/H] for 98 extra-solar planet-host stars. 2004a Exploring the probability of planet formation. Astron Astrophys. 415:1153–1166.

Santos NC, Adibekyan V, Mordasini C, Benz W, Delgado-Mena E, Dorn C et al. 2015. Constraining planet structure from stellar chemistry: the cases of CoRoT-7, Kepler-10, and Kepler-93? Astron Astrophys. 580:L13.

Sandora M, Airapetian V, Barnes L, Lewis GF. 2023. Multiverse predictions for habitability: Stellar and atmospheric habitability. Universe. 9:4.

Seager S, Kuchner M, Hier-Majumder CA, Militzer B. 2007. Mass-radius relationships for solid exoplanets. Astrophys J. 669:1279–1297.

Spaargaren RJ, Ballmer MD, Bower DJ, Dorn C, Tackley PJ. 2020. The influence of bulk composition on the long-term interior-atmosphere evolution of terrestrial exoplanets. Astron Astrophys. 643:A44.

Stamenković W, Noack L, Breuer D, Spohn T. 2012. The influence of pressure-dependent viscosity on the thermal evolution of super-Earths. Astrophys J. 748:41.

Stamenković W, Seager S. 2016. Emerging possibilities and insuperable limitations of exogeophysics: The example of plate tectonics. Astrophys J. 825:78.

Stein C, Finnenkötter A, Lowman JP, Hansen U. 2011. The pressure-weakening effect in super-Earths: Consequences of a decrease in lower mantle viscosity on surface dynamics. Geophys Res Lett. 38:L21201.

Suárez-Andrés L, Israelian G, González Hernández JI, Adibekyan VZ, Delgado-Mena E, Santos NC. 2018. C/O vs. Mg/Si ratios in solar type stars: The HARPS sample. Astron Astrophys. 614:A84.

Tackley PJ, Ammann M, Brodholt JP, Dobson DP, Valencia D. 2013. Mantle dynamics in super-Earths: Post-perovskite rheology and self-regulation of viscosity. Icarus. 225:50–61.

Thiabaud A, Marboeuf U, Alibert Y, Leya I, Mezger K. 2015. Elemental ratios in stars vs planets. Astron Astrophys. 580:A30.

Valencia D, O'Connell RJ. 2007. Inevitability of plate tectonics on super-Earths. Astrophys J. 670:L45–L48.

Valencia D, Ikoma M, Guillot T, Nettelmann N. 2010. Composition and fate of short period super-Earths. The case of CoRoT-7b. Astron Astrophys. 516:A20.

Wang HS, Lineweaver CH, Ireland TR. 2019. The volatility trend of protosolar and terrestrial elemental abundances. Icarus. 328:287–305.

Umemoto K, Wentzovitch RM, Wu S, Ji M, Wang CZ, Ho KM. 2017. Phase transitions in $MgSiO_3$ post-perovskite in super-Earth mantles. Earth Planet Sci Lett. 478:40–45.

Unterborn CT, Dismukes EE, Panero WR. 2016. Scaling the Earth: A sensitivity analysis of terrestrial exoplanetary interior models. Astrophys J. 819:32.

Unterborn CT, Hull SD, Stixrude L, Teske JK, Johnson JA, Panero WL. 2017. Stellar chemical clues as to the rarity of exoplanetary tectonics. arXiv:1706.10282v2.

Zhao L, Landi E, Lepri ST, Carpenter D. 2022. Depletion of heavy ion abundances in slow solar wind and its association with Quiet Sun regions. Universe. 8:393.

Zheng L, Sasselov D, Jacobsen S. 2016. Mass-radius relation for rocky planets based on PREM. Astrophys J. 819:127.

Zeng L, Sasselov D. 2013. A detailed model grid for solid planets from 0.1 to 100 Earth masses. Publ Astron Soc Pac. 125:227.