Large-scale photodissociation regions in nearby spiral galaxies
Heiner, Jonathan Surasa

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The previous chapters detailed the results of this work. Now the conclusions of this thesis will be summarized briefly. A discussion of future directions for this work follows.

7.1 The 'PDR method'

The study of photodissociation regions is a field of research in itself. However, when looking at large-scale PDRs and using their fundamental observable properties to obtain samplings of the underlying total (hydrogen) gas content, it becomes appropriate to label this approach the PDR method. This was proposed by Allen et al. (1997), then adopted by Smith et al. (2000) and now explored in detail in this work, applied to M33, M81 and M83.

The method was improved by introducing measurements of individual potential H\textsubscript{I} patches, as opposed to radial averages. These patches are local maxima in the H\textsubscript{I} column density image, assuming that these patches would indeed stand out from the general H\textsubscript{I} emission. Instead of assuming that the full H\textsubscript{I} column is produced by photodissociation, we attempted to estimate the local background level and subtracted it. Either a galaxy-wide background was assumed, or a local background. A galaxy-wide background is likely to be a lower limit because of possible local enhancements of the H\textsubscript{I} background level. On the other hand, a local background could be an upper limit since it is oftentimes harder to determine where the background level starts. In general, it remains uncertain what fraction of the observed H\textsubscript{I} emission is produced in PDRs. Even the local background could be produced by (diffuse) UV radiation. By subtracting a background, we try to connect a specific H\textsubscript{I} patch with a specific cluster of O and B stars. If a certain fraction of that H\textsubscript{I} patch was not produced by photodissociation, the H\textsubscript{I} column density in the method is overestimated.

Apart from the atomic hydrogen fraction, there is also the issue of beam smoothing and filling. Additional information is needed to derive what the beam filling fraction of the cloud is in the observer beam. Unresolved clouds will also appear smoothed and as having an underestimated column density. This seems to be an issue with the M83 H\textsubscript{I} data. As long as this effect is comparable in magnitude to the matter of the H\textsubscript{I} background level, it will not be the biggest contributor to the uncertainties in the results. A related but independent issue is the presence of optically thick H\textsubscript{I} columns. In that case the direct conversion from brightness temperature to H\textsubscript{I} column density is inaccurate. Lining up M83, M81 and M33 in order of distance, apparent H\textsubscript{I} column densities increase. We suspect that this is mostly due to beam smoothing. In the case of M33 we found indications that the H\textsubscript{I} might have true H\textsubscript{I} column densities that would put them in the optically thick regime. This means that the H\textsubscript{I} column density is generally underestimated.
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An initial attempt was made to model the H\textsubscript{I} distribution of a resolved patch (in CPSDP Z204), which showed an H\textsubscript{I} column density profile following a curve that is consistent with the H\textsubscript{I} being produced by photodissociation. While a total hydrogen density needed to be assumed for this prediction, it is the shape of the curve that potentially provides information about the structure of the underlying interstellar medium. In this case, we found evidence that the underlying medium is strongly clumped. This fits the view of far-UV radiation penetrating far into the giant molecular clouds.

Support for the presence of PDR-produced H\textsubscript{I} can also come from the detection of nearby PAH emission, as we showed in the case of M81. The PAH emission there accompanied the H\textsubscript{I} patches in almost all instances. PAH emission is believed to be an indication of recent star formation, pointing to the presence of GMCs as well as the likelihood of the presence of H\textsubscript{I} produced on the surfaces of those clouds.

An accurate derivation of the total hydrogen volume density is also dependent on the proper determination of the incident UV flux. By resolving the cluster of O and B stars at the heart of the candidate PDR, a more detailed calculation of the incident flux becomes possible. It enables a better calculation of what incident UV flux and what amount of H\textsubscript{I} are connected. Even so, treating the cluster as a single source of UV flux radiating uniformly is a good approximation. Resolving the central sources introduces the same projection issues that appear in the determination of the separation between the UV and H\textsubscript{I}, where the actual three-dimensional location of the H\textsubscript{I} patch is concerned. Another concern is the possible obscuration of one UV source by another one. Since the space-filling factor of an individual star is comparatively low, this is mostly an issue with the internal extinction in the OB star cluster. The incident flux $G_0$ is directly proportional to the total hydrogen volume density, so more flux means more hydrogen, assuming a constant value of $N_{H\text{I}}$.

