Introduction

What fraction of atomic hydrogen in galaxies is produced by photodissociation? How ubiquitous are large-scale photodissociation regions (PDRs) in galactic disks? What are typical densities of these large-scale PDRs? These questions drive the research behind this work and are bound to lead to intriguing new questions as well as, hopefully, provide some answers.

From the name astrophysics, or ‘the physics of stars’, we arrive naturally at the issue of star formation. Throughout the centuries, it has become evident that there are vast numbers of stars. Not only in our own Galaxy, but all galaxies contain stars — as far as we know. We know that stars consists primarily of hydrogen. We can also see how stars are being formed in dense molecular clouds. Detection of molecular hydrogen is therefore of great interest, if one wants to find out more about the process of star formation.

This thesis builds on and refines a method to detect molecular hydrogen by way of atomic hydrogen produced in photodissociation regions. By applying this method we gain valuable insight into the general distribution of molecular hydrogen throughout galactic disks, an important component in the process of star formation. Investigating nearby galaxies avoids the line of sight confusion that complicates the identification of large-scale PDRs in our own Galaxy. Nearby galaxies are still close enough to be able to (barely) resolve the expected hints of the presence of PDRs. At the same time, the target galaxies have to have detectable amounts of atomic hydrogen and the far-ultraviolet emission from young, hot stars that mark candidate PDRs. The sample of targets includes M33, M81 and M83, partially based on earlier, similar efforts.

After outlining the role of molecular hydrogen, I will go into the method that is central to this work, followed by a general overview of related topics.

1.1 The vital role of molecular hydrogen

Molecular hydrogen (H$_2$) is the basic building block of star formation. Its abundance in the interstellar medium (ISM) is therefore of great interest. Since it has no permanent dipole moment, it is a molecule that is hard to observe directly. H$_2$ may be observed through its quadrupole emissions in situations where the density or temperature is high. Another
way to detect $\text{H}_2$ directly is by taking absorption measurements, restricting this method to suitable line-of-sight occurrences.

Alternatively, molecular hydrogen can be detected indirectly. The most widely used method is based on the observation of the millimeter rotational spectrum of carbon monoxide (CO) and uses an assumed direct relation between the density of molecular hydrogen and the line strength of $^{12}\text{CO}(1-0)$ emission. Conversion factors have been derived for many nearby galaxies, including our own. This method using the so-called X-factor is usually applied with notes of caution acknowledging mounting concerns about its accuracy (further detailed below, in §1.2).

Because of these concerns, exploring different avenues that can give insight into the actual distributions of $\text{H}_2$ in various environments is of definite importance. A new method to estimate the density of $\text{H}_2$ in giant molecular clouds (GMCs) throughout the local universe, using a combination of measurements — 21-cm radio $\text{H}_1$, and satellite observations of far-ultraviolet (FUV) emission — was proposed by Allen et al. (1997), based on the findings of Allen et al. (1986).

My thesis work is an effort to expand and develop this alternative method that is based on straightforward and unavoidable processes — namely the physics of photodissociation regions (PDRs), and the measurement of atomic hydrogen and incident UV radiation that produced it — to probe the underlying total hydrogen reservoir. This method is independent of molecular excitation in the GMC, so we can expect to be able to detect more than just the warm, dense gas.

1.2 Observing molecular hydrogen indirectly

1.2.1 Carbon monoxide

Many papers have been written about CO and its observable transitions, since its first detection by Wilson et al. (1970). This brief summary of using CO as a tracer of $\text{H}_2$, therefore, does not claim to be complete.

Dickman (1978) was one of the first to attempt a quantitative connection between molecular hydrogen and carbon monoxide ($^{13}\text{CO}$), based on galactic interstellar dark clouds and valid in dense cloud cores. Outside our Galaxy, $^{13}\text{CO}$ becomes much harder to observe. A more convenient tracer is then the velocity-integrated $J = 1 \rightarrow 0$ $^{12}\text{CO}$ line intensity, $I_{\text{CO}}$ (Dickman et al., 1986).

