Molecular fingerprints of star formation throughout the Universe : a space-based infrared study

Lahuis, F.

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Chapter 1

Introduction

> *"A wise person must be able to see the unseen and know the unknown."*
> From: The Greatest Power by Demi
> (author/illustrator of children's books)

The young emperor Ping wants to bring the harmony of the heavens, which he views through his telescope, to his kingdom. To accomplish this he invites all the children in his kingdom for a year-long quest in search of the greatest power. He sends them out with the instruction *"A wise person must be able to see the unseen and know the unknown."* The child who succeeds will become prime minister. After a year the children present their findings. Some bring great weapons, others great beauty, great technology, or large amounts of money. The last child, a little girl named Sing, has reflected upon Ping's words. She presents a lotus seed, splits it before emperor Ping and speaks, *"The nothing in this seed is the space in between where life exists."* Emperor Ping is pleased and appoints her as prime minister.

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Figure 1.1 *Spitzer* IRAC 3.6, 4.5, 8.0μm and MIPS 24μm composite image of IC 348, a star forming cluster located 1,043 light years away from Earth in the Perseus Molecular Cloud. A large number of young stars still embedded in their envelope (reddish-pink dots) are seen in the midst of bright extended emission from heated polycyclic aromatic hydrocarbon (PAH) molecules and small dust grains in the cloud. PAH are excited by the radiation from neighboring stars and shine brightly in the infrared.

To see the unseen ... to know the unknown .... What could better apply to astronomy and in particular to the field of star formation. We now know that large numbers of young newborn stars exist in pieces of the sky that were previously believed to be devoid of stars – stars invisible in the visible. Star formation takes place in a mostly unseen world, i.e., unseen at visible wavelengths. Stars are born deep in dark molecular clouds and surrounded by dense envelopes – dust and gas-rich shells –, in which their initial growth takes place. When looked at in the infrared, these dark clouds prove to be very rich with a multitude of new-born stars. The first infrared satellite, the Infrared Astronomical Satellite (IRAS), operating in the eighties of the last century, mapped the complete sky in infrared light. It showed us an exciting and bright Universe filled with star formation from the local Universe in our Milky-Way out to the most distant galaxies. Figure 1.1 shows a Spitzer composite image of a star forming region in Perseus revealing multiple young stars in between the large scale emission of heated Polycyclic Aromatic Hydrocarbon (PAH) dust particles in the cloud.

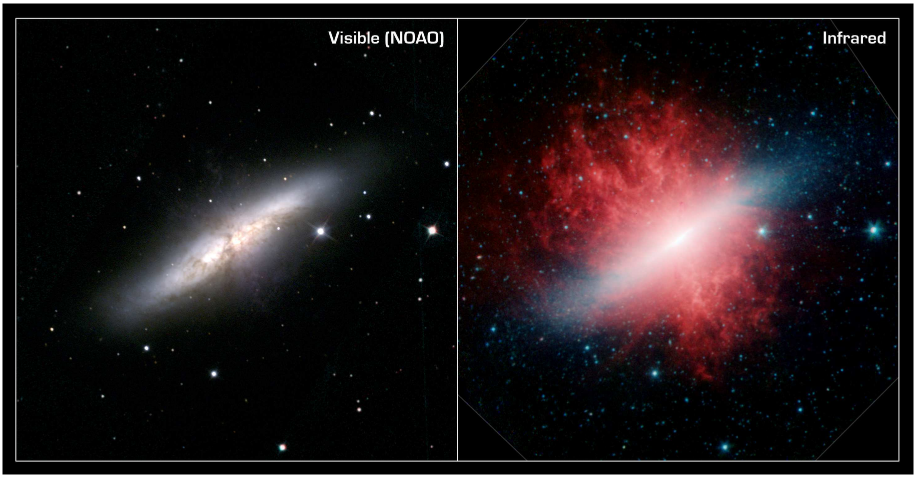

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Figure 1.2 Images in visible (left) and infrared (right) light of the Starburst galaxy M82. In the visible M82 looks like a normal galaxy. However, in the infrared a completely different galaxy is seen. The massive stars formed in the starburst reside in what shows up as a white band across the infrared image. Above and below this are huge amounts of hot gas blown away by the massive stars. For the full story see the NASA press release at:
`http://www.spitzer.caltech.edu/Media/releases/ssc2006-09/`

This thesis takes us through the infrared Universe in a few big leaps, from the disks around low-mass protostars to the envelopes around massive protostars ending up in the nuclei of distant ultraluminous infrared galaxies. A specific type of source is clearly not the central theme of this thesis. Instead the common factor is star formation itself and the chemical and physical processes taking place in the (dense) warm gas involved in the process. The methods by which these can be studied, by using space-based infrared spectroscopic instruments, is the second key aspect of this thesis.

