UV Photolysis and Creation of Complex Organic Molecules in the Solar Nebula

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Organic molecules in the young solar system

Carbonaceous chondrites contain upwards of 100 different amino acids, many of which have no known terrestrial occurrence [1,2]. The origin of these molecules is unknown. Comets also include high organic fractions, up to 30% organic carbon by mass.

Two proposed possibilities for the complex organics are that they are a) formed by Streck synthesis in ancient sub-surface aquifers on asteroid parent bodies [2], or b) by accretion of material created in the ISM [3,4]. Measured D/H ratios of the meteoritic amino acid samples imply a low-temperature origin, challenging model a). And dense molecular clouds are nearly opaque to UV penetration, challenging model b).

We propose here a third mechanism, by which complex organic molecules can be created in the young solar system directly by UV irradiation from external O and B stars in dense star clusters.

Creation of organic molecules

Complex organic molecules can be created by a variety of processes, including thermochemistry, lightning, charged particle irradiation, and solar- and stellar-driven photochemistry [5,6,7,8]. Photochemistry has usually been ignored outside the inner 0.5 AU because of the extreme line-of-sight optical depths within the proto-solar nebula (*"5 million to 110 million orders of magnitude"* of extinction, [5]).

However, UV from *external* O and B stars can be a bright source that is largely unaffected by any line-of-sight extinction.

Laboratory studies have shown that UV light hitting ISM-like ices (H_2O, CH_3OH, HCN, NH_3) can create organic molecules such as amino acids [4,9,10]. The yield of this process is approximately 0.1% (molecules/photon) [4]. The process is robust under a range of ISM-like temperatures, pressures, irradiation levels, and initial ice mixtures.

The Solar System is believed to have formed in a UV-bright environment, and thus UV photochemistry in the young disk may explain the Solar System's initial organic abundance, including the chondritic amino acids.

Disk Model

We developed and ran a numerical model which simulates the exposure of the young Solar System disk to radiation. Icy surfaces in the exterior skin layer of the disk are exposed to UV photons, which can photolyze ices into organic molecules.

Disk Processes in Model	
Grain growth	Throop et al 2001 [11]
Photolysis of ices	Bernstein et al 2002 [4]
Photo-evaporation of gas	Throop & Bally 2005 [12]
Viscous evolution	Pringle 1981 [13]

The disk is placed in a UV-bright environment and integrated numerically using a variable timestep Crank-Nicolson integrator. The UV exposure of ices in the disk is tracked as a function of time. As grains grow, surface area becomes locked away and cannot be further irradiated.

Our model does not include specific chemical reactions, but predicts the UV exposure of icy material in the disk as a function of time and location, for a variety of environmental and formation scenarios. The nominal parameters are listed below. Additional parameter sets explore debris disk, massive disks, slow/fast grain growth, and different disk structures.

Nominal Disk Parameters	
Disk Mass, Stellar Mass	0.04 M_{sol}, 1 M_{sol}
Disk Radius	40 AU
Gas:Dust ratio	50:1
Photolysis Efficiency	0.1%
UV Exposure	10^6 G_0
Run time	3 10^5 year

