



Universiteit
Leiden
The Netherlands

A molecular journey : tales of sublimating ices from hot cores to comets

Bogelund, E.G.

Citation

Bogelund, E. G. (2019, March 14). *A molecular journey : tales of sublimating ices from hot cores to comets*. Retrieved from <https://hdl.handle.net/1887/69725>

Version: Not Applicable (or Unknown)

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/69725>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/69725> holds various files of this Leiden University dissertation.

Author: Bogelund, E.G.

Title: A molecular journey : tales of sublimating ices from hot cores to comets

Issue Date: 2019-03-14

ENGLISH SUMMARY

Our galaxy, the Milky Way, is home to approximately 400 billion stars. One of these stars is the Sun. Orbiting the Sun are eight planets. Four of these are so-called rocky planets, that is, they have solid surfaces. Among the rocky planets is our home: Earth. The remaining four planets are so-called gas giants. These planets are much larger and more massive than the rocky planets and are predominately composed of gas, with no solid surface. In addition to the planets, smaller rocky bodies known as asteroids, and icy bodies known as comets also orbit the Sun. Together, the Sun, the planets, the asteroids and the comets are referred to as the Solar System.

Astronomically speaking, the Sun is not a very special star, in fact, the majority of stars in the Milky Way are very similar to the Sun; they have approximately the same mass, they consist of the same material and are of similar size. Orbiting planets are also not uncommon. Actually, the majority of Sun-like stars in the Milky Way seem to host at least one planet, although the combination of planets seen in the Solar System is fairly unique. What truly sets the Solar System apart is the fact that it is the only place, in the entire Universe, where we are sure that there is life. But what enabled life to evolve here? And, maybe even more exciting, what are the chances that life has evolved, or will evolve, somewhere else in the Universe? To address these questions, we first have to understand how the Solar System and life on Earth came to be. This includes understanding how stars and planets are formed, but also understanding the formation of the molecules (structures of atoms bound together by chemical bonds) which provided the basic building blocks of life as we know it.

The formation of stars and planetary systems

The areas where stars are born are known as star-forming regions. These regions consist of clouds of small dust particles and gas. The most common types of gas in the star-forming regions are hydrogen and helium but small amounts of oxygen, carbon and nitrogen are also present. These atoms are of particular interest to life since oxygen, carbon, hydrogen and nitrogen are the four most abundant elements in the human body. An example of a star-forming region is shown in Figure 1. In this spectacular image, a myriad of new stars are being formed within the dusty and gaseous structures of the region.

Once a star-forming cloud is sufficiently massive, it becomes unstable and starts to collapse. This collapse is due to the force of gravity which acts on all the atoms in the gas and dust, pulling them together. After the collapse, an infant star, a so-called protostar, is formed at the centre of the cloud. Surrounding the protostar is a disk of material, which feeds the young star with gas and dust from the parent cloud. Over time, some of the material in the disk starts to clump together. As the star-disk system evolves, the bigger disk-clumps start sweeping up smaller clumps and in this way grow to so-



Figure 1: The 'Mystic Mountain' of the Carina Nebula captured by the *Hubble* Space Telescope. This star-forming region is located 7500 light-years away in the southern constellation of Carina. The image shows mountains and pillars of dust and gas within which stellar nurseries are hidden. Due to the strong radiation coming from the newborn stars the pillars are shaped and compressed, triggering the formation of even more new stars. Streaming from the top of the towering peaks, infant stars buried inside jets of gas can be seen. Along the ridges of the structure, streamers of hot ionised gas can be seen while wispy veils of gas and dust, illuminated by starlight, float around it. The high densities in the inner parts of the pillars protect them from being eroded by radiation. Image credit: NASA, ESA, M. Livio and the Hubble 20th Anniversary Team (STScI).

