Optical spectroscopy of interstellar and circumstellar molecules
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Laboratory and Observational Astrophysics
Introduction

This chapter focuses on the experimental set-ups that are used in this study to obtain spectra of transient species of astrophysical interest. This chapter is split into four parts. The first part describes the principle of cavity ring-down (CRD) absorption spectroscopy. The CRD experiment is used to obtain electronic spectra of carbon chains and hydrocarbon species to compare to astronomical spectra obtained from diffuse interstellar clouds (see also Chapters 3-5). The second part of this chapter describes laser induced fluorescence (LIF) spectroscopy. Spectra of $C_2$ are presented and compared to astronomical spectra of the Red Rectangle proto-planetary nebula (see Chapter 6). The CRD and LIF experiments are combined with special plasma expansions that are described as well. The third part of this chapter describes the approach to identify these species in different environments and how simulations using intrinsic molecular parameters can assist our understanding in obtaining further information about rotational temperatures of the molecules in the laboratory and in the ISM. That way simulations are an important tool in assisting unambiguous assignments of the transitions detected in the laboratory and in the ISM. Finally, the fourth part of this chapter describes the observational techniques used to obtain the spectra of the Red Rectangle proto-planetary nebula and of the diffuse interstellar cloud located in the line of sight towards HD 183143.

2.1 Absorption Spectroscopy

Atoms and molecules absorb electromagnetic radiation at specific frequencies that are characteristic, i.e., each species possesses a unique “fingerprint” spectrum. The only chance of identifying molecules unambiguously in the interstellar or circumstellar medium (ISM or CSM) is to compare astronomical data with spectra recorded under laboratory controlled conditions. Absorption of electromagnetic radiation, under conditions where saturation does not occur is described by “Lambert-Beer’s” law:

$$I_l(\nu) = I_0(\nu) \times \exp(-\sigma(\nu)n \ell)$$  \hspace{1cm} (2.1)

In this equation $I_0(\nu)$ is the intensity of the incident radiation field at a certain frequency ($\nu$). $I_l(\nu)$ is the intensity after the radiation has passed a distance ($\ell$) through an absorbing medium. The transmitted light depends on the number of particles in the absorbing material ($n$) and the cross-section ($\sigma(\nu)$) of the absorbing material. The product ($\sigma(\nu)n \ell$) is also known as the absorption coefficient, labelled ($\alpha(\nu)$). A crucial point and a limiting factor when recording absorption spectra in the laboratory is to measure the energy change of the transmitted light. Absorption spectroscopy is not a very sensitive technique, as generally a rather small decrease in signal has to be measured against a large background signal. The number of species that can absorb ($n$) and the absorption pathlength ($\ell$) are the main parameters that can be increased in order to obtain higher sensitivity spectra. CRD spectroscopy is a special case of absorption spectroscopy that results in high detection levels. In CRD spectroscopy the absorption length is extended by using two highly
2.1 Absorption Spectroscopy

Figure 2.1 – The basic principle of CRD spectroscopy is shown. A laser beam traverses the first mirror (R1). With each round trip in between the cavity mirrors (R1 and R2) the intensity becomes weaker due to absorption by gas and mirror losses. The light leaking out of the cavity is detected using a photomultiplier tube and the ring-down signal is displayed on an oscilloscope. Fitting the exponential decay gives the ring-down time. Recording the ring-down time as function of laser frequency yields the absorption spectrum.

Reflective cavity mirrors that form a high finesse optical cavity in which the light can be trapped (typically $R \geq 99.9\%$). The intensity of the light leaking out of the cavity decreases by a fixed percentage during each round trip inside the cavity. This is due to the eventual absorption of the medium in the cell and the reflectivity losses of the mirrors. The intensity of the light leaking out of the cavity is then determined as an exponential function of time. In 1980, Herbelin et al. (1980) were the first to use this decay rate of light leaking out of an optical resonator to determine mirror reflectivities. The first paper on the CRD technique was published in 1988 (O’Keefe & Deacon 1988), applying the principle of reflectivity as a laser based direct absorption measurement technique.

