Creation of Pre-Biotic Organic Molecules in Young Circumstellar Disks

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TAKE-AWAY MESSAGE

Models for the early Solar System assume that UV processing of volatiles played virtually no role in the formation of organic molecules. However, if the Sun formed in a dense OB association such as Orion, ionizing UV flux from nearby massive stars would be increased by 10^7 times, providing sufficient flux to create a plethora of simple and complex organic molecules needed for life.

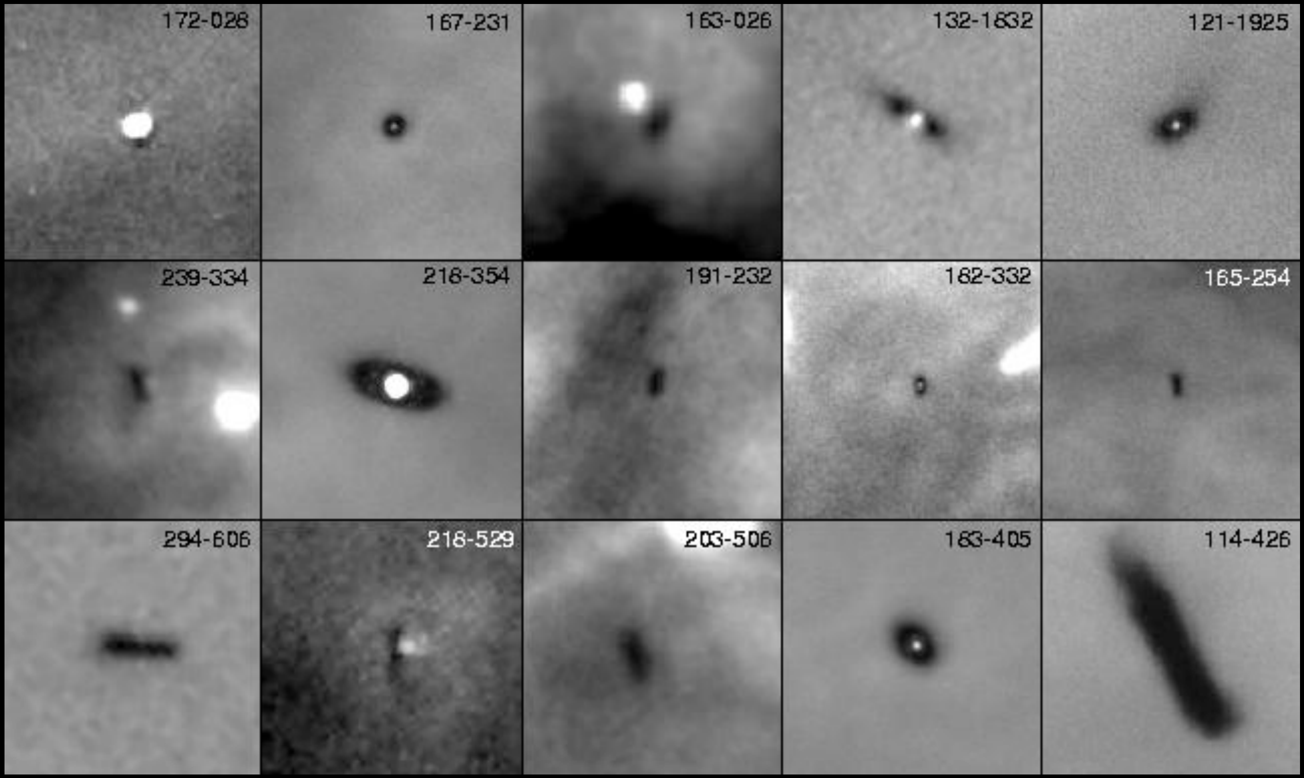
Where Did Our Solar System Form?

The vast majority of stars forming in the galaxy today form in dense star clusters ('OB associations') where young, Sun-like stars are bathed in UV radiation from nearby O and B stars 10^5 times brighter than our own Sun. Orion currently has ~2000 young stars. Recent observations indicate that up to 90% of stars may form in regions like this. Cool, dark clouds like Taurus are closer and better-studied, but much smaller: typical sizes are < 100 stars.

It is not known whether our own Sun formed in a large cloud like Orion or a small one like Taurus; however, the Solar System's creation would evolve very differently along each of the two paths, because of the UV radiation from close stellar neighbors in the dense clusters. Some isotopic evidence suggests that the Solar System may have formed near massive stars (cf. Hester et al). Such a star cluster would have long dispersed as its massive stars burned out, leaving the Sun isolated as it is today.