In the Earth's atmosphere most of the infrared radiation is absorbed by molecules, in particular water and carbon dioxide, prohibiting the observation of large parts of the infrared spectrum by ground-based instruments. Even from observatories at very high altitudes, like those on Mauna Kea in Hawaii, large parts of the infrared spectrum cannot be observed. Therefore the use of satellites, with infrared spectrometers, is essential for the study of star formation. In the last decade two major infrared satellites with strong spectroscopic capabilities (ISO and *Spitzer*, see §1.3 and Table 1.1) were launched with *Spitzer* still operational. In this thesis I make use of data from two mid-infrared spectrographs (the ISO-SWS and *Spitzer* IRS) on board of these satellites.

In molecular clouds where star formation takes place most of the radiation produced in the process is absorbed by the dust in the surrounding envelope and re-emitted in the infrared. Molecules and atoms in the cloud are heated and emit or absorb the radiation emitted by the dust. Each molecule or atom emits or absorbs light at very specific wavelengths, its spectral fingerprint. The detailed patterns of these fingerprints depend on the temperatures, the composition, the density, and the velocity structure of the gas. Thus, the analysis of these fingerprints provides the observer with a physicochemical snapshot of the regions. The main aim of this thesis is to analyze the origin of the observed radiation and use these fingerprints to determine the nature and evolutionary phase of the sources.

1.1 Star formation

The stars in the Universe are extremely diverse. Stars with a large variation in mass and energy output (luminosity) are found, isolated or in groups. Low-mass stars like our Sun have masses and luminosities of a few tenth (down to the hydrogen burning limit of $0.08 M_{\odot}$) up to a few times solar. Massive stars have masses up to tens of solar masses and an energy output of ten thousand to a hundred thousand times the energy output of the Sun. To date eight stars are known with masses more than forty times the mass of the Sun. The most massive stars (e.g. Pistol Star and Eta Carinae) have masses of $100 - 150$ times the mass of the Sun and an energy output of a few million times higher. The very first stars of the Universe are believed to be even more extreme, up to 1000 times more massive than the Sun. All these stars do not form in the same way. §1.1.1 and §1.1.2 give a short introduction to low- and high-mass star formation.

Star formation may start by spontaneous collapse of a molecular core or by 'triggered star formation'. A pressure wave passing through the molecular cloud, for example from a supernova explosion, can create a density enhancement and initiate a core collapse. The ultimate display of triggered star formation is observed in starburst galaxies and some ultraluminous infrared galaxies (see §1.1.3). In these galaxies the star formation occurs almost instantaneous across the entire galaxy or the central nucleus. The trigger is a near galaxy encounter or a galaxy collision. Figure 1.2 shows a spectacular display of triggered star formation in the starburst galaxy M82.

1.1.1 Low-mass star formation

The basic principles of low-mass star formation are well understood (Shu et al., 1987) and described in a four-stage evolutionary scenario (Lada, 1987; André & Montmerle, 1994) with sources in each phase identified as class 0, I, II, or III. The star formation process starts with the inside-out collapse of a pre-protostellar core in a molecular cloud. When the density in the center of the core becomes so large that the gravitational pressure is no longer balanced by magnetic fields or turbulence, the core collapses (Class 0). The protostar in the center continues to accrete matter, but part of the infalling material ends up in a rotating circumstellar disk to preserve the angular momentum. At this stage the young star and disk are still surrounded by a cold envelope (Class I). A bipolar outflow perpendicular to the disk gradually disperses the envelope and at a certain moment the star and disk become visible and a class II source is born. As the star evolves the gas in the disk is heated by stellar radiation or radiation from nearby massive stars and the gas in the disk starts to 'evaporate'. At the same time the dust particles grow and settle toward the midplane into a thin disk from which planets may form (Class III). Eventually, the original interstellar gas and dust that did not make it into a planet or planetesimal will be dispersed and any small dust grains observed in these systems are produced by collisions of planetesimals – a so-called 'debris' disk. In the first stages when the envelope dominates, the spectral energy distribution (SED) is dominated by cold dust emission with strong silicate and ice absorption features in the mid-infrared. As the envelope becomes thinner and gradually disappears, the silicate features go from absorption into emission and emission bands of polycyclic aromatic hydrocarbons (PAHs) appear.