Young and Scoville (1984) derived the $\text{H}_2$ mass in M82 using a conversion that would later become known as the 'X-factor' ($X_{\text{CO}}$), based on the empirical correlation of $\text{H}_2$ column densities to CO(1-0) line intensities for molecular clouds in our Galaxy (Young and Scoville, 1982). It is assumed that $X_{\text{CO}}$ is reasonably constant throughout the Milky Way and that the CO line intensity is determined primarily by collisions between $\text{H}_2$ and CO (Sanders et al., 1984). In our galaxy its value is $1.8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, as determined by Dame et al. (2001), who used far-infrared dust maps combined with $\text{H}_1$ data to predict the presence of $\text{H}_2$ quantitatively (see §1.2.2).

The principal analysis of the X-factor method comes from Dickman et al. (1986), and references therein. It is argued that, even though the CO lines are generally heavily sat-
urated, an ensemble of molecular clouds seen in CO would be a decent $H_2$ mass tracer. This depends on cloud overlap in the CO maps being a minor issue and on the clouds being virialized. The recent work by Wall (2007) provides a review of the justifications of using the integrated $^{12}$CO(1-0) line intensity, which by now includes the assumption that clumps within the molecular clouds need to be virialized, not necessarily the whole cloud. Significantly, he adds radiative transfer to the analysis, which puts the method on a firmer footing physically, while still obtaining X-factors consistent to within a factor of 2 of observed values.

Recent examples of the application of the X-factor include Casoli et al. (1998), who used a constant X-factor to study a survey of 582 galaxies, and Fumagalli and Gavazzi (2008), who used an X-factor based on the metallicity of each individual galaxy under consideration.

As the attempts to solidify the argumentation for the use of the X-factor continue, direct measurements of $H_2$ will ultimately provide the most insight into the effectiveness of the method. A result to note here comes from Burgh et al. (2007). They took direct $H_2$ UV absorption measurements in our Galaxy and compared them to CO observations. This allowed them to directly compare CO column densities to $H_2$ column densities, finding a highly variable ratio of the two. They stress the need to consider the physical state of individual clouds. For example, the total gas mass would be underestimated in diffuse clouds using the standard X-factor.

One of the problems with the X-factor is its dependence on the local metallicity. Figure 4 in Israel (1997) shows a clear dependence of a per-galaxy X-factor on the metallicity $[O]/[H]$. This is explained as an effect of photodissociation of the molecular gas, regulated by the presence of dust. A better understanding of this dependency would obviously improve the method, but that would also limit its applicability since metallicity measurement for individual galaxies are scarce.

Another question is: How well does CO trace the cold gas? Loinard and Allen (1998) found large, cold molecular clouds in M31 with kinetic temperatures close to that of the cosmic microwave background. This can be explained by the absence of strong UV / cosmic ray fluxes, leaving the molecular clouds cold and smooth. An intense UV flux would dissociate the gas, leaving clumpy high-density regions of CO emission as can be observed in our own Galaxy. Hosokawa and Inutsuka (2007) detect 30 – 40 K H\text{I}/H\text{2} as an H\text{I} self-absorption feature, which correlates poorly with detected CO emission. This highlights the need for additional ways to estimate the presence of molecular hydrogen, especially when it is relatively cold.

Finally, another related method to find molecular gas is worth mentioning. A combination of [CII] and [OI] lines can be used to get information about the molecular gas. They are the two main PDR cooling lines and show a correlation with far-infrared emission. These lines are the product of photodissociation of CO. The use of these lines in the context of PDRs is discussed extensively in Hollenbach and Tielens (1999). It can be noted that for these lines to be observable, higher (above 100 K) temperatures and densities are required (see e.g. Spaans, 1996).
1.2.2 Dust emission

Dame et al. (2001) determined the value of the X-factor in the Milky Way using 100 µm far-infrared dust emission maps and H\textsc{i} maps. This approach finds its origin in de Vries et al. (1987), where

\[ I_{100} = aN(H) + I_{100}(BG). \]  

(1.1)

BG indicates the background emission and \( N(H) = N(H\textsc{i}) + 2N(H_2) \), while the scaling factor \( a \) needs to be determined empirically.