The CRDS principle is displayed in Fig. 2.1. A light beam traverses the first mirror...
and enters the cavity. The light bounces back and forth between the two cavity mirrors (R1 and R2). A small portion of the light is leaking out each time when hitting one of the highly reflective mirrors and reaches the photomultiplier tube (PMT) detector that is located on one side of the cavity. The resulting exponential decay is given by:

$$I(t) = I_0 \exp(-t/\tau)$$

Here, (\tau) is the decay time or the so-called “ring-down time” and is a measure for the time the light pulse resides in the cavity. (I_0) is the signal intensity prior to its decay. The ring-down time is dependent on the medium inside the cavity and the mirror losses.

At first the losses for an empty cavity are determined:

$$\tau_0 = \frac{n \cdot l}{c \cdot (1 - R + X)}$$

where (n) is the index of refraction within the cavity, (c) the speed of light in vacuum, (l) the cavity length, (R) mirror reflectivity, and (X) takes into account other optical losses. If upon gas injection the wavelength of the laser coincides with an allowed transition of molecules inside the cavity the losses will be higher and the ring-down time of the incident light pulse will be lower.

$$\tau = \frac{n \cdot l}{c \cdot (1 - R + X + \alpha l)}$$

Here (\alpha) is the absorption coefficient, mentioned before, which is specific for each substance. The stronger the sample absorbs, the faster the light decays. Depending on the mirror reflectivity, the effective path length in a typical ring-down experiment can reach up to several kilometres. Detailed studies can be found in several review articles (Berden et al. 2000, Saykally & Casaces 2001, Paldus & Kachanov 2005) and several textbooks (Demtroeder 1996, Linnartz 2009) as well as in papers which discuss specific topics related to CRDS theory (Zalicki & Zare 1995, Lehmann & Romanini 1996, Hodges et al. 1996, Lee et al. 1999, Parkes et al. 2003). The fast fitting algorithm that was adopted here for the fitting routine of the exponential decay curve is described in detail by Halmer et al. (2004). Different CRD schemes exist. The work described in chapters 3-5 is based on a pulsed CRD detection scheme. This is essentially the most straightforward way to use this method, as a cavity is fully transparent for rather broad laser pulses, i.e., it is not necessary, as in continuous wave (cw) CRD schemes to scan the cavity length in order to induce a ring-down event (see e.g. Birza et al. (2002)). This makes pulsed CRD spectroscopy ideal to combine with pulsed plasma expansions that are described in the next section.

### 2.2 Production of Transient Species

The formation of transient species is a crucial step in this experiment. Discharge - or plasma sources are needed in order to create conditions that enhance the formation of
molecules that are not stable under normal (terrestrial) conditions. Different kinds of discharge sources are used here, with specific advantages and disadvantages.

### 2.2.1 Pinhole Nozzle

In Fig. 2.2 a pinhole discharge source is shown. The pinhole nozzle is used to form carbon bearing species, pure carbon chains, hydrocarbons, cationic species and radicals from a precursor gas. Here a mixture of 0.5% C$_2$H$_2$ in He is used.

The discharge body consists of several plates in a multilayer geometry as described by Zhao et al. (2010) (see also Chapter 5). More specifically one metal plate is connected to a negative HV supply (C, cathode) and a second metal plate is connected to ground (A, anode). The plates are separated by a ceramic insulator (I$_1$, insulator) plate. The bottom most ceramic plate (I$_2$) is used to prevent the discharge from clogging. Formation of the transient species mainly takes place between the anode and cathode plate. The HV leads to fragmentation of the C$_2$H$_2$ molecules. High backing pressures of $\sim$10 bar lead to collisions between all the fragments and enhance formation of new species. The exact chemistry inside a plasma environment is still not very well understood, but similarly as in space, it is assumed that chain structures are formed from a series of barrierless combination reactions starting from very small radicals, C$_2$, CH$^+$, CH, C$_2$H,..., and upon insertion into acetylene (C$_2$H$_2$) longer carbon chains or hydrocarbon chains are formed (Tielens 2005).