Results

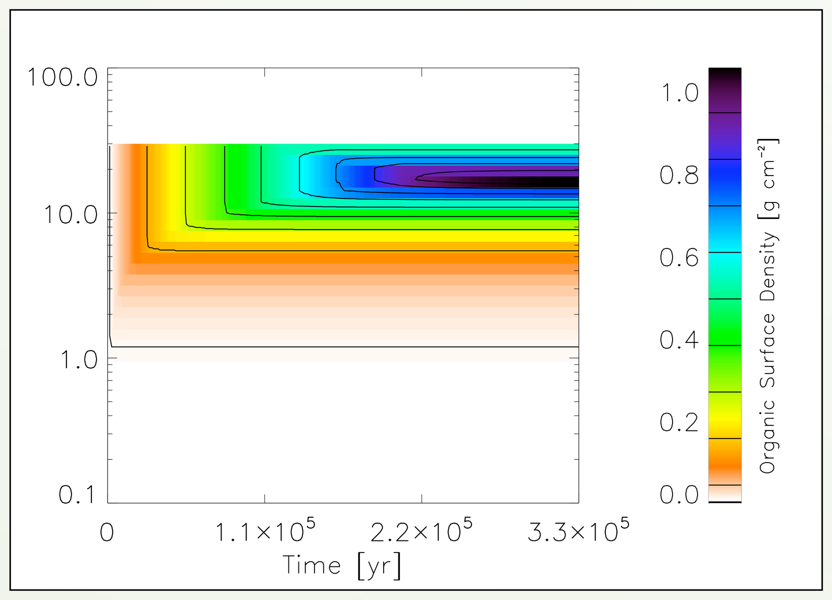
In the outer disk, we find UV energy depositions of up to 3000 photons/molecule (4 10^5 eV/molecule) in 10^5 years. This is *sufficient flux to photolyze the Solar System's entire volatile inventory outward of 20 AU* into complex organics, assuming 0.1% efficiency and no loss processes.

In the inner disk, the energy deposition is lower because of rapid grain growth (which locks up surface area) and the larger initial surface mass density. Nevertheless, the flux is still flux is *sufficient by a factor of 10^5x* to create the entire organic inventory of Murchison of ~20 ppb.

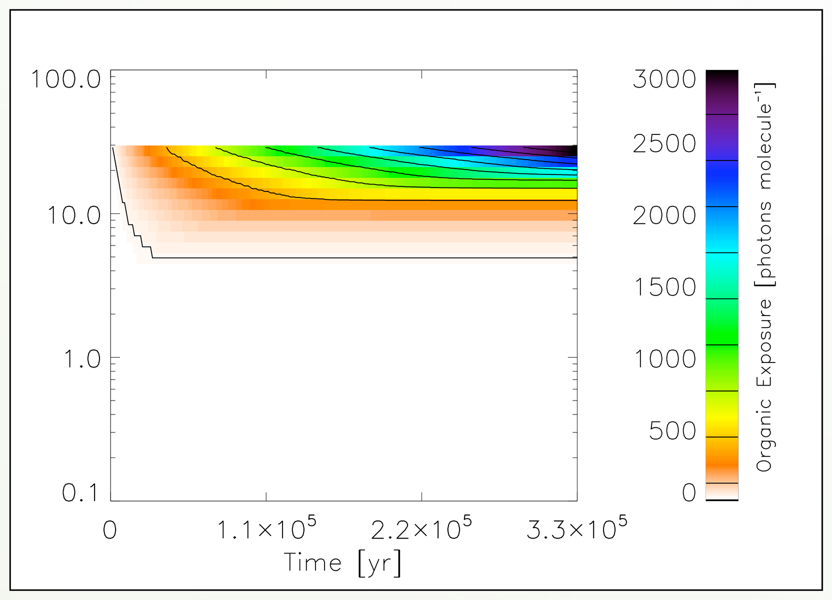
Our results are robust against most changes to the initial parameters. However, if grains are given 10^5-10^6 yr to grow in a dark environment before UV begins, then their surface area is locked away and UV photolysis can be prevented.

Our model does not explicitly consider loss processes (such as destruction of organics by UV) but assumes very conservative inputs; see paper for more details.