It is assumed that the total gas column density in regions free of CO emission is given solely by the H\textsc{i} content (and a constant background level). The infrared map is then corrected by this atomic gas map to yield an effective molecular hydrogen content map. Figure 11 of Dame et al. (2001) gives the derived X-factor as a function of galactic latitude. The method allows the ratio of 100 µm to H\textsc{i} emission to vary over large scales. This is similar to the work by Desert et al. (1988), who conducted an all-sky search, and Reach et al. (1998), who find that most of the molecular clouds in their results are relatively cold (15-20 K).

Israel (1997) uses a slightly different approach, applied to the Large Magellanic Cloud and small magellanic irregular galaxies. It is based on the same basic assumption: In regions free of CO emission, the gas is purely atomic and directly observable through the H\textsc{i} emission. They use the following formula to derive the H\textsubscript{2} column density:

\[ 2N(H_2) = [(N(H\textsc{i})/\sigma_{FIR})_0 f(T)\sigma_{FIR}] - N(H\textsc{i}), \]  

(1.2)

that contains the far-infrared surface brightness \( \sigma_{FIR} \) and a temperature-sensitive emissivity correction \( f(T) \). A constant dust-to-gas ratio is assumed, as well as a constant dust temperature distribution. The resulting X-factor for these galaxies is shown to be a firm lower limit and higher than the value of the X-factor for the Milky Way. A higher value means that the inferred H\textsubscript{2} column densities are also higher.

Interstellar dust particles can also be detected by their (sub-)millimeter wavelength continuum emission (which includes CO line emission). There is a good correlation with CO emission when the CO is bright. See for example Bot et al. (2007) and references therein. In this case,

\[ I(\lambda) = N(H)e_H(\lambda)B_\lambda(T_{dust}), \]  

(1.3)

where \( e_H \) is the emissivity per hydrogen atom (dependent, for instance, on the dust-to-gas mass ratio), and \( T_{dust} \) is the dust temperature. They suspect an X-factor different from the value in our Galaxy particularly in low metallicity environments.

1.3 Atomic hydrogen in nearby spiral galaxies — Produced in PDRs?

After this short overview of the use of carbon monoxide and dust emission in determining the molecular hydrogen content, we now turn to the subject of this thesis.

The element that is closely connected to H\textsubscript{2} by its very nature is atomic hydrogen (H\textsc{i}), making up the bulk of the readily visible matter in the universe. While it is generally assumed to be mostly primordial in nature, there are strong indications that a large fraction
of the H\textsubscript{i} in galaxies was formed in photodissociation regions (PDRs) under the influence of radiation from hot, young stars (Allen et al., 1986).

The process of H\textsubscript{i} being turned into H\textsubscript{2} and back into H\textsubscript{i} can be used to measure the abundance of H\textsubscript{2} in Giant Molecular Clouds (GMCs) through the measurement of H\textsubscript{i} formed in PDRs on the surface of these GMCs. It is the application and refinement of this method that is at the heart of this thesis. Theoretically, all the H\textsubscript{i} in a galactic disk can be photodissociated, since there is enough dissociating radiation available, as well as enough time for the H\textsubscript{2} to form and to be dissociated again (Allen, 2004). The fraction of H\textsubscript{i} originating from PDRs is likely to be lower in practice, but still significant, and this atomic hydrogen should leave its imprints on the larger-scale distribution of H\textsubscript{i} in galactic disks.

The concept of photodissociated atomic hydrogen, even at larger scale, is occasionally considered. For example, we can point to Wilson and Scoville (1991), who discuss how a relative offset of H\textsubscript{i} and CO in the southern spiral arm of M33 fits the view that the H\textsubscript{i} was produced by photodissociation of H\textsubscript{2}. Densities of \( n \) between roughly 40 and 160 cm\(^{-3}\) are required to make their model agree with observations. This is the kind of relatively low-density PDRs that we are looking for.