The above evolutionary picture does however not mean that the low-mass star formation process is fully understood. Many questions are still unanswered or at best poorly answered. To name just a few: Which processes drive the envelope dispersal? How are the gas and dust coupled at the different evolutionary stages? How and when do the giant planets form? What drives the chemistry in the inner (< 10 AU) disk?

Low-mass stars are studied in Chapters 5, 6, and 7 of the thesis. In Chapter 5 emission from the gas in disks around young stars is studied. Chapter 6 describes the observations of gas around young low-mass sources still surrounded by an envelope. Chapter 7 presents one particular disk source in which the hot gas and its chemistry very close to the central star are studied (see Fig. 1.3).

1.1.2 High-mass star formation

High-mass star formation is less well understood than low-mass star formation, mostly due to observational limitations. First, high-mass stars form fast (few 10^5 years, ~ 10 times faster than low-mass stars). Hence the number of high-mass protostars which can be observed is small. Second, high-mass protostars remain deeply embedded during most of the accretion phase making it difficult to study the formation processes close to the protostars.

An ongoing debate is whether high-mass protostars follow the same evolutionary track as low-mass protostars, including the formation of a circumstellar disk (Cesaroni, 2005b; Clarke, 2006). From the physics point of view, the formation of a disk is expected to preserve angular momentum. However, a disk forming around a massive star is subjected to vast amounts of hard UV radiation from the young star and the combination with the high accretion rates may quickly fragment the disk (Kratter & Matzner, 2006). Recently, good kinematic evidence of disks around some massive stars has been presented (e.g. Beltrán et al., 2005; Cesaroni et al., 2005). This suggests that massive stars can also form by disk accretion and at least some of them may follow an evolutionary scenario similar to that of low-mass stars.

An observed phenomenon in high-mass star formation is the 'hot-core'. This is generally thought to represent a short phase during the transition from the deeply embedded stage to the phase where ionizing photons can escape the protostellar accretion envelope and create a hyper-compact, and subsequently an ultra-compact, HII region (see review by Cesaroni, 2005a). The molecular composition of the hot core is very different from that of cold molecular clouds. This is thought to reflect the evaporation of ices when the envelope is heated by the newly formed star (Walmsley & Schilke, 1993). Subsequent high temperature gas-phase chemistry (see §1.4.2) significantly enhances the abundance of e.g. CH_4 (methane), C_2H_2 (acetylene) and HCN (hydrogen cyanide) (Viti & Williams, 1999; Doty et al., 2002; Rodgers & Charnley, 2003).

In Chapter 4 absorption spectra of C_2H_2 and HCN are used to observe the warm dense gas in the envelopes around the massive stars. The question is whether these molecules serve as good tracers of the envelope heating and if the observations can confirm the proposed evolutionary hot-core scenario.

