Hot chemistry and physics in the planet-forming zones of disks

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English summary

Right now new planets are born and we can read almost weekly about new planetary systems that are discovered. Having that in mind it is amazing how the human quest to explore new worlds has pushed astronomy, within 20 years from detecting the first planet outside of our own solar system to being able to determine which type of atmospheres these planets have and if they may have conditions which are even suitable for life. These types of discoveries however lead to even more questions than answers. Questions such as: Are planetary systems like our own common and are there other Earth-like planets out there? Are we and other life forms on this planet just a pure coincidence or something that can also be created in other places in the Universe? One important part of being able to answer these questions is to understand how different types of planets can form. The main goal of this thesis is therefore to contribute to the understanding of how different types of planets form and then especially the formation of Earth-like planets.

Planet-formation

To be able to understand the studies in this thesis we will start with some background on what we know today about planet-formation. In all galaxies, including our own, there are many large clouds of gas and dust with diameters up to 300 light years. These clouds are called cold molecular clouds, since they have temperatures of around -250 degrees Celsius. Such a cloud can suddenly start to contract under its own gravity so parts of it will get more and more dense, until the inner parts of it becomes so dense and warm that a star is born there. The rest of the gas and dust will then start building a disk that is spinning around the star. With time, part of the dust and gas in the disk will start to stick together and build up larger clumps until some of the clumps in the end evolve into being large enough to be called a planet. Since this disk is the birth place of planets it is called a protoplanetary disk. In Fig. 1 an artist's impression of such a protoplanetary disk is presented.

The different stages of planet-formation can be simulated in a planet-formation model and the evolution of the gas and dust in the disk is described in a disk

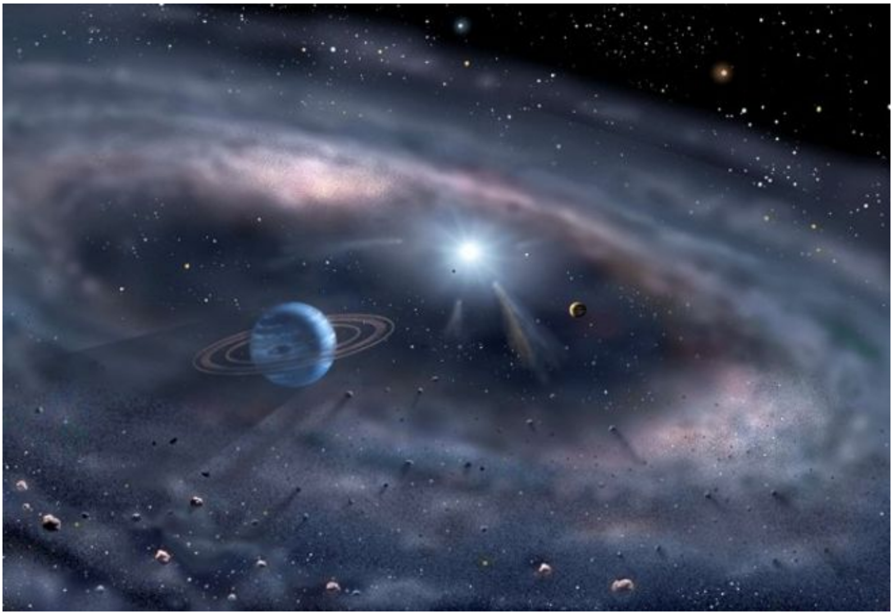

Figure 1 A young star with its protoplanetary disk around it that is in the process of forming planets (An artist's impression, © David A. Hardy/www.astroart.org).

evolution model. There are today several different kinds of planet-formation and disk evolution models and we still do not know which of them are the most correct ones. Another way to look at these models can be to see them as recipes for how to form planets. The input values in the model, for example the temperatures and densities of the gas at different radii can be seen as the ingredients in the recipe for making a planetary system. It is also interesting to see what type of molecules you have in the planet-forming zones of disks, since molecules are the building blocks of life.

A molecule is a group of atoms that are bound together. For example, water is a molecule that consists of two hydrogen atoms and one oxygen atom. Everything is built up by molecules which is why it is so important to see which molecules you have in these protoplanetary disks since this will tell us what the planets and their atmospheres will consist of. In addition it is interesting to investigate how much you have of each molecule at different radii of the disk. For example if you know that there is a lot of water in the inner parts of these protoplanetary disks then you can conclude that there is a high probability that you can also form planets with water on them in these regions. So how can we help to improve these models and check if they are correct or not?

The first step to be able to improve these models is to help constrain the input parameters, hence the ingredients, to the models. This can be done by using observations of the gas in the disks to estimate, for example, which temperatures and densities the gas has in these regions. Another way is to detect the different types of molecules that exist there and calculate their relative abundances. These results can then be compared to the exoplanets that we see today. Hence, do these models predict, for example, planetary systems with giant gaseous planets close to the star, as in some cases have been detected already during observations? Or is it common that these regions have good physical conditions such as the right temperatures and enough amounts of basic organic molecules to be able to produce more complex organic molecules, such as amino acids, that are important ingredients for building life on a planet?

Observations of protoplanetary disks

The main goal of this thesis is to provide and constrain the input parameters for disk evolution and the planet-formation models by determining the characteristics of gas in protoplanetary disks. By using observations we want to answer some specific questions such as for example:

- Which type of molecules can we find in these regions?
- What are the temperatures and densities of molecular gas?
- What is the origin of these molecules?

Figure 2 The Very Large Telescope (VLT) at Paranal in Chile. These telescopes are placed on one of the mountains peaks in the Atacama desert at 2,635 meters above sea level (ESO/G.Gillet).