In this thesis, we will try to identify H\textsubscript{i} features and assume that these features are the product of photodissociation.

1.3.1 Photodissociation regions — An alternative tracer of molecular hydrogen

The emergence of young, hot stars out of the massive clouds in the interstellar medium (ISM) leads to the formation of PDRs. Energetic UV photons from O and B stars, around 1000 Å, can dissociate nearby molecular hydrogen into atomic hydrogen (Stecher and Williams, 1967). Close to these stars, atomic hydrogen may be ionized, leading to the detection of H\textsubscript{II} regions. Further out, the photodissociating photons create a layer of H\textsubscript{i} on the surfaces of GMCs. The physics of PDRs was reviewed thoroughly by Hollenbach and Tielens (1999). We follow them in referring to these regions as photodissociation regions (others might prefer the term photon-dominated regions), since it is the aim of this work to provide a basis for viewing large-scale H\textsubscript{i} emission as a product of photodissociation.

In our own galaxy, these PDRs have been observed in, for example, the well-studied Orion Nebula. The size of such a region ranges from the sub-parsec scale to a few tens of parsecs. However, larger PDRs also exist and can have sizes of the order of hundreds of parsecs. In these regions the incident UV flux is noticeable and capable of dissociating H\textsubscript{2}. An example of such a cloud in our own Galaxy was provided by Williams and Maddalena (1996). At these scales the incident dissociating flux coming from the nearby OB stars still dominates the UV field radiating on molecular hydrogen, and the resulting 'blanket' of H\textsubscript{i} on the surface of the associated GMCs is much thicker (Hollenbach and Tielens, 1999). These structures can be detected, albeit not always completely resolved, out to a distance of roughly 10 Mpc with present-day telescopes.

At the linear resolution scale that we are dealing with in nearby galaxies, which is of the order of a few tens of parsec, the combined FUV flux from clusters of OB stars is still significant. We can expect to be looking at diffuse, large, low-density GMCs, or unresolved clusters of GMCs. Hollenbach et al. (1991) define low-density PDRs as lying in the param-
Figure 1.1: Figure 1 from Field et al. (1966) shows the different transitions of the molecular hydrogen molecule. It can dissociate from the upper levels.

1.3.2 PDR Theory

The following is based primarily on Sternberg (1988) and Allen (2004). Atomic hydrogen and molecular hydrogen can be treated as being in equilibrium, which means that the H$_2$ formation and destruction rates are matched. While the H$_1$ and H$_2$ are probably not actually in equilibrium, especially in denser regions (Bertoldi and Draine, 1996), we will assume that the large-scale PDRs are close enough to equilibrium for this analysis to be useful. It is also assumed that cosmic-ray destruction can be neglected.

A molecular hydrogen molecule can absorb a UV photon in the range of 912 to 1108 Å for photodissociation to take place, or from 13.6 eV to 11.1 eV respectively. 13.6 eV is the ionization energy of H$_1$, so higher energies are not available, while 11.1 eV is the lowest possible energy to get the H$_2$ into an excited electronic state (in lines of the Lyman and Werner bands). From there, the molecule decays back down into the ground electronic states, but 10 – 15% of the time it will dissociate into two hydrogen atoms. An illustration of this process, taken from Field et al. (1966), is included as Figure 1.1.

The interested reader is referred to Tielens (2005) for a full treatment of this subject. The H$_2$ destruction rate is

$$R_{diss} = D\chi e^{-T_{gr,1000}} f_s(N_2) n_2 \left[ \text{H}_2 \text{ molecules cm}^{-3} \text{ s}^{-1} \right],$$  \hspace{1cm} (1.4)
where subscript 2 is shorthand to indicate molecular hydrogen. Likewise, subscript 1 will indicate atomic hydrogen. $D$ is the unattenuated photodissociation rate, $\chi$ is a measure of the incident radiation field (see Equation 1.12) and $\tau_{gr,1000}$ is the grain absorption at 1000 Å. $f_s$ is the absorption line self shielding function, and is dependent on the H$_2$ column density.