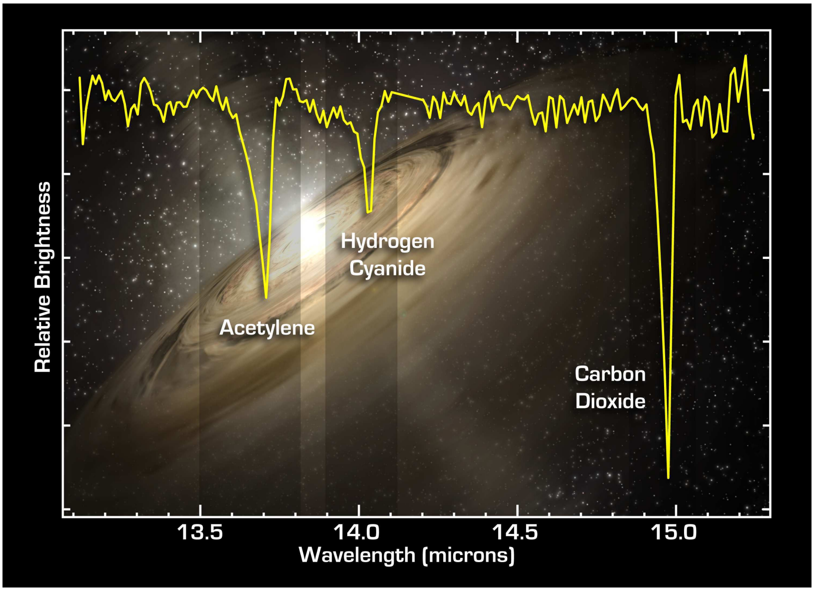

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Figure 1.3 Warm and abundant C_2H_2 (acetylene), HCN (hydrogen cyanide) and CO_2 (carbon dioxide) at $13 - 15\mu$m in the planet-forming zone of the circumstellar disk of IRS 46. This result was featured in NASA, Leiden Observatory, & SRON press releases. See the NASA press release at: `http://www.spitzer.caltech.edu/Media/releases/ssc2005-26/`

1.1.3 Ultraluminous infrared galaxies

Ultraluminous infrared galaxies (ULIRGs) are among the brightest objects in the Universe and emit most of their energy at infrared wavelengths. ULIRGs have a luminosity $L > 10^{12} L_\odot$, equal to the energy of hundreds of average galaxies together. ULIRGs are generally found in colliding or merging galaxy systems (e.g Armus et al., 1987; Sanders et al., 1988b; Murphy et al., 1996). During a merger large amounts of gas and dust are driven into the nucleus under high pressure (e.g. Mihos & Hernquist, 1996). This initiates a massive starburst and can also feed massive black holes in the nucleus. The starburst and the accretion of matter onto black holes releases large amounts of energy into the gas and dust in the nucleus. This heats the dust making it extremely bright in the infrared. If the energy output of black holes dominates, the source is referred to as an active galactic nucleus (AGN), otherwise it is a starburst. ULIRGs are without doubt the most spectacular sites of star formation and the ultimate display of triggered star formation. If AGNs are present, ULIRGs reveal them in their earliest most hidden phase.

Much effort has gone in trying to identify the dominant heating sources of ULIRGs. This started with Genzel et al. (1998), who used infrared PAH emission bands and high ionization fine-structure lines as indicators of star formation activity or AGN activity, respectively. This has later been expanded to include more optical, near-infrared and submillimeter star formation and AGN indicators (e.g. Lutz et al., 1999; Bushouse et al., 2002; Spoon et al., 2007). However different indicators can result in conflicting identifications (see Armus et al., 2007).

A special group of ULIRGs are the (deeply) obscured ULIRGs, characterized by the presence of broad absorption of amorphous silicates centered at 10 and 18 μm (Spoon et al., 2005). Some of their near- and mid-infrared spectra strongly resemble those of starburst galaxies and are undoubtedly powered by massive starburst activity. Other obscured ULIRGs however have spectral energy distributions (SEDs) which show similarities to those of bona fide AGN-dominated spectra and lack signs of clear starburst activity. None of these show indisputable evidence that the nucleus is dominated by an AGN, however. But, if AGNs do not dominate the nuclei of these ULIRGs, a major question is why there are no traditional signs of starburst activity such as strong PAH emission.

Chapter 8 provides a possible answer through the detection of large amounts of hot molecules, C_2H_2 (acetylene) and HCN (hydrogen cyanide). These molecules are also seen in the inner regions of envelopes around massive young stars. In the normal stellar evolution the envelopes are dispersed as the stars evolve. However, due to the very high pressure in the ULIRG nuclei this may not happen and the stars remain embedded in 'starburst cores' for a much longer time. As a result the typical star formation features such as PAH emission are weak or absent.

1.2 Infrared spectroscopic data

Spectroscopic data are essential to learn about the composition of the dust and the gas and to extract physical parameters. The infrared spectral region is a true treasure cave given the richness and diversity of the observed spectral features (see van Dishoeck & Tielens, 2001, for a review). It contains solid-state features of dust and ices and gas-phase molecular and atomic lines. The infrared spectral features sample a very large range of physical environments, from the very cold outer regions of the envelopes and disks around young stars to the hottest and densest inner regions close to the stars. In this thesis gas-phase spectral features are studied originating from the warm ($T \sim 100 - 1000\,\mathrm{K}$), dense regions.