Extinction in general is an important factor in the PDR model, through the incident UV flux $G_0$. While Smith et al. (2000) chose an internal extinction correction, we did not apply one for geometrical reasons (see Chapter 2). Assuming a spherically symmetric PDR, and ignoring foreground extinction (which we did correct for separately), the internal extinction towards the observer equals the internal extinction from the central source to the H\textsubscript{I} patch. However, if more information about the three-dimensional structure of a candidate PDR is available, it would be appropriate to consider an internal extinction correction. If the symmetry assumption of the PDR does not hold, the extinction can be both under- as well as overestimated. The foreground extinction serves to correct the UV flux that was attenuated in the direction of the observer, but not in the direction of the H\textsubscript{I} patch. A bigger foreground extinction means that the incident flux at the H\textsubscript{I} patch is corrected for an underestimation. On the other hand, more internal extinction means that the incident flux at the H\textsubscript{I} is overestimated. The net $G_0$ will then be lower, as will be $n$.

The total hydrogen volume density is heavily dependent on the dust-to-gas ratio. In this work, we extended the use of the method to larger galactocentric radii. Metallicity information at those distances from the center of a galaxy is still rare. At this time, it is uncertain whether the metallicity drops off or whether it proceeds to drop off gradually (Gil de Paz et al., 2007b). The trend that emerges appears to be one where the total hydrogen density remains flat out to large galactocentric radii.

The estimated uncertainties in the resulting volume densities were described in Chapter 2. The uncertainty in the dust-to-gas ratio generally has the biggest impact. We assume that the dust-to-gas ratio is directly proportional to the metallicity (Issa et al., 1990), which in turn has its own variations. The characterization of a galaxy with a single metallicity slope is a generalization that cannot hold on smaller scales (see Rosolowsky and Simon, 2008, in the case of M33) but is adequate for our purpose in M81 and M83 as it captures the general trend of the metallicity on a larger scale. Even when local values are available, it remains to be seen if the metallicities measured from ionized lines are appropriate for the PDRs that we claim to be seeing. The fraction of the measured atomic hydrogen
column that is actually produced by photodissociation, and is not a part of the local background, is another uncertainty that is described further in the Future Work section below.

The range of total hydrogen volume densities that is found with the PDR method is indicative of the properties of the GMCs in the galaxies under investigation, as well as the regime where the PDR method can be used (after considering the selection effects). In certain cases, densities up to a few thousand hydrogen particles cm$^{-3}$ can be detected. This requires a combination of a high incident flux and a small separation. In other words, the smaller and denser PDRs can be seen when the conditions are favorable. Typical densities that are observed, though, are in the range of 1 – 100 cm$^{-3}$. These are the densities that correspond to the GMCs that are thought to be the remnants of the parent clouds from which the observed OB associations formed, spanning a scale of up to several hundreds of parsec in size. We speculate that they consist of an ensemble of more compact, denser GMCs with a low volume filling factor, but a smoother low-density medium cannot be excluded. The presence of CO emission where the measured densities are the highest is a good indicator that the method is being applied correctly.

As a direct application of the PDR method we made an initial attempt to study the star formation law in M33. While it has become customary to compare the star formation surface density to the gas surface density, we have the opportunity to compare the gas volume density from the PDR method to the star formation rate indicated by the UV luminosity. As we saw in Chapter 6, the power law index of the star formation law as we obtained it probably lies between 1 and 2 depending on a proper correction of the data censoring. The uncertainties in our results are too great to get a more accurate result at this time and the result is therefore more of a proof of concept.

7.2 Future work

The results of this thesis evoke a number of questions. How can the PDR method be improved? How can the approach become more credible? What are the results of applying it to other suitable galaxies? I will first describe possible improvements to the method and to what other galaxies the method may be applied. Then I will detail my plans to determine the fraction of atomic hydrogen produced in PDRs and how to find out more about the temperature structure of the parent GMCs, which is an attempt to put the PDR method on a firmer footing.

