The standard building block from which stars are made is molecular hydrogen ($\text{H}_2$), or hydrogen gas. This gas can be found in the very sparse space between the stars, but it is hard to see because it does not emit much radiation by itself. One can still find it in our own Milky Way, with strong telescopes that can look in the infrared, but this does not work so well in other galaxies. Looking at other gases, or particles, that are strongly connected to hydrogen gas is better in that case. In this thesis, one such way of doing this is expanded and improved upon.

About hydrogen

It is thought that, of the 'normal' (or baryonic) matter in the universe, atomic hydrogen ($\text{H}_1$) is the most common element. It is a simple atom that consists of a proton and an electron. If you put two of these atoms together, you end up with hydrogen gas. Putting the atoms together goes the fastest if there are dust particles around: They help in bringing the atoms together on their surface. It can be done without dust, but then the process takes a lot longer. Atomic hydrogen is relatively easy to see in the universe. It radiates at the 21-cm radio wavelength. I worked mainly with observations of atomic hydrogen by the Very Large Array radio telescope.

Hydrogen gas can also be destroyed again, after which it goes back to its atomic form. This requires a lot of energy. This energy comes mainly in the form of light particles (photons) from the heaviest stars. These heavy stars burn up fast: They live only a few million to a few tens of millions of years. We can see the energetic light particles in ultraviolet light. In this thesis, I use images of galaxies taken in ultraviolet light, made with a satellite named GALEX, which stands for “Galaxy Evolution Explorer”. These images mainly show young, brightly shining stars.

Big gas clouds can be found between those stars that consist mainly of hydrogen gas. When these clouds are located close to the bright stars, the molecular hydrogen will be transformed into atomic hydrogen. **We call this a photodissociation region (PDR): A region where molecules are broken up by the light that shines on them.** These PDRs play the main part in my thesis. In our own Galaxy it is mostly the relatively small PDRs that have been studied well. These regions are compact, and they contain a lot of hydrogen gas. However, I am interested in the larger PDRs, that can span up to a few hundred lightyears. These PDRs are sparse: Only a few to a few hundred particles per cubic centimeter can be found there.

If one knows what happens in such a PDR, as accurately as possible, one can derive how much hydrogen gas can be found there. Since molecular hydrogen is broken up continuously, while atomic hydrogen gets combined into molecular hydrogen, the process is in a state of balance. The amount
of light shining onto a PDR is measurable, and so is the amount of atomic gas. Also, the amounts of
dust can be estimated, which helps in the making of hydrogen gas. I call this approach to calculate
the density of the hydrogen gas the 'PDR method'.

Application of the method

Carrying out the required measurements that I just described is not all that straightforward, and nei-
ther is interpreting the images properly. It involves dealing with many details, like determining what
part of the visible atomic gas belongs to the PDR that is being investigated. That is why this thesis
is important: To understand the PDR method better, to see if and where this method is valid, to
apply this method to a number of galaxies, and to interpret the results properly. The recipe: Find
groups of young, hot stars. Then, look at the atomic hydrogen, and determine how far away from
these stars it is. Also calculate how much dust is present. Finally, with these measurements, one can
calculate the total hydrogen density.

The PDR method is an alternative way to determine the presence of hydrogen gas. The most
commonly used method uses another molecule, carbon monoxide (CO). This molecule is relatively
easy to see, not just nearby but also further away. It is thought that the presence of $\text{H}_2$ is directly
linked to the presence of CO. The PDR method is independent of this assumption and can be used
in situations where the use of CO does not work so well.

Results

Firstly, I applied the PDR method to the galaxy M81, which is almost 12 million lightyears away from
us. It is an interesting galaxy, among others because it displays almost no radiation from carbon
monoxide. The hydrogen gas densities, found with the PDR method, were relatively low. I also
used infrared images made by the Spitzer space telescope that show more complicated, organic
molecules. The presence of these molecules (polycyclic aromatic hydrocarbons, or PAHs) are an
important clue that the regions we expect to be PDRs really are PDRs. Indeed, we find PAHs close to
almost every PDR.

The properties of M83 are slightly different. In contrast to M81, this galaxy shows a lot of carbon
monoxide. In the central areas of M83 we find clouds with higher densities than those in M81, but
the outer areas also show PDRs with respectable densities. Apparently carbon monoxide does not
radiate when the gas densities are relatively low. M83 is situated almost 15 million lightyears away.

Finally, I studied M33 extensively. This galaxy is relatively close, about 3 million lightyears away,
so we can see a lot more details than we can in M81 and M83. In order to see if and how the results
are dependent on the distance of a galaxy, I pretended that M33 was (approximately) as far away
as M81 and M83. To do this, the quality of the images of M33 have to be made poorer on purpose.
Then, if we look at the properties of the PDRs at full quality, it turns out that the results are not
fundamentally different, although the accuracy of the results improves.

An important contribution to the PDR method in my thesis is the way in which the extra details
that can be seen in M33, and not M81 and M83, are being dealt with. For example, the gas clouds are
not just a single dot on the picture, but they are a bit larger, and partially resolved. That way we can
try to predict how much atomic gas we would expect from the PDR method. This can be compared
to what we see on the picture, and the method seems to work well.

The spatial distribution of the atomic gas is very important to show that the gas is really coming
from PDRs. This makes the PDR method more credible and raises our confidence in its results.
There are also indications that the strongest concentrations of hydrogen gas occur where we also
see carbon monoxide. That is a good clue, but not solid evidence, that the PDR method works. It also means that the amounts of molecular hydrogen may be underestimated if carbon monoxide is used as the sole indicator, which it commonly is.

The measured densities of hydrogen gas in M33 are accurate enough for testing the so-called Schmidt star formation law. This law assumes that the rate at which stars are formed is directly coupled to the presence of hydrogen gas. This rate can be determined, among others, from the levels of ultraviolet light. Using the results from this thesis, we can see how well the star formation law works at low gas densities. There are a lot of influences that need to be taken into account, but sometimes we can use statistical methods to understand these effects better. This is a very promising application of the PDR method.

In summary, this thesis contains an extensive investigation of the densities of hydrogen gas clouds in three galaxies, using the 'PDR method'. The type of clouds that is observed through this method generally has a low density, but clouds with higher densities can also be seen. The PDR method has now been developed further, and there are indications that it works well. The method can also be used to study the star formation law.

Towards the future

This work offers enough inspiration to continue. It is important to find out more about the presence of dust in PDRs to make the method more accurate. At this time, the dust levels in many galaxies are not known at a high enough spatial resolution. Something that definitely deserves more attention, is how well the levels of predicted atomic hydrogen fit reality. The method can gain credibility this way. The method can obviously be applied to other galaxies. For example, M101 (better data became available since it was first studied using the PDR method), or M51 (which has the advantage of the availability of a lot of data).

Finally, we can try to understand molecular clouds better by looking at their temperatures. To do this, it is necessary to look at the different wavelengths at which carbon monoxide radiates. That is already sufficient to say more about these clouds. I am particularly interested in the existence of this type of clouds in the outer regions of galaxies.