For the experiments the pinhole nozzle has been optimized for obtaining high-resolution spectra of longer carbon chains. This is achieved due to the thickness of the bottom plate (I$_2$) which decreases efficiently the jet opening angle of the gas expansion and enhances collisions. Collisional cooling therefore becomes more efficient and the species are rotationally and vibrationally cold, but can be in an electronically excited state. In addition, the smaller expansion angle decreases the Doppler broadening and allows for spectra with higher resolution.

### 2.2.2 Slit Nozzle

The second type of discharge nozzle that has been used in these experiments, especially in the cavity ring-down experiment, is a so-called slit nozzle. A schematic overview is shown in Fig. 2.3.

The figure shows the slit nozzle with the pulsed solenoid valve at the bottom (gas inlet). The right panel shows a cut through the nozzle body. Gas is injected and distributed evenly over the whole slit. The discharge body consists of an anode (A) and a cathode (C) plate separated by a ceramic insulator (I$_1$) plate. The nozzle is used for the production of carbon chain species as well as hydrocarbons, similar to the pinhole nozzle described before. The main advantage of using the slit nozzle compared to the pinhole nozzle is the geometry which allows for a planar plasma expansion obtaining a nearly “Doppler-free” environment. Furthermore, the absorption pathlength is increased and as the density profile drops linearly with the distance to the nozzle orifice, the plasma environment is more efficient. The result is an increase in resolution compared to the pinhole nozzle.
The discharge comprises two metal plates used as anode (A, grounded) and cathode (C, negative HV), separated by a ceramic plate (I₁, insulator). The discharge is connected to a pulsed solenoid gas injection system (General valve series 9) that operates at high pressure, typically around \( \sim 3-12 \text{ bar} \) and separates the high pressure side from the vacuum side in the chamber (typically around \( \sim 0.1 \text{ mbar} \) for cavity ring-down spectroscopy and around \( \sim 10^{-4} \text{ mbar} \) for the laser induced fluorescence spectroscopy upon gas injection).

The disadvantage of the slit nozzle is that the cooling is less efficient which results in “hotter” spectra in which the molecules show more population in the excited rotational and vibrational levels. The main advantage of using both nozzles is the additional information that one can obtain by comparing the high resolution slit-nozzle spectrum (containing many congested bands) with the less “crowded” (colder) spectrum obtained...
2.3 The Experimental Set-Up - CRDS

Upon discharging the C$_2$H$_2$/He mixture, the carrier gas is expanded into a vacuum chamber. The supersonic plasma expansion is used to cool down the molecules adiabatically. Molecules in this environment have the characteristic of being rotationally and vibrationally (ro-vibrationally) rather cold, but can remain in an excited electronic state. This is an important aspect, since electronically excited species are also found in environments in the interstellar medium (see also Chapter 6).

In Fig. 2.4 the experimental set-up is shown as used at the Laser Centre at Vrije Universiteit Amsterdam. The set-up has been described in detail in (Linnartz 2009) and (Wehres et al. 2010b) (see also chapters 3–5). The light of a frequency tripled Nd:YAG laser (~ 355 nm) is coupled into a Sirah dye laser at a repetition rate of 10 Hz, with a pulse width of ~ 6 ns and a bandwidth narrower than 0.04 cm$^{-1}$. Absolute laser frequency calibration is performed using an iodine or tellurium reference spectrum that is recorded simultaneously to the experiment. The light is guided into the spectroscopy chamber and intersects the discharge expansion perpendicularly. The light leaking out of the cavity...
mirrors (Research Electro-Optics, $R \sim 99.998\%$ at 532 nm) traverses a narrow band pass filter and is then detected by a photomultiplier tube (PMT). The ring-down signal is analysed by a LabVIEW computer program and about 6-10 ring-down events are normally averaged to determine one data point. A complete spectrum is plotted showing the signal intensity with respect to the laser frequency. More details on this experiment can be found in detail in Naus et al. (1997), Witkowicz et al. (2004), Linnartz (2009), Wehres et al. (2010b).

