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Impact-induced Formation of Prebiotic Molecules on Terrestrial Planets

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Problem Statement

New species can form from **shock-induced reactions** upon formation of an impact **vapor plume** and its **interaction** with the background planetary **atmosphere** [1,2].

Previous studies have looked at:

Chemical reactions within plume BUT assuming **no atmosphere** present.	Effect of plume-atmosphere mixing BUT assuming **chemical equilibrium**.

Solving the **full chemical network** instead of assuming equilibrium **matters**: outcomes can differ up to **one order of magnitude** [3]

Questions we want to answer:

- **Which species** are produced in the plume-atmosphere interaction?
- How do their **abundances depend on**:
  - **atmospheric properties** (chemical composition, p-T profile)?
  - **impact parameters** (velocity, size, material)?
- Which conditions are **required** to synthesize **prebiotic** species?
  - **Prebiotic species** we are interested in are **HCN**, CH_4 and NH_3.

Model

HYDRODYNAMICS

- Modeling physical **expansion** of the **plume** into the atmosphere;
- Tracking **p-T** conditions;
- Implementation of **sector flow** model [4].

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KINETICS

- Modeling chemical **reactions**;
- Tracking **species abundances**;
- Implemented with **Cantera** package [5].

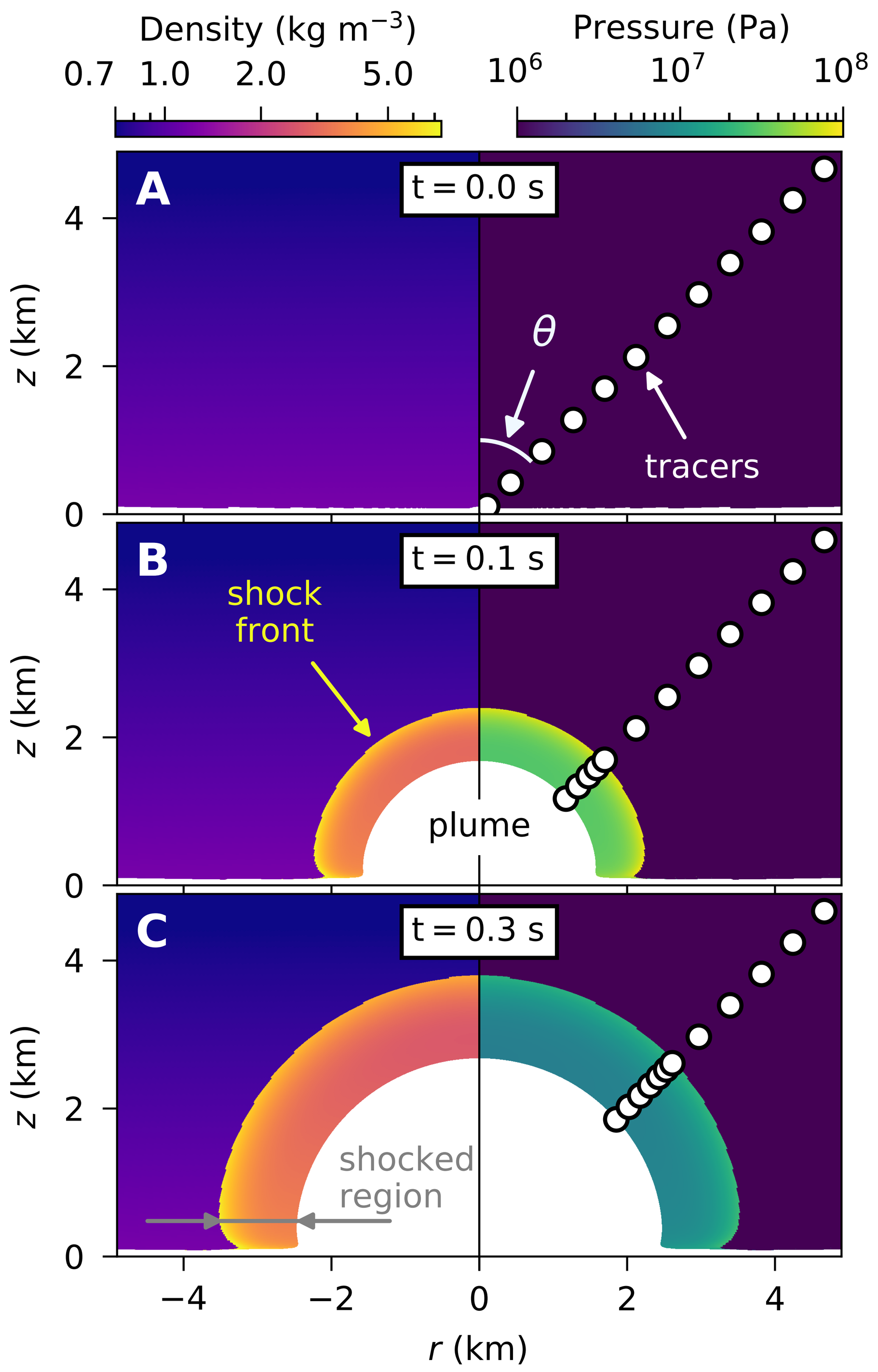

Figure 1. Atmospheric density (left) and pressure (right) evolution during plume expansion at different times after impact (A–C).

30-sec Takeaway Points

- We modeled the **interaction between impact plume and** planetary **atmosphere** to understand when **prebiotic species are formed**.
- We find **appreciable amounts** of HCN, CH_4 and NH_3 **produced** when:
  - **methane** is **present** in the atmosphere;
  - surface **density** is **large**;
  - impact **energy** is **low**.
- Our preliminary **results** are **sensitive to** the choice of **mixing ratio** between plume and atmosphere.
- Impacts on **present-day Solar System** planets are **unable to produce prebiotic** species.

Results

We investigated the dependence of species abundance on surface density (ρ), energy (E_k) and methane fraction (f_{CH_4}).