The H$_2$ formation rate is

$$R_{\text{form}} = \gamma_2 \times n \times n_1 \left[ \text{H}_2 \text{ molecules cm}^{-3} \text{s}^{-1} \right], \quad (1.5)$$

where $n = n_1 + 2n_2$.

Then, with the continuum opacity $\tau_{gr,1000} = \sigma(N_1 + 2N_2)$ (where $\sigma$ is the effective grain UV continuum absorption cross section), we can write

$$Rn N_1 = D \chi f_s (N_2) e^{-\sigma(N_1 + 2N_2)} dN_2, \quad (1.6)$$

where $R$ was written for $R_{\text{form}}$, while

$$\gamma_2 = 3.0 \times 10^{-18} (\delta/\delta_0) T^{1/2} y_F(T) \left[ \text{cm}^3 \text{s}^{-1} \right], \quad (1.7)$$

from Jura (1974). The quantity $T^{1/2} y_F(T)$ can be approximated as constant, since it varies only within a factor two of its assumed value (Hollenbach et al., 1971).

Jura (1975) estimated a formation rate of $3 \times 10^{-17} \text{cm}^3 \text{s}^{-1}$. More recent estimates of this value are given by e.g. Habart et al. (2004) and Wolfire et al. (2008).

Equation 1.6 is then integrated to yield

$$N_1 = \frac{1}{\sigma} \ln \left[ \frac{DG}{Rn} \chi + 1 \right] \left[ \text{cm}^{-2} \right], \quad (1.8)$$

where $G$ is an expression of the effective grain absorption cross section (which includes $f_s$) and is a constant for $N_2 \to \infty$. $G \propto (\sigma/\sigma_0)^{1/2}$. $R$ is the H$_2$ formation rate coefficient on grain surfaces and $R \propto \delta/\delta_0$. $\sigma \propto \delta/\delta_0$.

$n$ is the total hydrogen volume density, which is the main quantity we are interested in here. We will write $N(\text{H}_1)$ for $N_1$.

The previous expression reduces to

$$N(\text{H}_1) = \frac{7.8 \times 10^{20}}{\delta/\delta_0} \ln \left[ 90 \chi \left( \frac{\delta}{\delta_0} \right)^{-1/2} + 1 \right] \left[ \text{cm}^{-2} \right], \quad (1.9)$$

with numerical values from Madden et al. (1993), updated by Allen (2004) to include the dependency on $\delta/\delta_0$, the dust-to-gas ratio scaled to the solar neighborhood.

Rewriting to yield the total hydrogen volume density $n$ gives

$$n = 90 \chi \left( \frac{\delta}{\delta_0} \right)^{-1/2} \left[ \exp \left( \frac{N(\text{H}_1)(\delta/\delta_0)}{7.8 \times 10^{20}} \right) - 1 \right]^{-1} \left[ \text{cm}^{-3} \right], \quad (1.10)$$

and $G_0 = 0.85 \chi$, from Hollenbach and Tielens (1999); see also Allen et al. (2004), who derive this expression in their Appendix B. $\chi$ is defined in a way that is appropriate for an incident flux from distributed sources from $2\pi$ steradians on a PDR surface, while $G_0$ is an equivalent one-dimensional flux. $G_0$ is commonly used in PDR modeling.
Equation 1.10 can therefore also be written as

\[ n = 106G_0 \left( \frac{\delta}{\delta_0} \right)^{-1/2} \exp\left( \frac{N(\text{HI})(\delta/\delta_0)}{7.8 \times 10^{20}} \right) - 1 \right]^{-1} \text{[cm}^{-3}]. \] (1.11)

Remember that \( n = n_1 + 2n_2 \), the total hydrogen volume density. At the center of a GMC all the hydrogen is expected to be in its molecular form, so there \( n_2 = n/2 \).