Fig. 2.5 shows an absorption overview spectrum of a hydrocarbon plasma as recorded in the laboratory. The $\text{C}_2$ Swan band system ($d^3\Pi_g \leftarrow a^3\Pi_u$) is visible and shows impressively the manifold of rotational states that are populated. Also absorption bands of previously assigned larger carbon species such as $\text{HC}_4\text{H}^+$, $\text{C}_6\text{H}^+$ and $\text{C}_5$ can be seen (Prasad & Bernath 1994, Lloyd & Ewart 1999, Motylewski & Linnartz 1999, Raghunandan et al. 2009). The resolution of the laser is sufficient to resolve the rotational bands of $\text{C}_2$. For larger carbon chains the spacing between the rotational levels is decreasing fast and rotational levels sometimes form an envelope covering multiple transitions. Also lifetime broadening of states can lead to unresolved spectra which prevent clear identification of the carrier characteristics.
2.4 The Experimental Set-Up - LIF

The experimental set-up for laser induced fluorescence spectroscopy (LIF) is located at the Sackler Laboratory for Astrophysics at Leiden Observatory. The experiment has been described in detail by Volkers et al. (2004) with the modifications mentioned in Wehres et al. (2010a). In Fig. 2.7 the experimental set-up is shown. A Scanmate dye laser is optically pumped by a frequency doubled Nd:YAG laser. The repetition rate is at 10 Hz and the laser pulse width is \sim 7 \text{ ns}. The resolution is \sim 0.07 \text{ cm}^{-1}. Mirrors and

Figure 2.5 – The figure shows a typical absorption spectrum recorded through a supersonically expanding hydrocarbon plasma. Clearly visible are the many bands created from C\textsubscript{2} Swan band \((d^3\Pi\text{u} \leftarrow a^3\Pi\text{g})\) absorption.

Another spectrum illustrative of the high resolution that can be obtained using the slit-nozzle is presented in figure 2.6, which shows the A\textsuperscript{2}\Pi \leftarrow X\textsuperscript{2}\Pi origin band transition of C\textsubscript{6}H. The upper spectrum shows the spectrum as obtained in the laboratory and the lower (mirrored) spectrum shows the simulation using PGOPHER (Western 2007), a program that simulates the rotational contour and that will be explained in a bit more detail below. The laboratory spectrum shows that the P, Q and R branch can be recorded fully rotationally resolved for both spin-orbit components (Linnartz et al. 1999).
Figure 2.6 – The figure shows the high-resolution spectrum of C$_4$H recorded in a hydrocarbon plasma expansion using cavity ring-down (CRD) spectroscopy. The simulation is mirrored and yields a rotational temperature of 20 K for the laboratory experiment, which is comparable to temperatures in diffuse interstellar clouds. The resolution is about 0.08 cm$^{-1}$.

Lenses are used to focus the light into the vacuum chamber. The laser intersects perpendicularly with a supersonic jet expansion about 15 cm downstream of the plasma nozzle (see Fig. 2.7). The species in the plasma expansion may be in different ro-vibronical states (ground and electronically excited states may be populated). An iodine calibration spectrum is recorded simultaneously to obtain absolute frequency calibration. Upon absorption of laser light at a specific frequency by the molecular species in the expansion, the species will be (further) ro-vibronically excited. If de-excitation due to fluorescence takes place, the emitted light is detected by a photo-multiplier tube. The fluorescence signal is then recorded with respect to its absorption wavelength.

The advantage of LIF spectroscopy over “regular” absorption spectroscopy is the enhancement of the sensitivity. This is mainly achieved because the experiment is not based on a small decrease of laser intensity upon absorption of light of a certain frequency, but rather on the emission of light upon electronic excitation, i.e., fluorescence. Fluorescence is isotropic, which means that fluorescence takes place in all directions and can be monitored perpendicularly to the direction of the laser beam which in addition lowers background noise that can occur from scattering or reflection of the laser beam inside
the experiment chamber. Fluorescence will occur if the molecule has no possibility to relax due to internal conversion, followed by ro-vibrational relaxation back to the ground state. The excess energy is then emitted in form of light after a short moment (typically after a couple of nanoseconds). The disadvantage of LIF spectroscopy with respect to direct absorption spectroscopy – like CRDS – is that not all molecules fluoresce and that only specific molecules can be detected that way. A rather good indication for whether a molecule is likely to fluoresce is given by looking at their absorption spectra. If the absorption spectrum of a certain species shows distinct sharp absorption bands this indicates that the lifetime of a species is not too short and internal conversion is not favoured over fluorescence. If the absorption spectra show broadened absorption bands this may indicate that the molecule may have a very short lived excited state. Lifetime broadening occurs as the result of fast relaxation, mainly due to internal conversion, followed by ro-vibrational relaxation back to the ground state.