called planetesimals. Some of the planetesimal continue to grow and eventually become planets while other remain small. These smaller clumps are refereed to as asteroids if they are mostly rocky and comets if they are mostly icy. The gas in the cloud which forms the protostar is heated due to the accretion of material onto the forming star. In this process gravitational energy is converted to heat. Once the protostar is formed and the temperature at its centre exceeds approximately 1 million degrees Celsius, nuclear fusion reactions begin to take place. In these reactions, deuterium is fused into helium until the temperature becomes high enough to also ignite hydrogen fusion. This happens when the temperature at the center of the star reaches approximately 10 million degrees Celsius. The energy released from the nuclear fusion processes is enormous and after the hydrogen fusion has kicked in, the radiation coming from the newborn star is so strong that the remaining material in the disk is cleared out. At this point, the star and planetary system is fully formed. Depending on the mass accumulated by the newly formed star, it will be referred to as either a high-mass star or a low-mass star. Generally speaking, low-mass stars have masses which are lower or similar to the Sun. High-mass stars on the other hand, may be more than 100 times heavier than the Sun. Depending on the mass of the star, different elements will be formed in its centre. Eventually, when the star dies, these elements will be recycled back into space where they will be incorporated into new stars and planets. An overview of the star formation process is presented in Figure 2.

The formation of a star and planetary system is only the first step on the road to forming a habitable planet like Earth. In the case of the Solar System, 4.6 billion years has passed from the Sun and planets were formed to the Earth we inhabit today. During this time, the system has undergone considerable changes. The most dramatic of these include a proposed shift in the position of the giant gas planets and the continues collisions between bodies which still occur in the Solar System today. For the Earth, the dominant changes include the formation of an atmosphere and the presence of water on the surface of the planet. It is thought that the presence of water on the young Earth was key for the emergence of the first forms of life. Potentially, the molecules which evolved into these earliest forms of life may have been delivered to Earth by impacting comets or asteroids.

Because we cannot directly investigate what the newly formed Sun and Earth looked like, we turn our attention towards other systems which are currently being formed. By observing these systems and studying the molecules which are present there, we get a better idea of what may have happened during the formation of our own Solar System. In order to study these systems, advanced telescopes are needed. These telescopes are able to zoom in on the regions where the new stars are being formed and have the sensitivity to detect the multitude of atoms and molecules which are present there.

Studying atoms and molecules in space

The most powerful tool when studying atoms and molecules in space is the use of spectroscopic fingerprints. Just like human fingerprints, atoms and molecules have their own and unique fingerprints by which they can be identified. These fingerprints consist of a well-defined pattern of lines that arise when the atom or molecule emits radiation. The patterns of lines can be measured in laboratory experiments and are referred to as the spectrum of the atom or molecule. If multiple atoms or molecules are emitting radiation in the same region, many spectroscopic fingerprints will be observed at the same time. Figure 3 is an example of a spectrum containing the fingerprints of many different molecules detected towards a star-forming region located in the constellation Orion. By comparing the observations of this region with the spectra that are measured in the laboratory, the molecules which are present in Orion can be identified. Many of the