We can measure the FUV flux (in units ergs cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\)), at an effective wavelength of 1528 Å for GALEX data. This is a good substitute for the actual dissociating flux at 1000 Å, since the interstellar radiation field is fairly constant around that wavelength range (Draine, 1978). We then calculate the UV flux incident on the HI column by multiplying by \((D/\rho)^2\), which will give us \( \chi \):

\[ \chi = \frac{F_{\text{FUV}}}{F_0} \left( \frac{D_{\text{gal}}}{\rho_{\text{HI}}} \right)^2, \] (1.12)

where \( F_0 = 2.64 \times 10^{-6} \) ergs cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\), which is called the Habing flux after Habing (1968). This is a measure of the fraction of ultraviolet radiation that reaches the HI patch of which we measure \( N_{\text{HI}} \). \( \rho_{\text{HI}} \) is the separation between the central UV source and the HI patch and is corrected for projection effects as much as possible. We assume a spherical model, in which the candidate PDR is perfectly symmetric and where the HI patch is located at the edge of a sphere of radius \( \rho_{\text{HI}} \). Deprojection is achieved by considering the position angle and declination of the host galaxy’s disk, which is assumed to be circular.

Equations 1.10 and 1.12 constitute the PDR model that can be applied to observations. It can be seen that \( n \) scales linearly with \( G_0 \) and that \( N_{\text{HI}} \) is related to \( n \) exponentially. The dependency on \( \delta/\delta_0 \) is twofold. When \( \delta/\delta_0 \) is close to 1, the relation can be approximated by \( n \propto \delta/\delta_0^{-3/2} \). Lower dust-to-gas ratios will result in higher values of \( n \). Physically, this means that the same observed HI column density must be linked to a denser GMC if the dust-to-gas ratio is lower.

### 1.3.3 Introducing the ’PDR method’

The application of the PDR model on actual observational data can be dubbed the ’PDR method’, since it is an application based on the assumption of the presence of PDRs (’candidate PDRs’).

PDRs have been studied extensively in our own Galaxy (Hollenbach and Tielens, 1999). The notion that the HI in spiral arms was a product of star formation was first presented in the paper about M83 by Allen et al. (1986). The PDR method was subsequently proposed and applied to M81 in a limited fashion by Allen et al. (1997). This was followed by a full scale quantitative application of the method to M101 by Smith et al. (2000). The connection between HI and CO in photodissociation regions was treated by Allen et al. (2004).

I will now describe the application of the PDR method in some detail. A schematic view of a typical region in which PDRs can be expected, inspired by Hollenbach and Tielens (1999), is shown in Figure 1.2. An association of OB stars illuminates the remnants of the molecular clouds from which it was formed. On the surface of these GMCs, atomic hydrogen is formed in thin layers.
The basic recipe consists of the following steps:

- Adopt dust-to-gas values. Individual values per candidate PDR are ideal.

- Identify the OB star clusters where candidate PDRs can be found. In principle these are UV bright knots of emission.

- Photometry: Determine the FUV flux of the OB stars.

- Identify the associated H\textsubscript{I} patches on the surface of the GMCs and measure their column density.

- Measure and deproject the separation between the central UV source(s) and the H\textsubscript{I} patches.

- Compute the total hydrogen volume densities from the measured values.

This method can always be applied, but we will need to provide some support as to its applicability (see §1.4).
Adopting suitable dust-to-gas ratios

The photodissociation model is strongly dependent on the dust-to-gas ratio. This information is generally unavailable, so it is derived instead from the metallicity [O]/[H] from ionized oxygen lines (Issa et al., 1990). These metallicities are measured in HII regions. We will assume at this time that they are also appropriate for the general area. Since the dust-to-gas ratio is normalized to the solar value, a solar metallicity has to be adopted also (Allende Prieto et al., 2001). The metallicity is thought to vary by a power-law as a function of galactocentric radius. Most of the metallicity gradient measurements are available from Zaritsky et al. (1994). In the case of M81, Stauffer and Bothun (1984) and Garnett and Shields (1987) were used. For M83, it was Gil de Paz et al. (2007b). Finally, for M33, the results by Rosolowsky and Simon (2008) were used.

