Origins: From the Protosun to the First Steps of Life
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Chemistry in carbon-rich protoplanetary disks: Effect of carbon grain destruction

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Abstract. The Earth is dramatically carbon poor comparing to the interstellar medium and the proto-sun. The carbon to silicon ratios in inner solar system objects show a correlation with heliocentric distance, which suggests that the destruction of carbon grains has occurred before planet formation. To examine this hypothesis, we perform model calculations using a chemical reaction network under the physical conditions typical of protoplanetary disks. Our results show that, when carbonaceous grains are destroyed and converted into the gas phase and the gas becomes carbon-rich, the abundances of carbon-bearing species such as HCN and carbon-chain molecules, increase dramatically near the midplane, while oxygen-bearing species such as H_2O and CO_2 are depleted. The carbon to silicon ratios obtained by our model calculations qualitatively reproduce the observed gradient with disk radius, but there are some quantitative discrepancies from the observed values of the solar system objects. We adopted the model of a disk around a Herbig Ae star and performed line radiative transfer calculations to examine the effect of carbon grain destruction through observations with ALMA. The results indicate that HCN, $H^{13}CN$ and c-C_3H_2 may be good tracers of this process.

Keywords. astrochemistry, ISM: molecules, solar system: formation

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The carbon deficit in our solar system is a longstanding problem. There are several possible ways to release the carbon from the solid phase to the gas phase (Finocchi *et al.* 1997; Gail 2002; Siebenmorgen & Krügel 2010; Lee *et al.* 2010). Here, we perform model calculations in two extreme cases: all carbon in carbonaceous grains is either returned to the gas or remains locked in grains. The gas phase elemental abundance ratio satisfies $C/O > 1$ in the former case, while $C/O < 1$ is found in the latter case in our model. Our results show that the differences between two models exist particularly near the midplane of the inner region of the disk where CO is not photodissociated. In the carbon-rich case, the carbon-bearing species are abundant while oxygen-bearing species are depleted.

We calculate the solid carbon to silicon ratio at different disk radii (Table 1). Here we adopt the Solar abundances (C: 2.95×10^{-4} and Si: $3.55\ \times10^{-5}$) and assume that the initial gas phase carbon abundance is 7.30×10^{-5}. In the case without carbon grain destruction, the fraction does not change much with radius since the majority of carbon is locked in refractory form. In contrast, when all the carbon is released from the solid

Table 1. The ratio of carbon to silicon in the solid phase at different disk radius and the observation of comet, meteorites, and Earth (Bergin *et al.* 2015).

	without destruction	with destruction		observation value
10 au	6.25	3.62	Comet Halley	5.7
5 au	6.25	3.39	CI	0.71
4 au	6.28	3.39	CM	0.4
3 au	6.28	3.38	CV	0.08
2 au	6.25	3.31	CO	0.07
1 au	6.25	0.04	Earth (BSE)	0.001

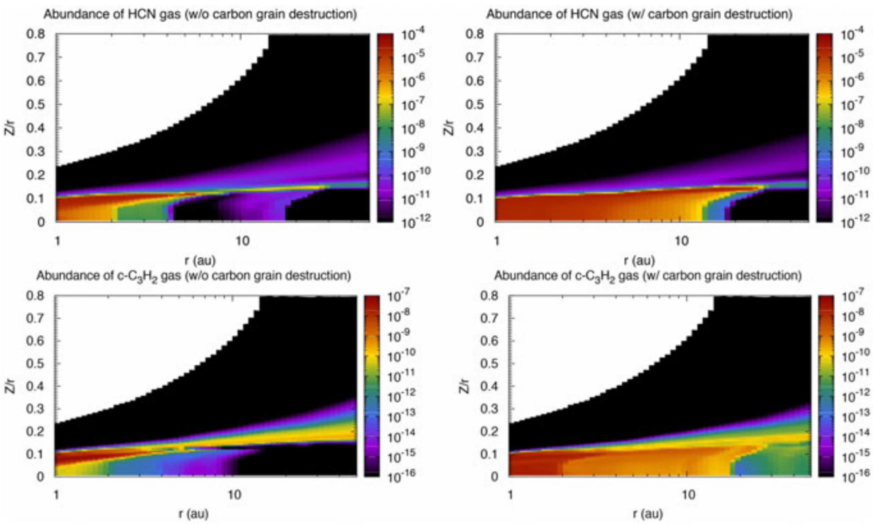

Figure 1. The 2-dimensional abundance distribution of gas-phase molecules for the models without (left) and with (right) carbon grain destruction as a function of radius and height of the disk around a Herbig Ae star.

phase to the gas phase, the fraction varies slightly at 2 au $<$ r $<$10 au and suddenly drops at r=1 au, depending on the fraction of carbon in ice. Though the model produces a radial gradient in the silicon to carbon ratio in the inner solar system, there are some quantitative discrepancies. The model predicts a relatively high carbon fraction in the asteroid belt and too much depletion at 1 au.

To examine whether or not the effect of carbon grain destruction is observable, we predict ALMA observations as well. Our results show that lines emission from T Tauri disks is too weak to probe carbon grain destruction but this effect can be probed through the line ratio of HCN/$H^{13}CN$ and c-C_3H_2 in Herbig Ae disks due to the stronger radiation and larger hot region (Fig. 1). The $H^{13}CN$ emission traces a relatively deeper layer compared to the HCN line and their ratio shows that differences due to this effect may be detectable with ALMA. See Wei *et al.* (2019) for details.

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