The molecular band presented in Figure 1.4 is called a vibration-rotation band by the nature of the molecular states involved in the transitions. Molecules can change their energy state by going from one rotational level to another rotational level. They may do so between rotational levels in one vibrational state – so-called pure rotational transitions –, or by going from a rotational level in one vibrational state to a rotational level in another vibrational state, so-called vibration-rotation or ro-vibrational transitions. The energies involved in pure rotational transitions are much smaller than in ro-vibrational transitions, so that they occur at lower frequencies. Most molecules have pure rotational transitions at far-infrared and submillimeter wavelengths. An exception is H_2 with pure rotational transitions in the mid- and near- infrared. Molecules without a permanent dipole, such as CO_2 and C_2H_2, do not have strong rotational transitions in the submillimeter. Therefore infrared observations are required to observe these molecules.

Ro-vibrational transitions involving an electric dipole change of the molecule yield the strongest lines. These are called P-, R-, and Q-branch transitions depending on the rotational quantum level J change between the upper and lower vibrational state. P-, R-, and Q-branch transitions have a J change of respectively -1, $+1$, and 0. For some molecules or vibrational states the Q-branch transitions do not exist due to symmetry.

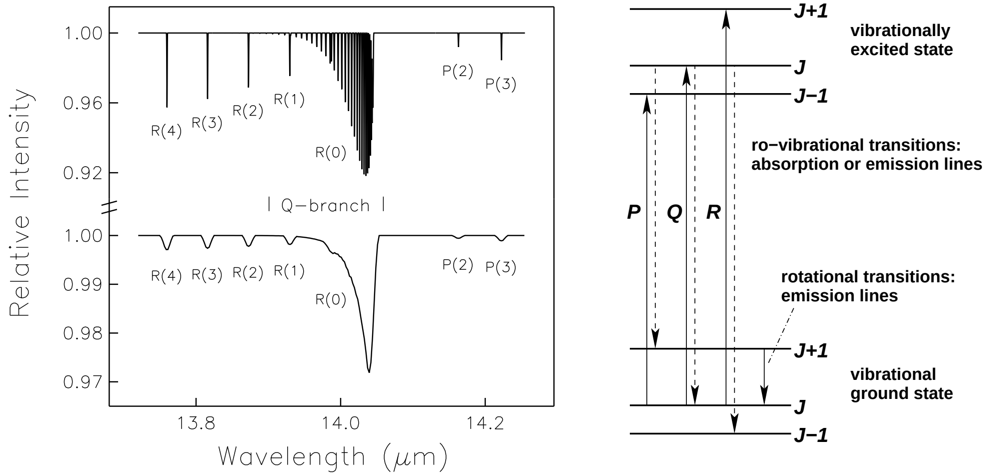

Figure 1.4 Left: absorption within the ν_2 vibration–rotation band of HCN showing the complete Q-branch and the lowest P- and R-branch lines. Since the energy differences of the various Q-branch transitions are very small, the individual lines can only be separated at very high spectral resolution. In the top spectrum, the band is shown at a spectral resolution of 30,000 and in the bottom one at 1800, typically for our data. At lower resolution the Q-branch lines blend into a single unresolved band and the unresolved P- and R-branch lines become weak (note difference in vertical scale). Right: an illustration of the state changes involved in P-, Q-, and R-branch ro-vibrational transitions and pure rotational transitions.

Figure 1.4 shows the central part of the absorption band of HCN at 14 μm typical for the molecules observed in this thesis. Lines from R-, P-, and $Q-$-branches are indicated. The Q-branch lines are only resolved at very high spectral resolution. At lower resolution they blend into a single resolved spectral feature. The relative strength of the lines (and therefore the shape of the Q-branch) depends on the temperature of the gas and their depth on the amount of molecules observed.

Chapters 5 and 6 present observations of unresolved molecular hydrogen and atomic fine structure line emission. Chapters 4, 7, and 8 present observations of gas-phase molecules which have a complex band structure.