7.2.1 Improvements to the PDR method

The dust-to-gas ratio is the dominant component of uncertainty in the results presented here. Depending on the quality of the data that are available, a galaxy can have a global metallicity measurement, a metallicity slope (it is either flat or declining going outward), or data are available on individual regions in a galaxy. In the latter case it has become clear that the metallicity fluctuates significantly from region to region. The PDR method is very sensitive to this. Ideally, individual cloud measurements would be used, but since these vary from cloud to cloud, this is not expected to reduce the scatter in the range of cloud densities that will be found.

At the level of metallicity slopes, limited information is available. I have taken observations that will lead to the determination of the slopes of a number of nearby galaxies, namely NGCs 1291, 1744, 1792; UGCA106, and HIPASS J0145-43. This will enable the application of the PDR method on a somewhat more global scale to these galaxies, when combined with H$\alpha$ and far-UV observations.

Another necessary improvement to the method is a better treatment of the attenuation of the dissociating radiation field. We suspect that the interstellar medium near the OB associations is very clumpy (see Chapter 4), which allows the UV radiation to penetrate further (Városi and Dwek, 1999). Internal extinction information (between the UV source and the GMCs) is sparse, but has
been applied by Smith et al. (2000). For reasons of geometry we decided not to apply such a correction to our galaxies (see Chapter 2), but a more detailed analysis needs to take this into account. In general, a three-dimensional approach to individual candidate PDRs would be helpful, but will be challenging at the distances of the galaxies where the PDR method is advantageous to use.

### 7.2.2 Application of the PDR method to other galaxies

We have applied the PDR method to three (nearly) face-on spiral galaxies, where far-UV images were available at a resolution of around 100 parsec as well as comparable HI maps. A metallicity gradient for these galaxies was required. Since this is the scale at which we suspect the dissociating radiation field is still capable of producing HI that creates visible structures, it is more or less the minimal linear resolution necessary to apply the PDR method. A poorer resolution would still be suitable for a global analysis of the radial profile of atomic hydrogen, to get an idea of how much of it is produced by photodissociation at the galactic scale. Because of geometrical issues and projection effects, face-on galaxies are preferable for the method. Foreground extinction as well as internal extinction information will help to compare the results to those obtained in other galaxies.

In principle, the PDR method as described in this thesis can be readily applied to a number of galaxies, like M51 and the Magellanic clouds. This would provide more insight into the differences between the GMCs in the various spiral galaxies. It would also be interesting to attempt the application of the PDR method to elliptical galaxies to the extent that they have detectable amounts of atomic hydrogen gas.

In short, a checklist for the application of the PDR method would look as follows:

- The galaxy is (nearly) face-on.
- Far-UV and HI images are available at a linear resolution of around 100 parsec.
- Metallicity gradient information is available or individual measurements throughout the disk.

### 7.2.3 HI profiles and detection of PDRs

The project I propose to carry out consists of two stages. First I will investigate the connection between HI and FUV emission in M33 and M83 at a very detailed scale (less than 100 pc), using high resolution archival VLA/GBT and GALEX data. Other galaxies could be targeted if data at sufficient resolution is available. A certain fraction of the observed HI is expected to be produced by photodissociation. Then, I will use the PDR method to derive total gas densities and use those together with star formation rates derived from the FUV emission to elucidate the star formation law.

The level of detail provided by GALEX UV images (e.g. Gil de Paz et al., 2007a) and 21-cm VLA HI maps by THINGS (Walter et al., 2005) and Thilker & Braun (2007, private communication: M33) provide the opportunity to discover if the distribution of atomic hydrogen is consistent with the PDR view, and to what extent. The linear resolution of the M33 data is on the order of 20 pc. The M33 results so far show HI features which appear to be on top of a general background level of atomic hydrogen produced by nearby prominent UV sources. The diffuse UV emission, however, permeates the interstellar medium, and this radiation can also keep some of the hydrogen in its atomic form.