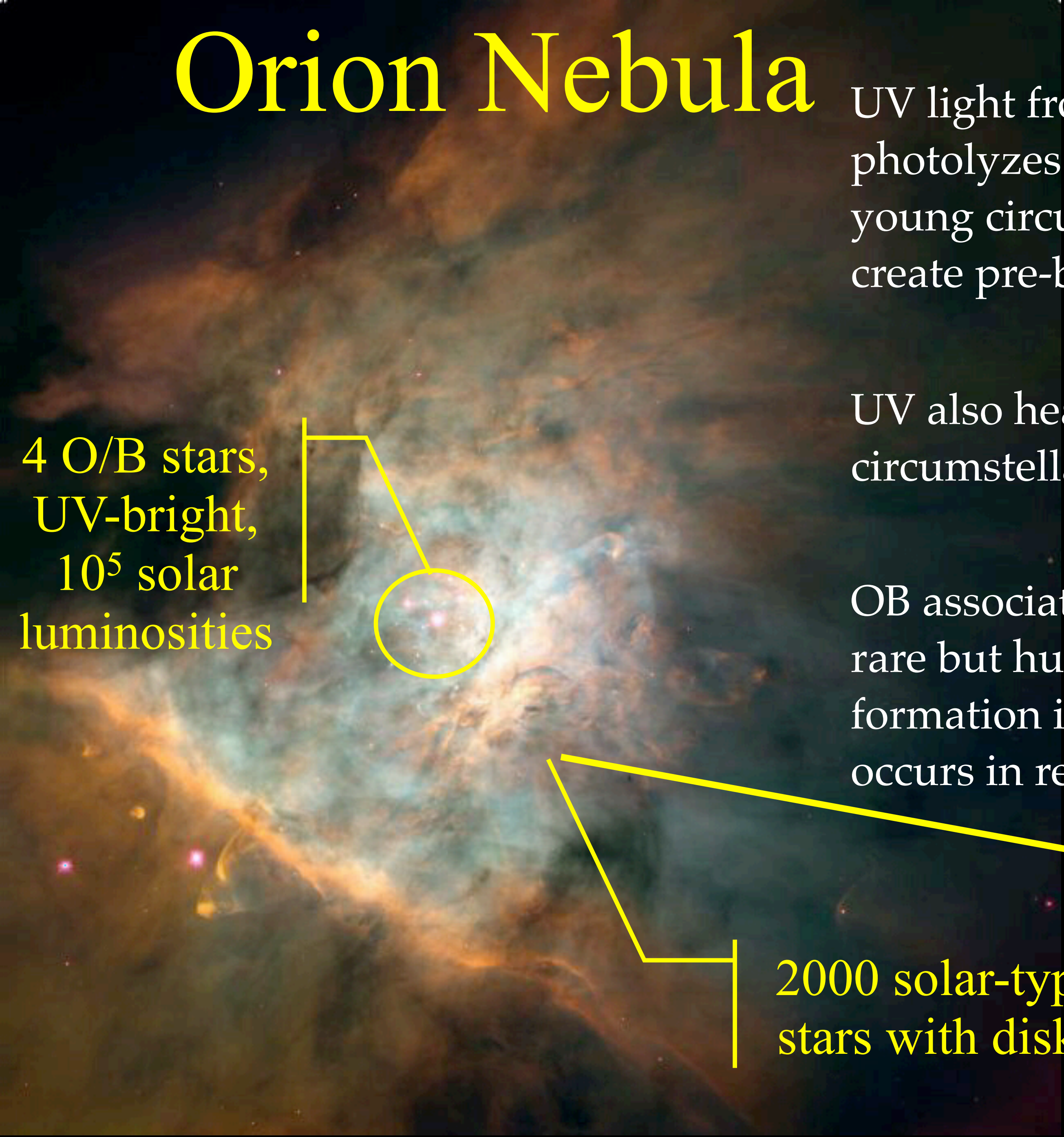
Almost all solar system formation models assume that the Sun formed in isolation, away from the effects of external stars. We are re-examining that assumption, both as it applies to our Sun and to other potentially life-bearing systems.

Circumstellar Disks In Orion



Observed disks range in size from 100 to 1200 AU. Most disks in Orion are being photo-evaporated by nearby O stars. Figure from Bally et al (2000).