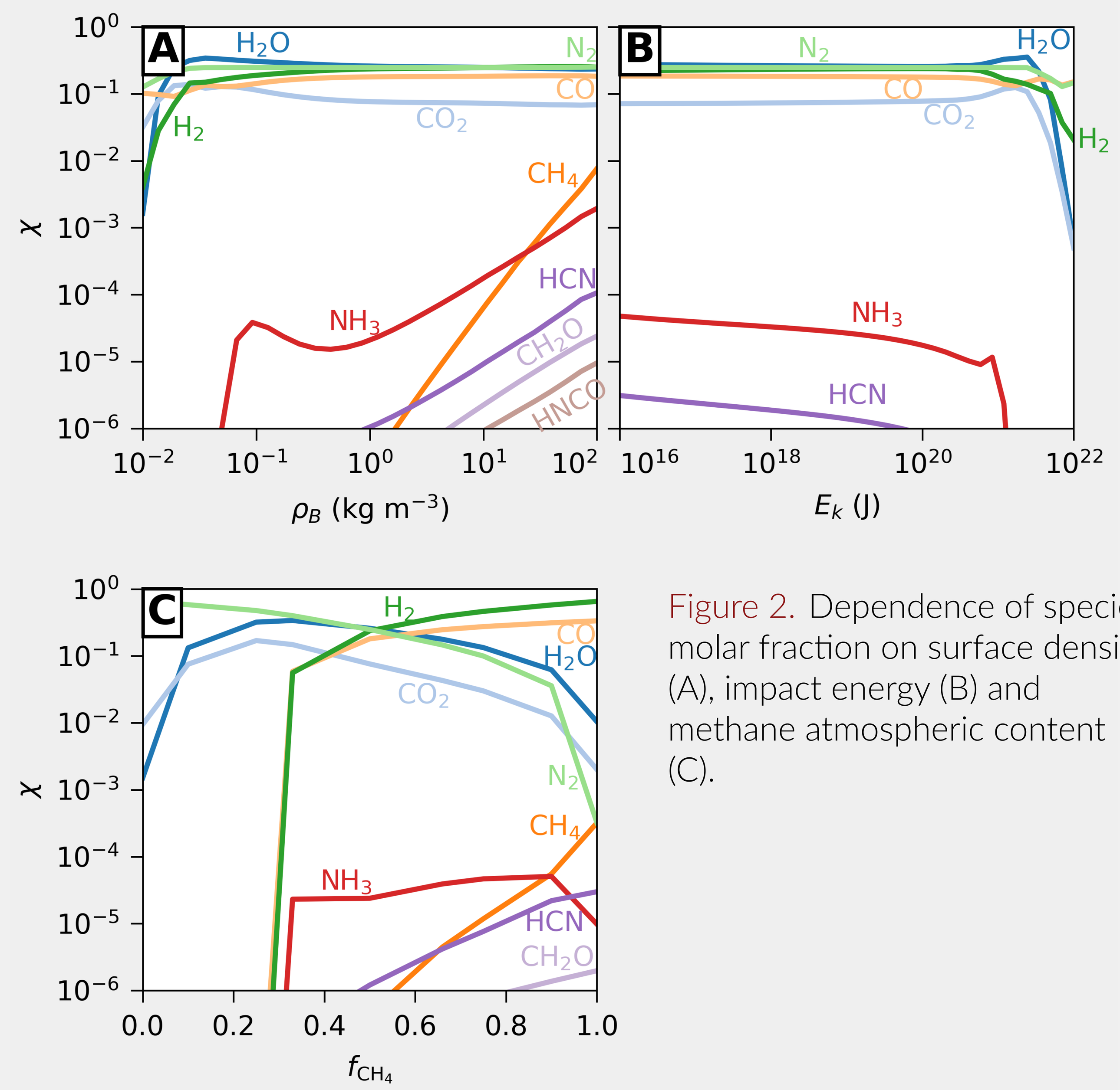

Figure 2. Dependence of species molar fraction on surface density (A), impact energy (B) and methane atmospheric content (C).

We assumed a **fixed** Earth-like **size** and EH-like surface **composition** planet. The **default features** are:

- **binary** 50% CH_4 and 50% N_2 **atmosphere**;
- **Earth**-like surface **density** ($\rho = 1.225$ kg m^{-3});
- hit by **projectile** with E = 2.38×10^{19} J.

(A) Prebiotic species abundances increase as ρ increases.