Identifying OB star clusters

Associations of O and B stars are selected on the basis of FUV imagery. In practice, all UV sources have associated HI patches within a few hundred parsec. Most of the OB associations have HII regions (see e.g. Allen et al., 1997). In the case of M33, some regions were selected based on the availability of supplemental data, like metallicity data or CO detections nearby. It must be noted that completeness was not a goal, so the collection of candidate PDRs obtained in this work is not necessarily statistically representative of all large-scale PDRs in a given spiral galaxy. However, attention was focused on understanding the selection effects influencing the results.

Determination of the incident FUV flux $G_0$

The GALEX UV maps are made publicly available fully processed$^1$. The images have pixel values in counts / second / pixel. Integrated pixel values can be converted to fluxes in ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

The FUV flux is determined by taking concentric circles around the center of the source (determined by fitting a gaussian function to the source). The aperture size (the radius of the largest circle in which the flux is measured) in arcsec is determined by the first local minimum in the value of the average intensity of the concentric circles. The background level is measured at this radius. It is also assumed that this background level is representative of the one at the HI columns associated with this source, which is used to calculate the background incident flux $G_{bg}$.

The actual $G_0$ is the incident flux on a particular HI patch and can be calculated using $\rho_{HI}$, the separation between the UV source and the HI patch.

$$G_0 = 0.85 \cdot \chi = 0.85 \cdot \frac{F_{FUV}}{F_0} \left( \frac{D_{gal}}{\rho_{HI}} \right)^2$$  

(1.13)

The ambient background radiation is calculated in a slightly different way. The measured background intensity is integrated over half the sky, since it is incident on what is approximated by an infinite slab.

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$^1$http://galex.stsci.edu
The background level is calculated as

\[ \chi_{bg} = \frac{I_{bg}}{\text{pixel}} \cdot d^2_{\text{pixel}} \cdot 4.25 \times 10^{10} \left[ \text{arcsec}^2 / \text{sterad} \right] \cdot \frac{2\pi}{F_0}, \quad (1.14) \]

where \(d_{\text{pixel}}\) is the pixel separation of the UV image. The map units need to be converted into a flux per steradian. Finally, \(\chi_{bg}\) is normalized like \(\chi\).

\(\chi/\chi_{bg}\) is identical to \(G/G_{bg}\). (Note that this quantity is independent of \(F_0\).) I will generally refer to this as the source contrast.

The source (to background) contrast ratio ranges from very small (1% of the background level) to several times the background level. A higher value can be considered a stronger indication of the presence of a PDR, since the dissociating radiation stands out more from the background.

'Patches' of atomic hydrogen

Identifying atomic hydrogen produced in photodissociation regions, and particularly identifying the atomic hydrogen connected to the nearby OB stars, is complicated by the presence of a general H\textsc{i} background. Roger and Dewdney (1992), for example, discuss the detectability of "H\textsc{i} zones" against low- and high density surroundings and note the need for sufficient resolution.

Any local maximum of the atomic hydrogen column density could be considered produced by photodissociation under the influence of the nearby UV source. We tried to estimate the fraction of the H\textsc{i} column produced by photodissociation by subtracting a background level. In the case of M81 and M83, a general background level was adopted. The same approach was followed for M33, except that for the analysis at full resolution local values were taken.

The morphology of the PDR remains unknown in the PDR method, but we assume that we can deproject the galactic disk by its position angle and declination. This means in practice that the separation \(\rho_{\text{H}\textsc{i}}\) between the UV source and every H\textsc{i} patch was corrected for this. Unfortunately, no information on the actual orientation of the patch with respect to the UV source is available, so potential projection effects into the plane of the galaxy remain (see Chapter 2, Figure 2.4 for an illustration).