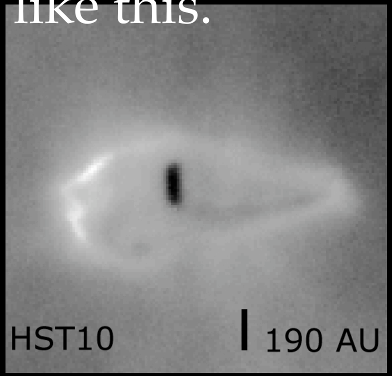
Orion Nebula



UV light from massive O/B stars photolyzes ices in nebula and young circumstellar disks to create pre-biotic organics.

UV also heats and destroys circumstellar disks.

OB associations like Orion are rare but huge – majority of star formation in the galaxy probably occurs in regions like this.



Circumstellar Disk Evolution Model

Our numerical model simulates the evolution of a circumstellar disk. The disk is divided into a 50x50 grid which tracks abundance of four species (gas, silicate, inorganic ices, and organic ices) as the disk evolves. A time-stepping method is used. We consider the following processes:

- o Photo-evaporation (Johnstone et al 1993)
- o Grain growth (Markiewicz et al 1988)
- o UV photolysis and production of organic molecules from ices (Gerakines et al 2004, Bernstein et al 2002)

Our model begins with solar-mass star surrounded by 0.1 M_{Sun} of material distributed out to R=400 AU. Initially this material is distributed between four distinct species: gas (H_2), rock (silicates), and ices (volatiles). All components have a distribution taken from the interstellar medium (ISM) near Orion.

The system is then evolved forward in time. The outer disk is heated by UV radiation and removed. Large grains grow and settle to the midplane. As the gas is removed, icy particles that have settled to the midplane are exposed to UV. This radiation produces more complex organic molecules from the simple initial species.

The amount of organic material produced depends on the UV flux, the quantum efficiency of conversion, and the projected surface area of icy grains in the disk. We take the net conversion efficiency from ice to organics to be be 10^{-3} (molecules per photon); in reality, this number will change with time as the species evolve.

Results

We evolve the system for 10^5 year. By this time the gas has been removed by photo-evaporation inward to 5 AU. 100% of the H_2 gas outside of this distance has been removed, along with nearly 75% of the silicates and ices. Of the remaining ices, approximately 25% has been converted into organics.   This is an enhancement of several times over the organic content of the solar system produced by standard models (cf. van Dishoeck et al 1993)

The strongest factor in determining the amount of organics produced is the rate of grain growth. If grains grow quickly, surface area is `locked up' and protected against the beneficial effects of irradiation. If grains grow slowly or grain collisions cause frequent breakup and re-formation, however, new un-processed surface area is exposed; this new material can then be efficiently photolyzed into organic material.

The Irony

UV irradiation has traditionally been considered to be a hindrance to planetary formation, because it heats and destroys young circumstellar disks and planet-forming material on timescales much faster than planetary formation timescales (< 1 Myr). However, this very same UV radiation can also cause the formation of pre-biotic organic molecules. Which process dominates: Are solar systems formed near OB associations likely to **encourage** life, or **discourage** it?

In other work, we showed (Throop et al 2004, astro-ph/0411647) that UV photo-evaporation may indeed encourage the rapid formation of planetesimals, by removing the gas which inhibits a gravitational instability. **Combining those results with the present work, therefore, we find that rather than producing a limited number of dead planets, formation in an OB association may rather produce a large number of planets teeming with organic molecules.**

Organic Molecules in the Young Solar System

Comet Halley was estimated to carry up to 30% organic material by mass. Carbonaceous asteroids are typically up to 5% carbon polymers by mass, and several percent of this mass is in amino acids. These fractions exceed by several times those observed in the ISM. Traditional models for early chemical evolution of the nebula use a variety of thermal and chemical processes to explain this enhancement (cf. van Dishoeck et al 1993)

UV radiation has long been ignored as an important factor in nebular evolution, because UV radiation from the Sun is shielded by high optical depths of both gas and dust along the equatorial plane. However, nearby massive stars **external** to the disk produce large amount of UV flux (10^7 x higher; typically 10^{14} photons/sec/cm^2) across the entire disk. This flux is absorbed directly by small dust grains in the nebula.