(B) Abundances tend to decrease with increasing energy.

(C) Abundances increase as more CH_4 is available in the pre-existing planetary atmosphere.

Sensitivity

For kinetics, we use a mixture of **50%** vapor **plume** and **50% atmosphere**. **Changing** the **fraction** ϕ of atmosphere leads to **different final abundances**.

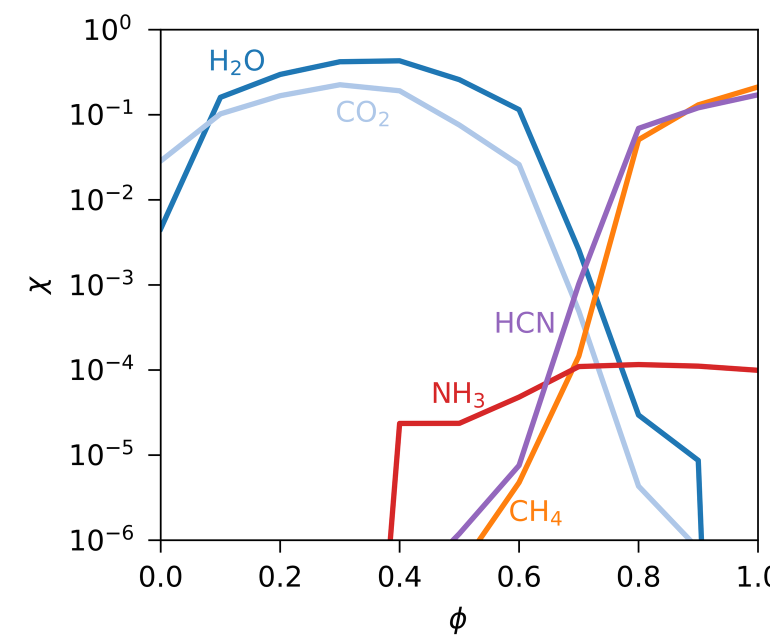

Figure 3. HCN abundance as a function of the fraction of atmosphere in reacting mix (ϕ): the molar fraction of prebiotic species peaks where $\phi = 1$.