Calculating the total hydrogen volume density

After the previous steps, enough information is available to use with Equation 1.11. The resulting values of \(n\) are "spot" measurements relating the observed atomic hydrogen columns to the local total hydrogen reservoir. It should be stressed that one or more such measurements are available for every OB association (one for each H\textsc{i} patch), which are all independent probes of the underlying GMCs.

Error estimates

The uncertainties in this method remain relatively large due to various factors, like the uncertainty in the dust-to-gas ratio. Qualitatively speaking, the UV photometry is relatively accurate, as is the measurement of H\textsc{i} column densities (provided the H\textsc{i} columns are not...
optically thick). The separation between the OB star clusters and the candidate PDR H\textsc{i} patches is subject to projection effects as it is measured on the plane on the sky.

The dust-to-gas ratio, based on metallicity measurements of H\textsc{i} regions, fluctuates significantly from one region to another. The single metallicity gradient that we generally used introduces uncertainties due to ignoring the local fluctuations.

The general formalism to estimate these errors is described in the appendix to Chapter 2. In the case of individual regions at full resolution in M33, the fractional uncertainty can drop to around 0.2, but uncertainties can be as high as a factor two in the value of the total hydrogen volume density. A fractional uncertainty of around 0.8 is common in the M81 and M83 results.

1.4 Connections to the PDR method

Several ways to put the PDR method on a firmer footing can be explored.

We can use the PDR model to predict the distribution of H\textsc{i} spatially. Assuming a certain total gas density, combined with the local metallicity, and the measured incident UV flux, the PDR model can be used to calculate the H\textsc{i} column density. Since $G_0$ is dependent on the distance between the central OB cluster and the H\textsc{i} patches, a profile of the expected amount of atomic hydrogen with an increasing separation can be produced. This approach is used in Chapter 4.

Another indication of recent star formation, and the presence of PDRs, comes from PAH emission. See, e.g., Hollenbach and Tielens (1999). This property is used in Chapter 2, in which we search for the presence of PAH emission, as derived from 8 \textmu m images of M81.

The PDR method can be compared qualitatively to CO emission measurements. It is expected that CO would generally trace the denser molecular clouds, as opposed to the smooth, lower-density gas. This is explored in Chapter 4.

Finally, the PDR method can be used to study the star formation law, which will be treated in Chapter 6. Schmidt (1963) proposed that the rate of star formation in our Galaxy can be parametrized by the amount of available interstellar gas to a certain power $n$. Since we determined hydrogen gas densities $n$, and because the far-UV flux is related to the local star formation rate, we have a tool to study the star formation law.

1.5 Outline of this thesis

In short, this work focuses on atomic hydrogen, produced in photodissociation regions, as a product of recent star formation. This property can be used to probe the underlying GMCs, remaining after star formation, by calculating the total hydrogen available locally. The PDR method was applied and expanded, and supporting evidence for its applicability were pursued.

This thesis is structured chronologically, in the order of which the research was carried out. Candidate PDRs in M81 and M83 were investigated first, after which M33 was studied in more detail. Throughout this process, supporting evidence of the presence of large-scale PDRs was sought.
• Chapter 2 deals with the properties of candidate PDRs in M81 and how they are found to have corresponding PAH emission.

• Chapter 3 contains the M83 PDR results, which are also compared to detections of CO emission.

• Chapter 4 presents first results of the analysis of M33 candidate PDRs. In two of these regions, it can be seen how the higher gas densities correspond to detections of CO emission, and an attempt is made to model two example H\textsuperscript{i} features using the PDR model.

• Chapter 5 displays the full resolution M33 PDR results.

• Chapter 6 compares the M33 results to the M81 and M83 results and deals with the connection to the star formation law.

• Chapter 7 summarizes the results of this thesis and offers a view towards future work.