Amino acids are usually assumed to be formed in warm, wet conditions such as those found on the young Earth. This does not easily explain their presence on asteroid surfaces. However, Bernstein et al (2002) found that UV photolysis of a 10 K solid H_2O / CH_3OH/NH_3/ HCN mixture produced amino acids such as serine and glycine. If such processes occurred in the ISM in dense OB associations, organic molecules could be easily distributed throughout the young solar systems forming there, without the need for warm, aqueous chemistry.

Caveats

- Our model assumes a single species and conversion efficiency. Organic chemistry is much more complex than this!
- We model only the production of organics, not their loss by UV photolysis
- Photo-sputtering (which we do not consider) will convert some ices into gas which may be subsequently lost.
- Grain growth rates play an important role, but are poorly understood. If grains grow rapidly into km-scale bodies, only limited surface area for photochemistry sites is available.

Conclusions

- There is sufficient flux in the UV to account for the creation of the Solar System's current organic content.
- The total UV dose received during the first 10^6 yr exceeds 10^4 photons/molecule.
- Our model predicts a greater conversion of inorganic ices to organic molecules in the outer solar system relative to the inner.
- The amount of UV photolysis experienced depends on the grain growth rate: slower grain growth allows more exposed surface area and thus greater UV production.

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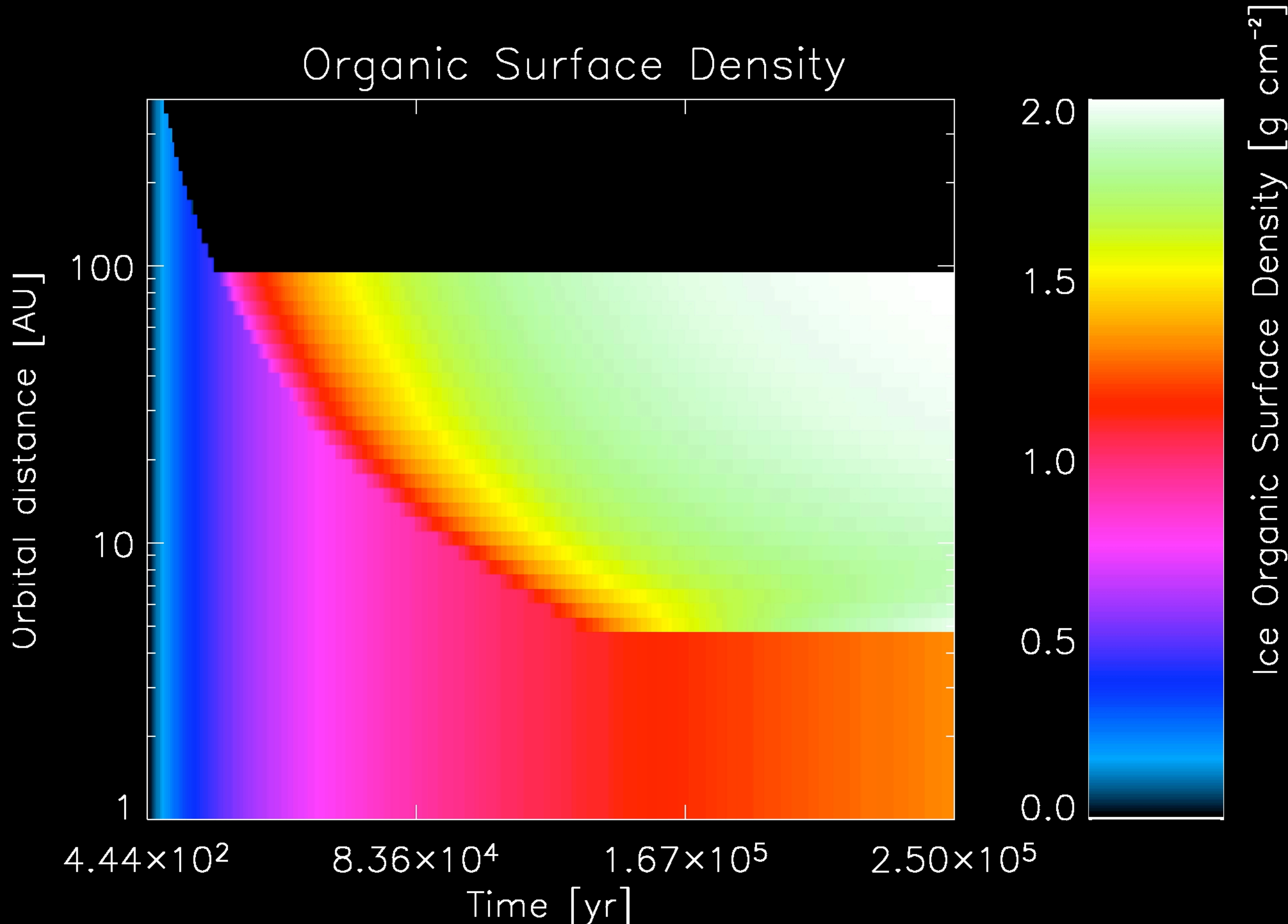
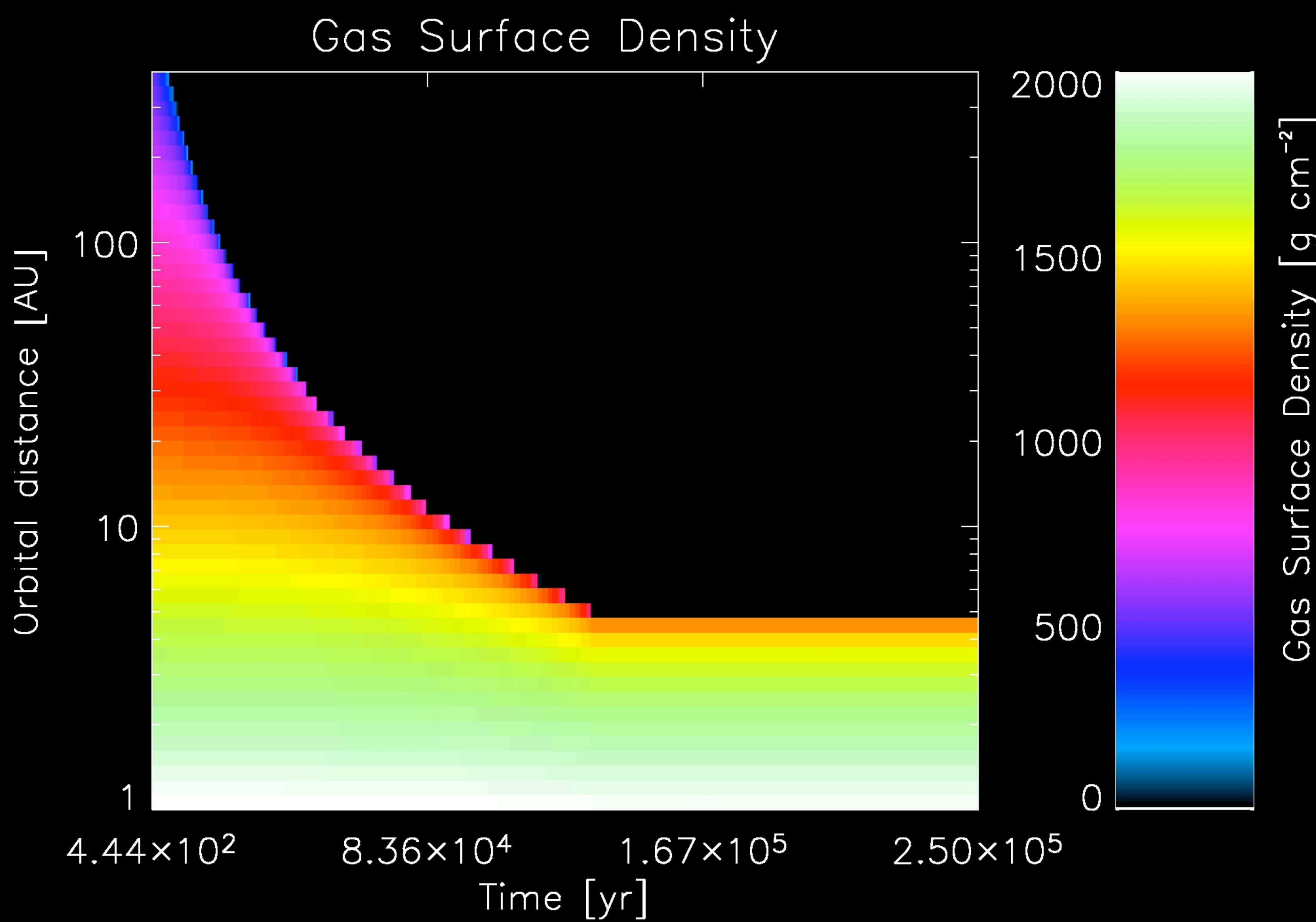
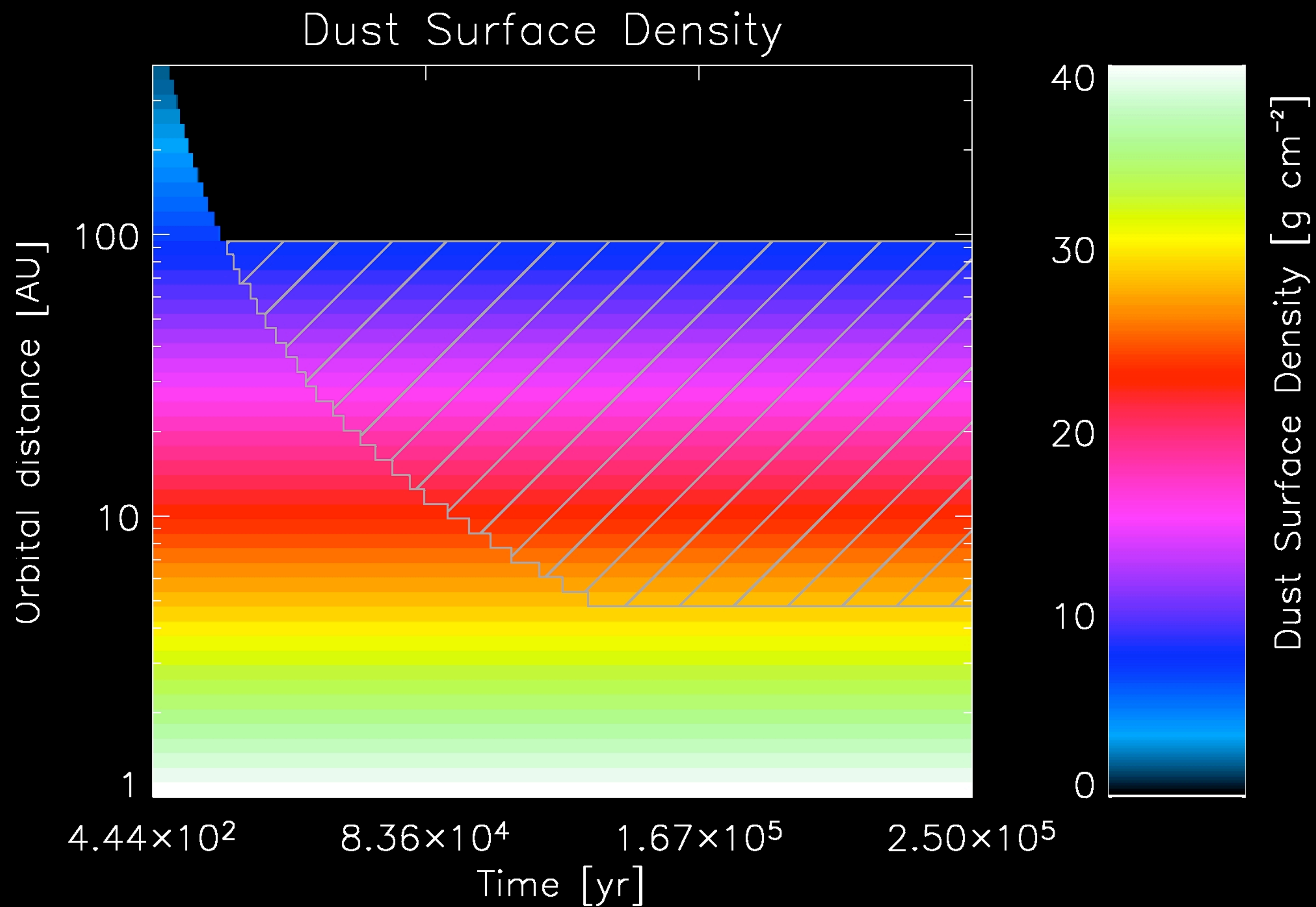


Organic molecules are created in the disk by photolysis of ices. The initial organic abundance is zero. Ices throughout the disk are slowly photolyzed. After the gas envelope is removed from the outer disk (green portion), then remaining ices are rapidly photolyzed. Organic production remains slower at the inner disk because grain growth is faster (sequestering surface area) and because the remaining gas envelope blocks UV penetration.



UV radiation heats and removes gas from the disk. After 10^5 years, the gas outward of 5 AU is removed.



Dust is removed from the disk. Grains inward of 20 AU have grown large enough to be retained.