1.3 Infrared space instruments

The last two and a half decades have been a golden age for infrared space astronomy with the successful missions of four large infrared satellites, the InfraRed Astronomical Satellite (IRAS), the Infrared Space Observatory (ISO), the *Spitzer* Space Telescope, and the *Akari* Infrared Space Telescope. Of these *Spitzer* and *Akari* are still operational. Within the next decade two major infrared space missions will fly, the Herschell satellite and the James Webb Space Telescope (JWST).

An overview of the near- and mid-IR spectroscopic capabilities of the past, present, and future missions is presented in Table 1.1. For the studies presented in this thesis data from the ISO-SWS and *Spitzer* IRS instruments are used, mostly from its medium resolution ($R = \lambda/\delta\lambda = 600 - 2000$) modes.

Table 1.1. Spectroscopic capabilities of near- and mid-IR space missions

Satellite	Operational period	Instrument	Wavelength range [μm]	Resolving power
IRAS	1983	Low Resolution Spectrograph – LRS	7 − 23	20 − 60
ISO	1995 − 1998	Short Wavelength Spectrometer – SWS	2.4 − 45	1,000 − 2,500
		SWS Fabry-Pérot	11.4 − 44.5	20,000 − 35,000
		Long Wavelength Spectrometer – LWS	43 − 197	150 − 200
		LWS Fabry-Pérot	43 − 197	6,800 − 9,700
		Camera+Circular Variable Filter – CAM-CVF	2.3 − 16.5	35 − 50
		Photometer-Spectrometer – PHT-S	2.5 − 5; 6 − 12	90
Spitzer	2003 − (2008)	Infrared Spectrograph – IRS		
		IRS low resolution SL & LL	5.2 − 38	60 − 120
		IRS high resolution SH & LH	9.9 − 37.2	600
Akari	2006 − 2007	Infrared Camera + prism/grism – IRC	1.7 − 26.5	20 − 50
JWST	(2013−)	Mid-Infrared Instrument – MIRI		
		MIRI Integral Field Spectrometer	5 − 28.3	2,000 − 4,000
		MIRI Low Resolution Spectrometer	5 − 10	100

1.4 Physicochemical properties

Retrieving fundamental physical and chemical properties is essential in trying to understand the process of star formation. This includes density, temperature, total mass, and the (relative) abundances of different species present in the gas. These are obtained by analyzing the observed spectra and combining them with theoretical models.

The spectral energy distribution reveals information about the temperature components of the dust with the cold dust emitting strongly in the far-infrared and warm/hot dust emitting strongly in the near- and mid-infrared part of the spectrum. From the optically thin millimeter continuum emission an estimate of the total dust mass can be obtained. Combined with a source size retrieved from imaging data this provides an average density. However, the density and temperature generally depend strongly on the location in the region and can have contributions from envelopes, disks and/or general cloud material. To retrieve that information, detailed modeling of the spectral energy distribution and millimeter line and continuum emission is required (e.g. van der Tak et al., 1999; Jørgensen et al., 2002; Young et al., 2004, and Chapter 7 of this thesis).

To understand the chemistry in clouds, envelopes or disks requires a similar approach. Observations of emission and absorption features of various species provide the first basic insight. Features sensitive to different temperature and density regimes are obtained to make the observational picture as complete as possible. Detailed chemical models, using among others the density and temperature structures and stellar radiation as input, are run. The input is derived from observations as described above or a generic model for the type of object (for example an envelope or a disk) is used. The modeled distributions of multiple species are then used to predict line intensities and profiles which can be compared to observations (e.g. Doty et al., 2002; Markwick et al., 2002).

In this thesis molecular and atomic spectral features are observed to derive physical and chemical parameters, in particular temperature and abundances. These results are compared against physico-chemical models from the literature to draw conclusions about the location of the observed species and the nature of the sources.