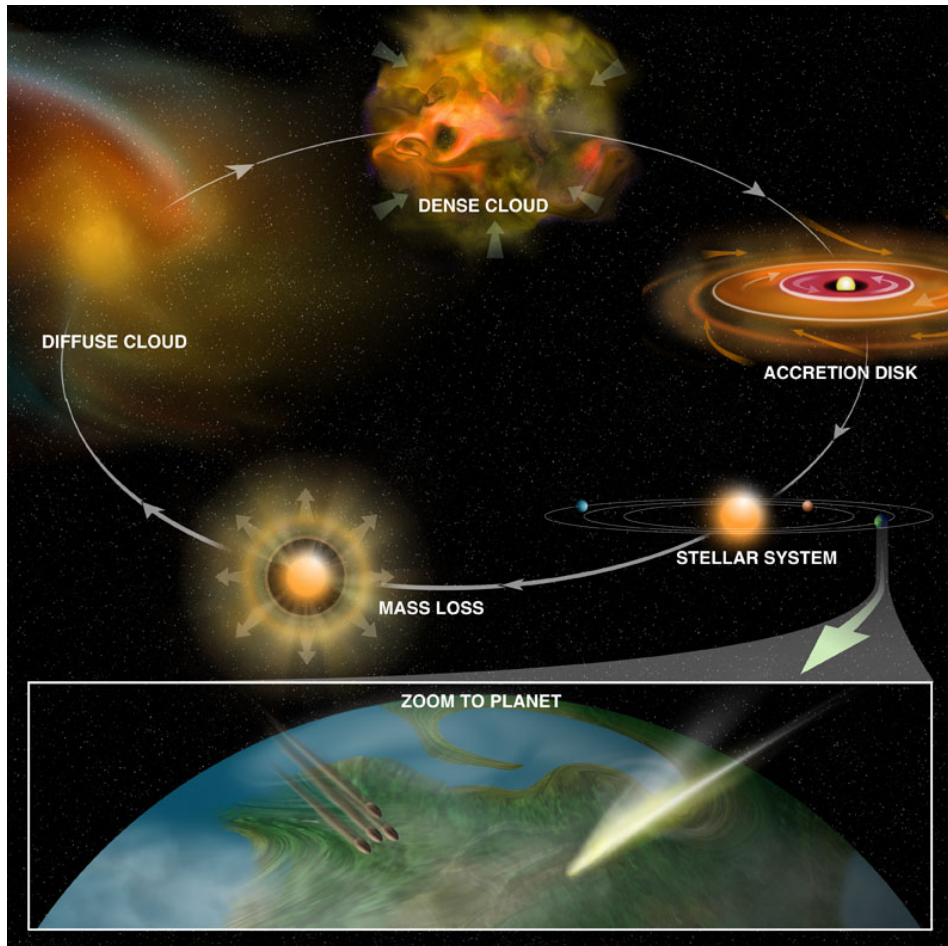


Figure 2: Schematic view of the formation of a star and planetary system in the life cycle of interstellar material. From a dense cloud of dust and gas, a so-called protostellar system is formed. This system consists of a central protostar and a rotating disk of dust and gas that accretes material from the parent cloud. Planets and comets will eventually form from the material in the accretion disk. As the system evolves, the temperature and density of the forming star increase, igniting thermonuclear reactions. In this process, light elements are processed into heavier ones in the stars interior. Radiation from the newly formed star removes gas and dust from the disk leaving only planets, comets and small interplanetary dust particle in orbit around the star. A zoom to one of the planets in the system shows how organic material may have been delivered to the planetary surface by passing comets and asteroids. As the star evolves, the enriched materials which are formed in its centre are recycled back into interstellar space in processes known as mass loss. These include the continuous removal of material from the stellar surface via stellar winds but also supernova explosions as the stars die. Finally, the material which has been recycled in the stars and blown back into interstellar space, accumulates into new clouds from which new stars can form. Image credit: B. Saxton, NRAO/AUI/NSF.