With the high resolution data I will be able to perform a well-informed selection of areas in spiral arm regions and in between these arms that are expected to contain photodissociated HI. This atomic hydrogen can then be directly connected to the UV emission through photodissociation physics. Knowing the range of sizes and densities of large-scale PDRs from my previous work and assuming a certain filling factor for the plane distribution of GMCs (as was calculated for example in the case of M81; Heiner et al., 2008a), the amount of observed HI can be predicted with the PDR method. This would be a strong indication that the PDR model is valid and, at the same
time, determine how much of the H\textsc{i} present is accounted for by photodissociation. Other important clues can come from the literature, like CO data (e.g. Rosolowsky et al., 2007), PAH/dust maps from Spitzer, and metallicity information (Rosolowsky and Simon, 2008).

To further strengthen this project I anticipate taking advantage of the EVLA’s improved resolution and sensitivity capabilities as they become available. For example, NGC 604, the brightest H\textsc{i} region in M33, lies on the edge of an H\textsc{ii} spiral arm. To the west the H\textsc{i} column densities drop below the noise level, although single dish GBT data does show diffuse emission there (Thilker, 2008, private communication). Since UV emission is present in that area, albeit relatively faint, the distribution of H\textsc{i} will be indicative of how well the PDR method works. Other promising regions can be selected based on the results of my thesis.

The densities from the PDR method can be used together with the star formation rate represented by the UV emission, to produce a Schmidt Law plot (see Chapter 6).

The total hydrogen volume densities obtained by the PDR method provide a measure of the total gas content independent of the use of CO and are not limited to the areas where CO is detected. They can therefore be used to probe the star formation law in the H\textsc{i} dominated regions and provide important clues as to the possibly changing nature of the star formation law in that regime.

The second part of my proposed research, therefore, is to improve the M33 results by, among others, better fitting, taking into account the known selection effects using Bayesian fitting or Monte Carlo simulations. Markov Chain Monte Carlo (MCMC) simulations appear particularly promising to deal effectively with selection effects. The UV emission can be converted to a star formation rate with extra corrections for internal extinction. The results from the first part of the project will be added in to further improve the results.

7.2.4 Temperature and densities of GMCs

After building on the method using atomic hydrogen formed in large-scale photodissociation regions, and expanding on it, we found total hydrogen densities that essentially span a constant range of values across the disk of the spiral galaxies that we investigated. We suspect that the physical properties of most of the gas in GMCs throughout these disks are basically the same, namely predominantly low density (a few times $10^2$ cm$^{-3}$) and low temperature (around 10 K). A census of CO(1-0) emission across M33 by Engargiola et al. (2003) finds molecular clouds distributed all across the H\textalpha disk, for example.

Apart from a need to explore the metallicity gradients of nearby galaxies and to take a fresh look at the M101 results of Smith et al. (2000), the results lead to new questions about large-scale photodissociation regions, like how do they connect to the presence of carbon monoxide? What is their morphology and their temperature structure? We find that previous detections of CO(1-0) emission generally coincide with higher total hydrogen volume densities derived with our method. CO should be detectable if the GMCs are either dense enough or warm enough, even out to larger galactocentric radii. In fact, Braine and Herpin (2004) find molecular hydrogen beyond the optical edge of the spiral galaxy NGC 4414. We need temperature measurements of the molecular gas in our candidate PDRs. To do this, we need measurements of higher transition lines of CO, like CO(2-1) or CO(3-2), combined with structural information (see, for example, the work of Loinard and Allen (1998) on M31), or modeling.

Such data on the galaxies that I have been studying is limited. Unless the molecular clouds are warm, the ratio of any higher line to CO(1-0) will be smaller than 1. The CO(1-0) in M81 is barely detectable (Knapen et al., 2006). For M83, Lundgren et al. (2004) give a useful table of previous observations. With their own observations (CO(1-0) and CO(2-1)), they detect giant molecular associations in several locations along the spiral arms of M83. Their resolution, however, is limited to the scale of those GMAs, namely 500 pc approximately. Other studies focus exclusively on the nucleus of
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Figure 7.1: Panel from Wilson et al. (1997), Figure 1, showing their detection of $^{12}$CO J=2-1 and 3-2, and $^{13}$CO(2-1) in NGC 604, the brightest HII region in M33.