An important issue in this experiment is the timing of the different pulsed parts that have to match in order to obtain spectra with high signal quality. The gas injection via the solenoid pulsed nozzle has been overlaid with a pulsed HV gate. Upon discharging the gas, the molecules are created rotationally and vibrationally excited (ro-vibrationally); in some cases the molecules can also be in an excited electronic state (ro-vibrationally excited) in the plasma expansion. Expansion into the vacuum is followed by laser excitation of the still (electronically and) vibrationally excited species. Therefore the pulsed laser needs to match timely with the expansion in the vacuum chamber. The detector is time-gated and switches off for the moment when the laser pulse enters the spectroscopy chamber. This is mainly used to prevent the detector from saturating. In addition a broad bandpass filter is mounted in front of the detector which prevents the detector from stray light of the laser beam. Sophisticated light shields have been implemented to decrease the background noise which mainly is due to straylight from the plasma source when discharging the acetylene/helium mixture and from scattered photons from the laser. The plasma light was the mayor problem in this experiment since for high discharge powers it could still be detected up to 100 ms after the discharge pulse and thus was still detected by the PMT when recording the fluorescence signal. Active baseline subtraction of the noise from the signal did not yield any better results. Optimization of the system was performed with C₂ and resulted in a multi-step trigger scheme which is plotted for completeness in Fig. 2.8.

In this experiment the focus is on fluorescence of carbon bearing species that are created by discharging a mixture of 0.2% acetylene (C₂H₂) in helium. The pressures are lower than for the CRDS experiment and range typically between 10⁻³ and 10⁻⁴ mbar. In Fig. 2.9 the vibrational transitions of the Swan band system of C₂ is presented. The spectrum shows the δ¹Πₓ → a¹Πₓ (0,1) transition (Wehres et al. 2010a). The Swan bands are known to have very strong oscillator strengths and have been recorded in many astronomical environments as well as in combustion processes (Bakker et al. 1996, Klochkova et al. 1999, Gredel et al. 1989, Sarre 2006, Glinski et al. 2009, Wehres et al. 2010a). The spectrum shows the assignments of the rotational transitions and a simulation is overplotted as a dotted line. The simulation yields a rotational temperature of ~ 12 K.

The main goal to look for fluorescence of carbon chains or hydrocarbon species in-
Figure 2.7 – The figure depicts schematically the laser induced fluorescence (LIF) set-up. Excitation spectra of transient species are recorded in high-resolution and compared to spectra of the Red Rectangle proto-planetary nebula.

Instead of obtaining their spectrum is to compare the laboratory spectra to the astronomical spectra of the Red Rectangle proto-planetary nebula. This object has been described in Chapter 1 and will be described in more detail in Chapters 6 and 7. The importance of this object lies in the fact that it shows a very rich emission spectrum in the visible and since only specific molecules show fluorescence it is a very unique and also very well suited object to restrict the search for molecules of astronomical importance to molecules that indeed show fluorescence.

2.5 Rotational Contour Simulations

The spectra that are obtained in the laboratory, using CRDS and LIF spectroscopy, have the potential to identify species in the laboratory environment and subsequently also in the interstellar medium. The absorption experiment is used to compare the spectra immediately to spectra of diffuse interstellar clouds, especially towards HD 183143. In this line of sight many diffuse interstellar bands have been detected and an online catalogue allows
2.5 Rotational Contour Simulations

Figure 2.8 – The timing scheme for the LIF experiment is presented. The Master trigger is set to a repetition rate of 10 Hz and triggers the laser and the gas valve. All other instruments have to be matched in time using delay units to guarantee overlap of the gas pulse with the discharge, the laser and the detector gate.