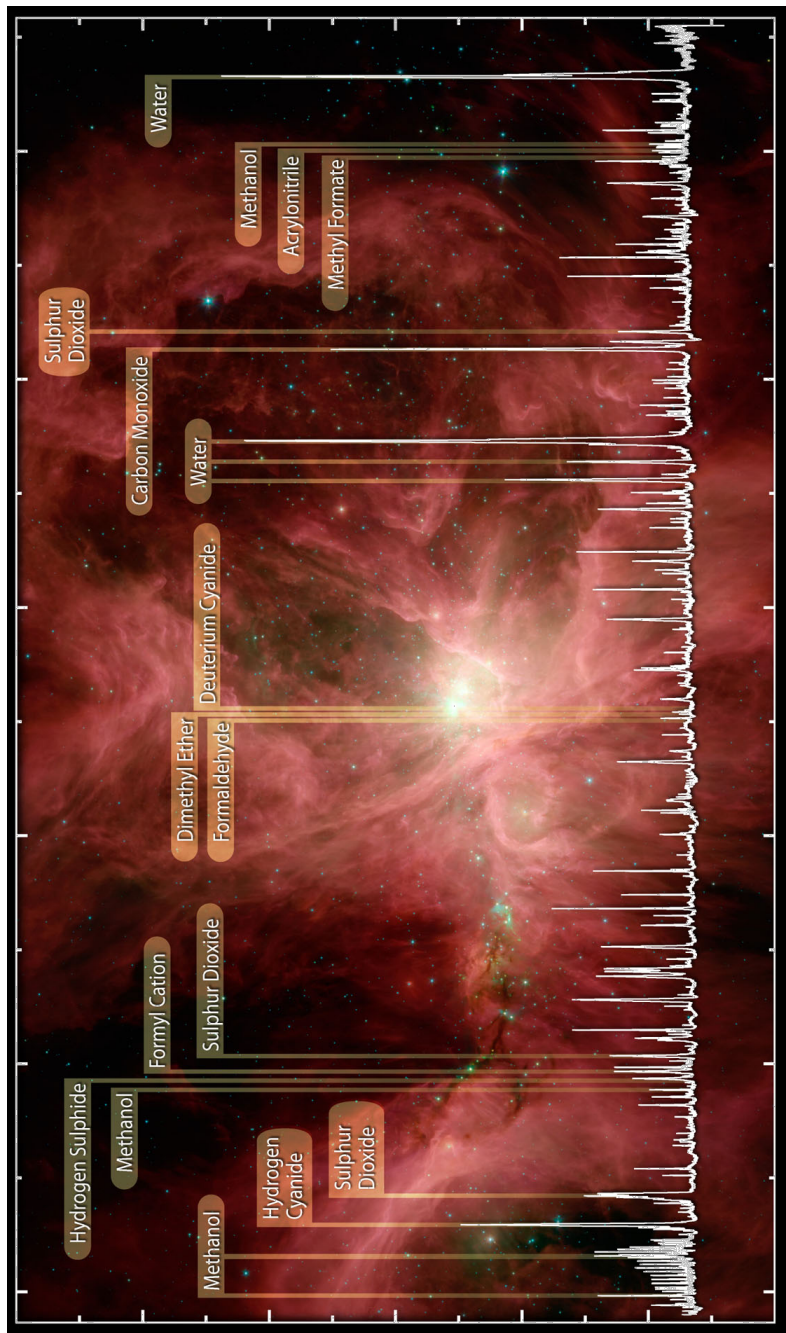


Figure 3: Detailed spectrum (shown in white) of the Orion Nebula (background image). The Orion Nebula is located approximately 1300 light years away, making it one of the nearest stellar nursery in our Milky Way galaxy. This spectrum is recorded by the *Herschel* Space Observatory using the HIFI instrument. The dense pattern of 'spikes', known as emission lines, seen in the spectrum, represents the emission of light at particular wavelengths by particular atoms and molecules in the Orion Nebula. Some of the most prominent lines are labelled. The detected species included: water (H_2O), carbon monoxide (CO), formaldehyde (H_2CO), methanol (CH_3OH), dimethyl ether (CH_3OCH_3), hydrogen cyanide (HCN), sulphur oxide (SO) and sulphur dioxide (SO_2). Image credit: ESA/HIFI/HEXOS; NASA/Spitzer (background image).

detected molecules are ‘organic’ molecules, which does not mean that anything is alive, but simply that they contain particular arrangements of carbon and hydrogen atoms. Similar molecules must have been present on the early Earth. The organic molecules are of particular interest because they are precursors of important biological molecules and therefore can be considered the first step on the way to forming life. Seeing these so-called prebiotic molecules in a star-forming region such as Orion can provide key information as to how they are formed in star-forming environments.

Thesis overview

In my thesis I have investigated the molecules which are present in a number of different star-forming regions. I have compared these molecular inventories to each other in order to find out if different molecules are specific to particular regions. By doing so, I try to understand what conditions are needed for the different molecular species to be formed. I have also investigated the molecular composition of two Solar System comets. By comparing the composition of the star-forming regions with that of the comets, a direct link between the star-forming regions and the Solar System can be made. This is possible because the comets contain remnants of the material from which the Solar System formed.

The thesis is divided into five chapters. The first chapter presents an introduction to star formation and the chemical processes related thereto. The subsequent chapters present the results of the in-depth analysis of each of the studied regions. The main results and conclusions of these chapters are summaries as follows:

Chapter 2: In this chapter, I have investigated how much of the molecule methanol (CH_3OH) is present in the region NGC 6334I. This region is a high-mass star-forming region, actively forming new, massive stars, much heavier than the Sun. Methanol is of particular interest because it is one of the most abundant organic species in star-forming regions and therefore is often used as a reference when comparing the molecular composition of different sources to each other. An accurate characterisation of methanol is therefore essential. The analysis in this chapter revealed that the methanol composition of NGC 6334I is similar to the composition of other regions which are forming massive stars but different from systems forming stars with masses similar to the Sun. Based on models, we conclude that this difference in methanol content may be due to a difference in the temperature of the dust grains in the different regions. If that is the case, the temperature of the dust grains in NGC 6334I was likely higher than the temperature of the dust grains in the regions which form stars similar to the Sun.