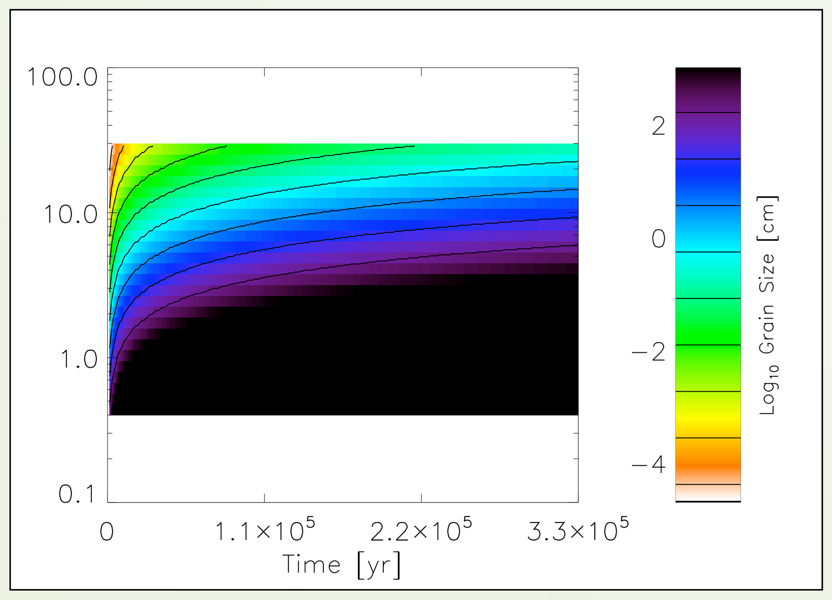
A. Organic Surface Density



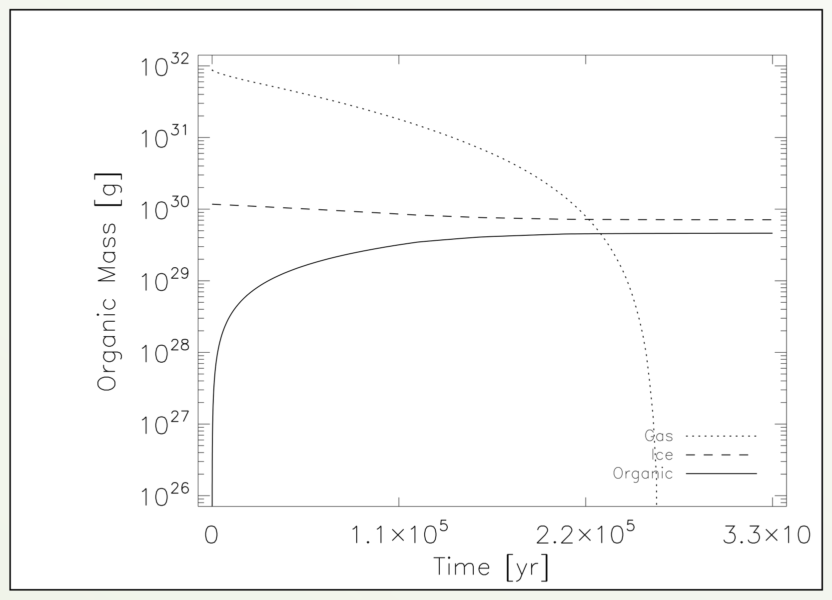
B. Energy Deposition Density



C. Ice Grain Size



D. Disk Mass (Ice, Gas, Organic)



A. *Production of organic molecules from ices. After 3 10^5 years, there is sufficient UV flux to entirely photolyze all ices in the disk outward of 20 AU.*
B. *The net flux deposited into the disk reaches 3000 UV photons/molecule at the outer edge.*
C. *Grains grow rapidly at the inner disk edge. The slow growth at the outer edge allows ices there to be exposed for longer times, allowing for more photolysis.*
D. *At the end of the simulation, about 1/3 of the disk ice inventory has been photolyzed into organics. The disk's gas is lost after 2.5 10^5 years, due to photo-evaporation.*

Conclusions

1. UV irradiation of young disks -- including the Solar nebula -- by external stars can play a substantial and unappreciated role in determining the solar system's chemical and organic composition.
2. The organic production by UV photolysis in a disk within a dense star cluster can be many orders of magnitude higher than by any other process.
3. Synthesis of the meteoritic amino acids is readily possible in a nebular disk illuminated by external O/B stars, and does not require warm asteroidal aquifers, nor creation of complex organics in the dark conditions of the ISM.
4. Although extreme UV-bright environments such as Orion are usually thought to be hazardous to planet formation, they may in fact cause the planetary systems which form there to be extremely rich in pre-biotic materials and thus a potential haven for life.

References

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