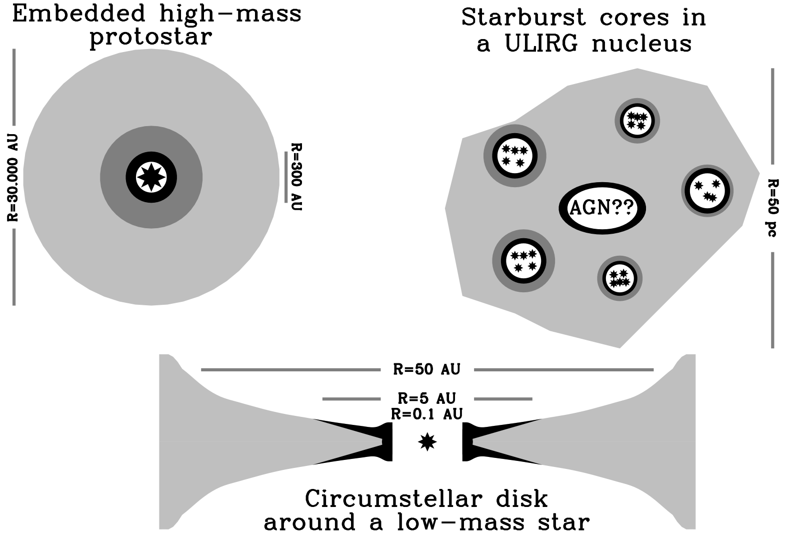

Figure 1.5 Illustration of the location of the warm dense regions in the disk of a young low-mass star and in the envelope around a young high-mass star, and around the starburst cores in the nucleus of a ULIRG. Typical size scales for the different types of objects are indicated.

1.4.1 Hot dense regions

Regions with hot dense gas are found in distinct stages of all forms of star formation. Hot dense gas is found in the inner disk regions around low-mass stars, the inner envelopes of high-mass stars, and in the swept-up medium close to compact starburst cores. Figure 1.5 illustrates the location of this dense warm gas in the types of sources studied in this thesis. The dense hot gas is ideally suited for observational studies in the near- and mid-infrared spectral region. Emission lines of molecular hydrogen (H_2) and atomic species, and emission or absorption bands of simple molecules such as carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), methane (CH_4), acetylene (C_2H_2), and hydrogen cyanide (HCN) have multiple transitions in the infrared spectral region. Chapter 5 and 6 show observed molecular hydrogen and atomic fine structure line emission from the disk and envelopes around low mass young stars.

A special technique for studying the warm gas is absorption spectroscopy toward embedded sources. The hot dust in the inner regions close to the central source provides the infrared continuum against which the molecules can be observed in absorption. The continuum emitting regions are generally small ($< 0.1''$). Therefore the absorption observations probe a single line-of-sight and the strength of the absorption is (almost) directly related to the amount of absorbing molecules in that line of sight. In contrast, emission lines have contributions from all lines of sight contained in the aperture of the spectrometer. Submillimeter lines are also affected by beam dilution when the emitting region becomes smaller than the telescope beam. This beam dilution makes it difficult to observe submillimeter high density tracers from the compact hot regions. Infrared absorption spectroscopy is used in Chapters 4, 7, and 8 to probe this hot gas.

1.4.2 High temperature chemistry

Hot dense regions close to the young stars are particularly interesting because an active chemistry takes place which is very different from that in the cold clouds out of which the stars form. High temperature chemistry is dominated by the evaporation of molecules from the grains with subsequent gas-phase processing. At very high temperatures, the hydrocarbon and nitrogen chemistry are particularly enhanced because most of the oxygen is converted into water by neutral-neutral reactions. The abundances of molecules such as C_2H_2, CH_4, and HCN can be increased by orders of magnitude (e.g. Doty et al., 2002; Rodgers & Charnley, 2003) while at the same time the formation of CO_2 is reduced because its primary formation route through OH is blocked. Thus the abundances of C_2H_2 and HCN increase with temperature by orders of magnitude in the hot $200 - 1000$ K range in models that focus on the inner envelopes around massive stars. A similar chemistry applies to the inner regions of disks around low-mass stars. Recent inner disk models (e.g. Markwick et al., 2002) predict strongly enhanced abundances of HCN and C_2H_2 also for the very inner ($1 - 5$ AU) disk.

Chapter 7 presents the first observations of hot abundant C_2H_2, HCN, and CO_2 in the inner disk of a young low-mass star, IRS 46. This attracted world-wide attention after the joint press-releases by NASA, Leiden Observatory, SRON, and Keck Observatory focusing on their importance for prebiotic chemistry in the planet-forming zones of circumstellar disks (see Fig. 1.3).