M83, for example Petitpas and Wilson (1998), where high excitation, high temperature CO emission is detected. They suggest that this CO is formed in PDRs in the nucleus. Muraoka et al. (2007) find molecular gas near the end of M83’s bar, at about 450 pc resolution, in their CO(3-2) maps. Israel and Baas (2001) produced data of various CO transitions ($^{12}$CO J=2-1, 3-2, 4-3 and $^{13}$CO(3-2)) and were able to perform temperature modeling on the largest scales. As to M33, Thornley and Wilson (1994) reported the first CO(3-2) detections and find very dense molecular gas (up to 3000 cm$^{-3}$). Wilson et al. (1997) detect seven GMCs in M33, in $^{12}$CO J=3-2 and 2-1 and $^{13}$CO(2-1) spectroscopy. Using large velocity gradient modeling, they derive temperatures (down to 10K) and densities (40 cm$^{-3}$ and up). A CO(2-1) map of the northern half of M33 was published by Gardan et al. (2007), in which they managed to find more clouds in that region than Engargiola et al. (2003) did in their CO(1-0) maps. They also report finding possible traces of diffuse emission from clouds smaller than their beam size (their resolution was 11$''$). Their estimated H$_2$ mass agrees with the estimates from Rosolowsky et al. (2007), who conducted a high-resolution CO(1-0) survey of the inner 5.5 kpc of M33. Finally, their work raises questions about star formation efficiency at low metallicities.

The Sub-Millimeter Array (SMA) is just the right instrument to learn more about the temperature and spatial structure of the GMCs in nearby galaxies. According to its online archives, it has targeted M33 only once and has not targeted M83. The CO intensities of CO(2-1) and CO(3-2) that Wilson et al. (1997) detect in a handful of M33 molecular clouds are well within reach of the SMA (Figure 7.1). We used the SMA online beam calculator to estimate the noise levels for comparison, finding them well within the needed sensitivity limit. The abundance of clouds to observe was illustrated by the 11$''$ map of a part of M33 by Gardan et al. (2007).

I propose to have an in-depth look at a number of the candidate PDRs that were identified in M33 and M83 in search of further evidence of the existence of GMCs in those regions, by mapping them with the Sub-Millimeter Array in the CO(2-1) and CO(3-2) lines. Using the Compact Array setup, a suitable sensitivity is achieved combined with an angular resolution of 2-3$''$, superior to the previous observations mentioned above. I will focus on some of the more dense regions that I have identified using the photodissociation method, while trying to target regions both in the inner and outer parts of these galaxies and taking into account the local metallicity. For example, CO(3-2) measurements could complement the available CO(2-1) partial map of M33 (Gardan et al., 2007). In M83, large-scale giant molecular associations have already been detected, including the global locations of molecular arms (Lundgren et al., 2004), but the detailed structure or GMCs in M83 is unknown. 12$''$ is the best resolution currently available. I will focus on the outer regions of M83, since the nucleus and the bar have been well studied.
By carrying out this project, valuable insight into the temperature and density structure of these clouds will be gained, as well as more information on their sizes and morphology. I intend to match the larger hydrogen densities found near candidate PDRs to molecular gas. This will provide a valuable benchmark to the idea of HI formed in photodissociation regions. The results can then be connected to other properties, such as the local star formation rate.

Finally, it can be noted that the Atacama Large Millimeter Array (ALMA), is currently under construction. Once completed, it will provide an order of magnitude increase in resolution and it will also be much more sensitive. Once in service, it can be expected to be particularly well suited to study the lower density molecular clouds, and to resolve the GMCs in M33.

7.3 Executive summary to this thesis

In short, our conclusions are as follows:

- The PDR method was improved.
- Ranges of hydrogen densities were found in M33, M81 and M83 that show no radial variation.
- Detailed investigation of candidate PDRs shows HI emission consistent with the PDR view.
- HI emission was statistically linked to PAH emission in M81.
- There is a strong suggestion of CO being linked to detection of high cloud densities in M33.

Future work topics could include:

- Application of the PDR method to other galaxies.
- Connecting the metallicity with HI and H\textsubscript{2} appearance.
- The fraction of the observed HI that is produced in PDRs.
- The modeling of HI features using the PDR assumptions.
- Temperature and densities of GMCs in nearby galaxies through a full analysis of CO transition lines.