Chapter 3: This chapter continues the exploration of the molecular composition of NGC 6334I, this time focusing on simple molecules which contain nitrogen atoms. Specifically, I have studied the molecules methanimine (CH_2NH), methylamine (CH_3NH_2), formamide (NH_2CHO) and methyl cyanide (CH_3CN). These molecules are of particular interest when searching for the building blocks of life because nitrogen-containing bonds are essential for the formation of different biological structures, for example, nucleobases which are the basic components of DNA. In particular, the molecule CH_3NH_2 is thought to be a key molecule. However, so far CH_3NH_2 has only been securely detected at one location, namely in a region forming high-mass stars located near the Galactic Center. If it is true that CH_3NH_2 is an important building block for biological molecules, we expect it to be present in many more star-forming regions. To better understand how CH_3NH_2 is formed and how significant it is for the formation of more complex species,

it is important to detect CH_3NH_2 in other regions of the Galaxy. This chapter reports the first detection of CH_3NH_2 towards NGC 6334I. These results indicate that CH_3NH_2 is not a very rare molecule and that the reason why we have not detected it before is because its spectroscopic fingerprint is weak and only now do we have telescopes sensitive enough to detect it.

Chapter 4: This chapter presents an extensive analysis of the molecular inventory of the high-mass protostar AFGL 4176. The AFGL 4176 system is interesting because it is one of the few known examples of a high-mass protostar which has a disk surrounding it. In contrast to low-mass stars which are almost always surrounded by a disk, disks around high-mass stars are rarely observed. Studying the spectrum of AFGL 4176, revealed the presence of 23 different molecular species. The majority of the detected molecules are oxygen-bearing, that is to say, they contain at least one oxygen atom. Fewer of the detected molecules contain an atom of nitrogen or sulphur. I compare the molecules detected in AFGL 4176 with the molecules detected in other star-forming regions. When doing so, it becomes clear that AFGL 4176 has more in common with the low-mass protostar IRAS 16293–2422B than with the high-mass star-forming region called Sagittarius B2(N). The similar molecular composition of AFGL 4176, which is a high-mass protostar, and IRAS 16293–2422B, which is a low-mass protostar, indicates that the production of molecules does not depend at lot on the type of sources. Alternatively, the molecules observed towards AFGL 4176 and IRAS 16293–2422B may have been formed already in the cloud before the protostars appear.

Chapter 5: In this chapter, I have investigated two comets, called C/2012 F6 (Lemmon) and C/2012 (ISON). Comets are bodies of dust and ice that were leftover from the time when the planets of the Solar System were formed. In contrast to the planets, the material in the comets has remained fairly unprocessed since they were formed. Therefore, the comets can be seen as a sort of fossils, each containing a frozen sample of the material in the disk which eventually evolved into the Solar System. Studying the material in the comets can therefore provide a link between the composition of the cloud of dust and gas from which the Sun formed and the planetary system which orbits the Sun today. For most of their life, the comets are far away from the Sun and remain deeply frozen. However, if a comet gets close to the Sun, its ice will start to evaporate. In this chapter, observations of a number of different molecules which are released from the comets as they are heated by the Sun are presented. I model the observations in order to figure out which of the detected molecules are released from the comets directly, so-called parent molecules, and which are formed from reactions between parent molecules, so-called daughter molecules. By doing so, we get a better understanding of the molecules which were present in the disk surround the proto-Sun.

Based on the results of the individual chapters, the overarching conclusion of the thesis is that the majority of the molecules which are present in both high- and low-mass star-forming regions, are also present in the Solar System comets. This indicates that many of the same molecules which were present when the Solar System formed, and which eventually evolved into life on Earth, are also present in other star-forming regions. So even though life has still not been detected in any other place than on Earth, the basic building blocks for the molecules of life are definitely present in other forming systems. Continued studies of these systems may provide the key pieces of information need to answer the question of how and why life was able to evolved in the Solar System.