1.5 Outline of this thesis

This thesis presents observations of gas-phase mid-infrared spectral features associated with star formation processes. The observations are done using space-based spectrometers. The observed features trace warm mostly dense gas and they take us on a journey throughout the Universe. The molecules reveal the gas in disks around low-mass stars, in the inner envelopes around massive stars, and in the nuclei of ultraluminous infrared galaxies where they are associated with hidden starburst activity.

To reliably observe the often weak spectral features, the limits of the instruments need to be pushed. Chapters 2 and 3 of the thesis therefore pay attention to some aspects associated with reducing mid-infrared spectroscopic data. Chapter 2 presents the data reduction aspects important on the fundamental instrumental level, in particular the detector readout and spectral artifacts introduced by the electronics of the ISO-SWS instrument. Chapter 3 focuses on the spectral extraction of *Spitzer* IRS echelle data. The pipeline developed for the reduction of the IRS data of the *Spitzer* “Cores to Disks” legacy project is described.

Chapter 4 presents ISO-SWS observation of C_2H_2 (acetylene) and HCN (hydrogen cyanide) in the envelopes of massive young stellar objects. Chapter 5, 6, and 7 present data from the “Cores to Disks” legacy program with observations of a large sample of low-mass young stellar objects in five nearby star-forming regions. Chapter 5 presents molecular hydrogen and atomic fine structure line emission from circumstellar disks around low-mass stars. Chapter 6 presents these lines from the more embedded young stars and from edge-on disks dominated by absorption. The first detections of C_2H_2, HCN, and CO_2 (carbon dioxide) from the inner planet-forming zone in a disk around a low-mass young star are shown in Chapter 7. Finally Chapter 8 takes us from our own

Galaxy to the nuclei of ultraluminous infrared galaxies where the spectral absorption features of C_2H_2 and HCN are observed and are shown to be associated with a phase of deeply embedded 'hidden' starburst activity.

The main conclusions of this thesis are:

- Observing gas-phase spectral features with infrared spectrographs is rewarding but also difficult. Since the features are often weak it puts high demands on the reliability and quality of the reduction. The results presented in this thesis show that it is important and worthwhile to invest a significant amount of resources in trying to achieve the most optimal data reduction possible.
- The mid-infrared vibration-rotation bands of C_2H_2 and HCN form unique probes of the warm dense gas associated with star formation toward different types of sources, both in our Galaxy and beyond.
- The observations of C_2H_2 and HCN in the envelopes of high-mass stars confirm the 'hot-core' scenario for these sources. Here the chemical structure is dominated by gradual heating of the inner envelope by the young star. As the envelope heats up, the molecules are evaporated off the ices followed by an active high temperature chemistry. This yields enhanced abundances of some molecules, among others CH_4 (methane), C_2H_2, and HCN, by orders of magnitude.
- Lines of [Ne II] and [Fe I] emission are detected with the *Spitzer* IRS toward a significant fraction of disks around low-mass stars for the first time. The strong [Ne II] emission is a good tracer of X-ray/EUV irradiation of the disk. The [Fe I] emission may point to the presence of massive gas-rich disks around the sources for which it is observed.
- Hot ($T \gtrsim 500\,\mathrm{K}$) H_2 emission is observed toward some disk sources. The observed line fluxes are not reproduced by recent disk models which include heating of the gas by UV radiation or X-rays. Therefore this hot H_2 emission may be evidence of a new emission component in the circumstellar disk.
- The discovery of C_2H_2, HCN, and CO_2 in the inner disk of IRS 46 proves the strength of mid-infrared absorption spectroscopy. Combined with submillimeter line emission and high spectral resolution near-infrared spectroscopy they give insight into the physics and chemistry of the gas in the inner disk and the process by which the gas in the disk is cleared.
- The mid-infrared absorption features of C_2H_2 and HCN are observed in the nuclei of a diverse sample of obscured ULIRGs and imply the presence of strong starburst activity. The high molecular abundances for a range of excitation temperatures point to the existence of an extended phase of deeply embedded star formation. The extreme pressures and densities of the nuclear starburst environment are believed to inhibit the expansion of H II regions and the global disruption of the star forming molecular cloud cores, and to have 'trapped' the star formation process in an extended Hot Core phase.