for comparison. The spectra recorded in the LIF experiment are used to compare to emission spectra of the Red Rectangle proto-planetary nebula. Rotational contour simulations using PGOPHER (Western 2007) have a two-fold purpose here: First they assist in the identification of the intrinsic molecular parameters by simulating as precisely as possible the spectrum in the laboratory, followed by the identification of the specific transitions. Second, by simulating the spectrum for different resolutions and rotational temperatures we can identify the species and their transitions in the interstellar ~ or circumstellar environment. Furthermore, the simulation allows for a rough temperature estimate of the identified species in a specific environment and thus assists our understanding of the physical conditions in the interstellar medium. To allow for comparison of the high-resolution laboratory data to the observational (telescope) data obtained at medium resolution, simulations are therefore essential to identify the molecule in the ISM. Temperature differences between the laboratory environment and in the interstellar medium can be taken into account and can result in very different spectra. An example of the laboratory experiment and the corresponding simulation is given in Fig. 2.6 which models the rotational contour of the C₆H molecule. The simulation at a rotational temperature of ~ 20 K yields a nice fit to the laboratory spectrum.
Figure 2.9 – Example of the rotationally resolved C$_2$ spectrum as recorded using laser induced fluorescence (LIF) spectroscopy is shown and the assignments are given. The experimentally obtained spectrum is overplotted by a simulation (dotted line). The spectrum will be discussed in detail in Chapter 6. The arrows indicate two additional rotational lines, which are not reproduced by the simulation using a temperature of $\sim 12$ K, but can be reproduced using higher rotational temperatures in the settings of the simulation.

The simulation for different rotational temperatures and resolutions is an important point, since spectra can vary to a large extent. This is shown in Fig. 2.10. The figure plots three molecules: C$_2$ in the first panel, as a very simple diatomic species. The middle panel plots simulations for the linear hydrocarbon molecule C$_6$H. The third panel shows the simulation for the non-linear carbon chain C$_9$H$_3$. The first trace plots the simulated rotational contour of all species as a stick diagram at 10 K. The second trace shows the same spectrum at a resolution of 0.07 cm$^{-1}$, as obtained in the laboratory work. In the third trace the simulation is plotted at elevated temperatures of $\sim 30$ K and the last trace shows the simulation for 30 K and a degraded resolution of 0.2 cm$^{-1}$ (for C$_2$ $\sim 0.5$ cm$^{-1}$), respectively. Note, for the observations on the Red Rectangle proto-planetary nebula (Chapter 6) the resolution was about 3.5 cm$^{-1}$ only.

The overall contour of the molecular spectra is strongly dependent on the intrinsic molecular characteristics, i.e. the moment of inertia along the principal axis. These moments of inertia (or rotational constants that are the inverse of the moments of inertia) mainly determine the overall shape of the molecular spectra. It can be seen that the spec-
Figure 2.10 – The simulated spectra for C\textsubscript{2}, C\textsubscript{6}H and C\textsubscript{9}H\textsubscript{3} are shown for different resolutions and varying rotational temperatures. In the upper trace, the stick diagrams at 10 K are shown. The second trace gives the spectra at 10 K, with the resolution of the laser in the laboratory setting. The third trace shows the spectra at 30 K and the resolution of the laboratory experiment. The last panel degrades the resolution from 0.07 cm\textsuperscript{-1} to 0.2 (0.5 cm\textsuperscript{-1} for C\textsubscript{2} respectively) and for rotational temperatures at 30 K.

tra can become very complicated for larger species, and that the rotational levels that are populated even at low temperatures increase rapidly for larger and more complex molecules like C\textsubscript{6}H and C\textsubscript{9}H\textsubscript{3} (as can be seen in the stick diagrams, respectively).

## 2.6 Optical Spectroscopy using the New Technology Telescope

In February 2008 optical long-slit spectra using the EMMI (ESO multimode instrument) at the New Technology Telescope (NTT) in La Silla, Chile, were obtained. The goal of the observations was to obtain medium resolution data (R=5000 (~ 3.5 cm\textsuperscript{-1}) and R=2600 (~ 7.3 cm\textsuperscript{-1})) of the Red Rectangle proto-planetary nebula at different off-sets from the central star. The wavelength coverage of all spectra is between 5500 and 6800 Å. The slit was positioned at the central star and at 3, 7, 16 and 20\arcsec distance from the central star for
Figure 2.11 – The slit positions for obtaining the long-slit spectra of the Red Rectangle proto-planetary nebula are depicted schematically. The slits were positioned at a fixed rotator off-set angle of 105° east from north, perpendicular to the nebula’s symmetry axis. The slit dimensions are 1″ × 200″ and cover the nebula over the entire width. The image was taken from the ESO archive and taken by (Van Winckel et al. 2002).