The observations of protoplanetary disks can be done in several different ways depending on which part of the protoplanetary disk we want to study. Our main interest was to probe the inner regions of the disk which lie within the same distance from the star as Earth, Mars and Venus are from the Sun. Hence this is the zone in a protoplanetary disks where more Earth-like planets could be forming or at least planets which have a solid surface and in contrast to Jupiter and Saturn do not consist primarily of gas. This means that by studying these regions we can better understand how our own planet formed around 4.6 billion years ago and also get more information about if other stars have good conditions for Earth-like planets to be able to form.

Since this region of a protoplanetary disk is rather close to the star it means that the gas that we are studying is very warm, ranging from temperatures of a few hundred to a few thousand degrees Celsius. Such warm gas emits infrared radiation (which is the same type of radiation that other warm bodies emit and we feel as heat). This type of radiation can be observed using one of the Very Large Telescopes (VLT) which lie in the Atacama desert in Chile (see Fig. 2). These 4 telescopes have mirrors with a diameter of 8.2 meters and are positioned at 2,635 meters above sea level. The main results of this thesis come from a large observational program of 24 nights of observations of a sample of over 50 protoplanetary disks using one of these telescopes. The advantage of having such a large sample is that we can study disks with different ages and therefore giving us information about how the gas within the disks evolves with time.

How an astronomer can estimate temperatures and densities of gas light years away from Earth.

So one main question remains, though. How can we estimate for example the temperature and the density of the gas without being able to go there and measure it. This is the main problem for an astronomer, we cannot go to the objects we study to test our theories. The solution is to instead study the light these objects emit and how this light is affected by physical conditions in the place it is emitted. The main method to measure this light and to extract information is called spectroscopy.

One way to explain spectroscopy is to first understand that white light consist of many different colours. That can be seen when you let white light go through a prism. Then you can see how the light goes from white light to all the colours of the rainbow. What a spectrometer does is to measure how much of each kind of colour is present in the light that is observed, hence if it, for example, has more red light than blue. The variations of the different amounts of colour are related to which temperature the source of the light has.

In this case, we can see the star as a lamp that emits white light. If we would gather this light with a telescope on Earth and let the light go through a spectrometer we would see a rainbow. However if we would have a cloud of gas between us and the star, that the light would pass on its way to us, some of the light would be absorbed by the gas cloud. Depending on which type of gas it is, different colours gets absorbed and this colour will not be seen in the spectrometer at Earth. Hence you will see a rainbow pattern with black lines in it where the colour should have been which got absorbed. Hence, each type of gas has its own finger print. So by just measuring the light from a star which goes through the gas which lies in the disk around the star we can see for example if there is water or not. We can also then measure how much water is present and estimate which temperatures both the star and the water vapour in the disk have. This is one of the main methods used in this thesis for studying protoplanetary disks.

The main discoveries in this thesis

New unexpected location of carbon monoxide and water.

Detection of water in the inner zones of protoplanetary disks was a big discovery in 2008 (Carr & Najita 2008, Salyk et al. 2008). This discovery plus subsequent detections showed that water seems to be a common molecule in regions where planets form. What this thesis shows however is that their analysis, which concludes the water to be in the disk, does not always correctly locate the water and some of the other detected molecules such as carbon monoxide, hydroxyl radical, and prussic acid. These molecules instead seem to be located both in a rotating disk and in a disk wind. A disk wind is caused by gas thrown off from the disk due to radiation from the star that heats of the gas so it leaves the disk. It is important to be aware of these different origins of the molecules since it means that if we are not doing this, we will estimate the wrong molecular abundances which will lead to the wrong results of which type of planets can form there or how the chemistry will evolve in the protoplanetary disks.

Detections of new molecules

In previous studies just water, carbon monoxide and hydroxyl radical molecules were detected in the inner warm regions of the disk. However, we now also detect prussic acid and acetylene using a new observational tool that we developed. We show that this tool can also be used to detect even more molecules such as for example ammonia and methane. All of these molecules are important to detect and estimate their abundances since they are crucial building blocks for more complex organic molecules. In addition the temperatures of the gas in which they are located are estimated to be around 800 – 1200 degrees Celsius which will help to constrain the temperature structure in the disk evolution models of these regions.

Radiation fields in protoplanetary disk models

When astronomers detect the light from the stars that has gone through the gas in the disks they have to make several approximations to be able to estimate the temperatures and densities of the gas. This is done to make the calculations easier since they are already very complex. What is shown in this thesis is that it is important to take both the UV-field and X-rays from the star into account in the models and not just one of them as is usually done. Not doing this will give incorrect estimates of the molecular abundances.

An organic inventory of protoplanetary disks

There are still very few molecules detected in these inner planet-forming zones around stars. Models predict that there should also be other larger organic molecules in these regions which are very important for building up planets with atmospheres which provide good conditions for life. A search for these larger organic molecules was therefore performed since this has not been done before. The results gave only upper limits rather than clear detections. This is because the telescopes today are still not powerful enough. However, our results show that new telescopes that are being built now will be able to detect these molecules. We also show that the molecular abundances in comets are similar to those detected in the protoplanetary disks which supports the theory that comets are formed in the same chemical environment as the planets.

Final words

As was stated earlier, a planet-formation or disk evolution model can be seen as a recipe on how to build different kinds of planetary systems and the specific outcomes depend on the ingredients we put into this recipe. This thesis has contributed by giving us many more of these ingredients, such as for example detections of new molecules by improving the knowledge of their location, by determining the temperature variation within the disk, and by clarifying how we should include different types of radiation fields from the star. This shows how with today's observations we can start to understand not just how other planetary systems form, but also how our neighbouring planets one time formed and if it is possible that other worlds like ours are out there.