Solar System Analogs

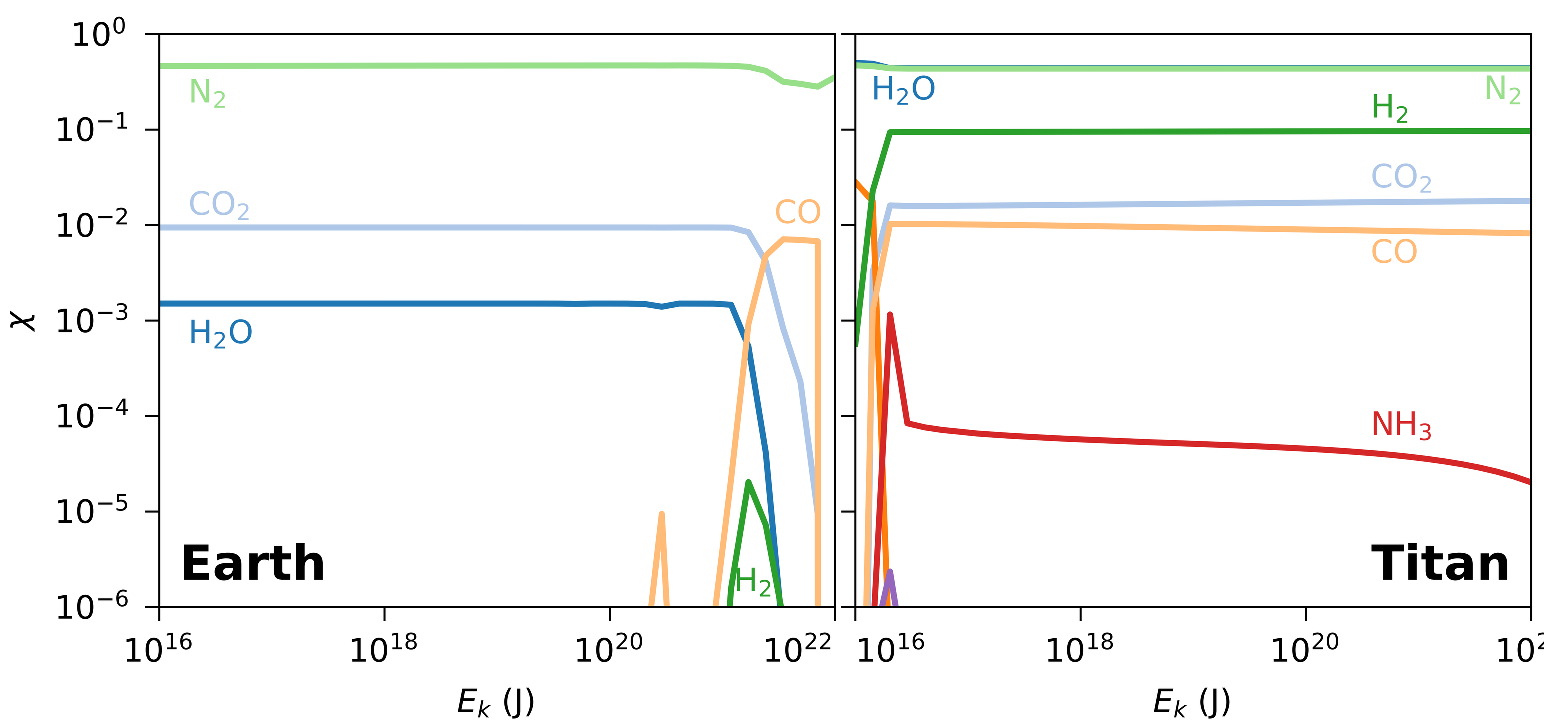

Figure 4. Molar fractions as a function of impact energy for Earth- (left) and Titan-like (right) analogs.

Impacts on **Earth**-like planets (N_2 + O_2 atmospheres) are **not able to synthesize prebiotic** molecules. The same applies to the CO_2-rich Venus and Mars analogs.

Titan-like bodies can **produce ammonia**, with abundances decreasing with impact energy.

Future Prospects

- Inclusion of **sulfur chemistry**.
- Application to known **exoplanets analog** and **ancient Solar System** objects conditions.
- **Net production** during sustained **bombardment** from impactor fluxes and N-body simulations.

Acknowledgements

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References:

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[5] Goodwin, D. G., Moffat, H. K., Schoegl, I., Speth, R. L., and Weber, B. W. (2022). https://www.cantera.org (v. 2.6.0)