The different observations (Wehres et al. 2010a). The angle of the slit was fixed at 105° east from north, perpendicular to the nebula’s symmetry axis and is depicted in Fig. 2.11. The slit dimensions were chosen such that the slit lengths covered the entire width of the nebula to collect the light completely. The dimensions were 1″ × 200″.

The nebula itself can be traced up to about 60″ away from the central star and the distance of the Red Rectangle is estimated to be about ~ 710 parsec (Men’shchikov et al. 2002). Its visual magnitude is 9, but decreasing fast further away from the central object. The exposure times thus varied between 60 s at the central star going up to one hour for distances as far as 16 or 20″.

The long-slit spectra that are obtained show a two-dimensional spectrum of the nebula in Fig. 2.12. On the x-axis the wavelength information is preserved and the y-axis
2.7 Optical Spectroscopy using the Mercator Telescope

Figure 2.12 – The two dimensional raw image of the Red Rectangle proto-planetary nebula is shown for a distance of 7” distance to the central star. The x-axis contains the wavelength information (here between \( \sim 5500 \) and \( 6200 \) Å). The y-axis contains the spatial information. After collapsing the spectrum into one single point an increase of the S/N ratio can be achieved, resulting in a one-dimensional spectrum as can be seen in Chapter 1 (Fig. 1.5).

contains the spatial information. This results in the advantage of long-slit spectroscopy over single aperture spectroscopy, since the nebula is traced in small steps when positioning the slit along the outflows. The advantage of long-slit spectroscopy over integral field spectroscopy, which also preserves spatial information, is that the S/N ratio can be increased for faint objects by collapsing the two dimensional slit spectrum into a single pixel row. That way the spatial information is still preserved, but the signal is amplified. A one-dimensional spectrum of the Red Rectangle nebula is plotted in Chapter 1 (Fig. 1.5) and the spectra will be discussed in more detail in Chapters 6 and 7. Data reduction was performed using the MIDAS software package and is described in more detail in Chapters 6 and 7 as well.

The spectra that were recorded here, have been compared to and combined with spectra taken by Van Winckel et al. (2002) and resulted in a set of spectra at the central star as well as at 3, 6, 7, 11, 14, 16 and 20” distance to the central star. The aim of this extensive data-set is to establish an archive of the spectral changes with distance to the central star. Identification of the species in the nebula and tracing the changes of the spectral shape with respect to the distance of the central source can then give information of the physical conditions and about the ongoing chemistry in that object at a given distance.

2.7 Optical Spectroscopy using the Mercator Telescope

In Summer 2009 a high resolution optical spectrum of the diffuse cloud towards HD 183143 has been obtained using the Mercator telescope on La Palma, Spain. Very recently the HERMES (high efficiency and resolution Mercator echelle spectrograph) had been in-
stalled (Raskin & Van Winckel 2008) which allowed for a resolution of $R = 100,000$ ($0.02 \, \text{cm}^{-1}$). The 1.2 m telescope is operated by the Katholieke Universiteit Leuven, Belgium, and the Observatory in Geneva, Switzerland. The fiber-fed cross dispersed spectrograph has a fixed spectral format and the spectrum that was obtained covered the whole wavelength between $\sim 3800$ and $9300$ Å. The exposure times of the diffuse cloud spectra averaged to 1200 s each. A reference spectrum of the star HD 164353 was obtained to discriminate between stellar lines and absorption bands in the diffuse interstellar cloud. The spectrum was reduced using the Mercator pipeline as will be described in more detail in Chapter 3. Spectra of diffuse interstellar clouds are discussed in Chapters 3-5 and are used to compare to the laboratory absorption spectra using cavity ring-down spectroscopy. The aim is to identify the carriers causing the absorption bands as seen in these clouds and to constrain the chemistry and physics going on in these environments.