POSSIBLE FORMATION SCENARIOS AND MINERALOGICAL TYPES OF CARBON-RICH SOLID PLANETS.
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Introduction: A broad range of exoplanetary mineral compositions is being expected for the terrestrial-like planets. Based on the composition and main structural properties terrestrial planets can be belonged to the following categories: silicate-rich planets, coreless planets, iron planets, carbon-rich planets. The most important elementary ratios in the bulk mineral compositions of terrestrial planets are the Mg/Si and the C/O ratios. Earth is a carbon-poor planet containing less than 0.01 wt % carbon [1]. Carbon-rich planets (formed in case of C/O > 0.8) are further divided into two categories: carbon planets (C/O > 1) [2] and carbon-silicate planets (C/O is between 0.8-1) [3].

Possible formation scenarios and main types of carbon-rich-planets: Super-Earths (M_P =1-10 $M_\oplus$) and the mega-Earths (M_P >10 $M_\oplus$) may also appear to have a carbon-rich compositions. Large fraction of their populations are expected to have a predominantly carbide (mostly SiC) composition, therefore, their nomination are proposed to be carbide-super-Earths and carbide-mega-Earths, respectively.

Interestinghly, the Galileo-measured abundances of CH_4 and H_2O in Jupiter's atmosphere: O is depleted by a factor of 4 and C is enriched by 1.7 relative to solar abundances, accordingly, C/O = 1.8. Lodders proposed that Jupiter could have formed from a carbon-rich embryo, which may have formed where the solar nebula was locally carbon-rich [4]. Thus, it is likely that one part of the population of carbon planets may be the giant planetary core, which have originally formed as the core of gaseous planets and they lost their atmosphere by a given physical effect such as photoevaporation process or a giant impact event.

Carbon-rich exoplanets have been proposed to form around binary stars [5], pulsars and white dwarf stars in c-enhanced circumstellar enviroments.

An interesting c-rich celestial body has been known in a binary companion, which one member of it, orbited the 5.7 ms pulsar PSR J1719−1438 [6], had been transformed from a star into a planet-like object. This is an ultra-low mass carbon white dwarf, with a mass of ~2,6 $M_{JUPITER}$ and a minimum mean density of 23 g/cm^3. Based on its physical parameters and bulk chemical composition, PSR J1719−1438 b is likely to be composed of diamant.

The formation process of the massive solid carbon planets are thought to have been similar to the massive silicate-dominated planets. Accordingly, they could be formed in the massive protoplanetary disks, in which the C/O ratio is higher than 1.

Plausible mineralogical types of carbon-rich-planets: The mineralogy of carbon-rich rocky exoplanets depends on C/O, Mg/Si, Ca/Si, S/Fe (Hakim et al. 2018)[7] and the C/Si may also be an essential factor.

In summary**,** solid **c**arbon planets can be divided into the following main categories: graphite/diamant planets (at a very high carbon ratio → c-rich Fe-core+graphite/diamant mantle), carbide planets, carbon-silicate planets. It is interesting to note that pure carbon monoxide (CO) planets may also exist [8], which could form in a stellar disk derived from a CO white dwarf that has been disrupted by the more massive component of its stellar binary [9].

A typical carbon-rich (carbide) planet (prototype) is proposed to be composed of metallic/carbide compounds : (core)/Fe, iron-carbides; (mantle)/carbides; (diamant)-graphite (crust) combination. The SiC based planets may have a pure iron core [10]. Thermal convection may be more intensive in the deep interiors of Earth-sized Si-rich carbide exoplanets than in the similar-sized silicate-dominated planets [11]. Carbon planets are thought to have methane (hydrocarbon)-bearing water-poor atmosphere.

Given basic types can be further divided into mineralogical subtypes based on the elemental enhancements in the constituent minerals.

The methane molecule is expected to be abundant in planetary systems. Accordingly, methane/methane-rich planets may exists being built up from a carbon core, methane envelope and hydrogen atmosphere [12].

According to the study of Hakim et al. (2018) the fully differentiated small c-enriched rocky exoplanets (for the case of Fe-Si-C system) are consist mainly of an iron-rich core, a silicate mantle and a graphite layer on the top of the mantle. In Fe-S-Si-C quaternary system, the composition may be even more diverse. Depending on given elementary ratios and physical conditions the cores of c-rich planets may built up from S-poor Fe inner core surrounded by a S-rich Fe outer core. Moreover, the core may composed of multiple metal-rich layers: solid Fe_3C inner core with a S-rich Fe outer core or a solid Fe inner core plus Fe_3C middle core surrounded by a FeS outer core [13]. At adequate pressure/temperature conditions, a diamond layer could form beneath a graphite layer thick enough. Interestinghly, convection may strip off diamonds from beneath the graphite layer resulting in a diamond-silicate mantle. It is likely that diamonds can likewise be found in SiC-dominated mantles. The Si-C planets with a high carbon content, may composed of SiC core, alternatively of a deep SiC_2 layer and a thick diamond mantle[14] (Table 1.).

Carbon may appeared in form of binary and ternary carbides, namely MAX ($M_{n+1}AX_n$) phases, in which the characteristic compound elements: M= Mg, Ti, Cr, Mn, Co, V; A=Si, Al, Ge, P, S, As; X=C, respectively. It is likely that abundant mineral compounds may be in the Fe-C, (Fe, Ni) C, Ti-C, Al-C, Ti-Al-C, Ti-Si-C, Co-Al-C, Ni-Al-C systems in carbon-rich planetary interiors (Table 2.)

Core	**Mantle**	**Crust**
C-rich Fe core iron-carbides	Graphite/Diamant	Graphite
	Carbides/Diamant	Graphite
	Silicates	Graphite[7]
S-poor Fe inner core S-rich Fe outer core	Carbides Silicates	Carbides[13] Silicates
Solid Fe_3C inner core S-rich Fe outer core	Carbides Silicates	Carbides[13] Silicates
Solid Fe inner core Fe_3C middle core FeS outer core	Carbides Silicates	Carbides[13] Silicates
Solid Fe_7C_3 inner core Fe_3C outer core	Carbides Silicates	Carbides Silicates
SiC core	Deep SiC_2 layer [14] Diamant	SiC
Binary/ternary carbides	Binary/ternary carbides	Binary/ ternary carbides

Table 1. Plausible compositions for the basic mineralogical types of carbon-rich planets. Given compositions are taken from the literature [7, 13, 14].

The carbon-enhanced solid exoplanets may be exotic worlds with yellow colored sky, moreover, methane-, oily mud and tar lakes may be in their surfaces. C-rich planets also still have a diamant ring, which may form from the material of a tidally-fragmented moon.

System	Carbides
Ni-C	Ni_3C
Cr-C	Cr_3C_2, Cr_7C_3, Cr_3C_6
Mn-C	Mn_3C, Mn_7C_3, Mn_5C_2
Co-C	Co_2C
V-C	V_2C, V_4C_3
Fe, Ni-C	$(Fe, Ni)_3C$, $(Fe, Ni)_7C_3$
Ti-Al-C	Ti_2AlC, Ti_3AlC_2
Ti-Si-C	Ti_2SiC, Ti_3SiC_2

Table 2. Carbides in different mineralogical subtypes of carbon-rich planets.

Summary:C-enriched rocky exoplanets are thought to have a great diversity in their mineralogical composition. The study of the chemistry of the carbon-rich extrasolar giant planet's atmosphere can provide useful information for understanding the formation of massive carbon-rich terrestrial objects.

References:

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