

Chapter 1

Introduction

This thesis is a study of the properties of ionized gas in nearby starburst galaxies using radio recombination line observations. In this chapter, we present a review of starburst galaxies, an overview of the formation process and properties of radio recombination lines and end with a summary of previous work and the motivation for this thesis.

1.1 Starburst Galaxies

We describe the starburst phenomenon in this section in detail – their defining properties, causes of starburst, identification and classification of such galaxies, and the various triggers of starburst. We then move to the stellar and ISM content in starburst galaxies – the molecular and neutral gas, dust, stars and specifically massive star clusters, dating of starbursts, and the interaction between the starburst and the ISM. We end with a brief discussion of the starburst-AGN connection, high redshift starbursts and their cosmological implications. We have primarily referred to two excellent reviews on this subject: Sanders & Mirabel (1996) and Moorwood (1996).

1.1.1 The starburst phenomenon

In the early 1970s, a class of galaxies with excess infrared (IR) emission were identified, and were classified as ‘Infrared Galaxies’ (Low & Kleinmann, 1968; Kleinmann & Low, 1970a,b). A variety of galaxies seemed to belong to this class (Neugebauer et al., 1976; Rieke, 1978; Rieke & Lebofsky, 1978; Lebofsky & Rieke, 1979; Harper & Low, 1973; Telesco & Harper, 1980). The infrared continuum and the optical spectra of these galaxies were remarkably similar to those of galactic HII regions. The infrared luminosity of these objects were comparable to, if not greater than, their optical luminosities. It was suggested that this excess IR radiation is due to thermal emission by dust which is predominantly heated by stellar radiation and was shown to be clearly so in the case of NGC 253 and M 82 by Rieke et al. (1980). Using the derived strength of star formation, the size of the dust emitting region and the amount of gas in that region, it could be seen that the star formation at the present rate would exhaust all of the gas in a fairly short time. The star formation rate (defined as the total mass of stars in a given mass range, formed per unit time, usually measured in $M_{\odot}$ per year) was derived to be much higher than in other normal galaxies (Harwit & Pacini, 1975). Hence it was concluded that this enhanced star formation is a short-lived phenomenon, and such galaxies were termed ‘*starburst*

galaxies', the phrase coined by Weedman et al. (1981) (though meant as an adjective, it is used extensively as a noun and even as a verb). The short lifetime of the starburst necessitates a triggering mechanism and possibly requires another mechanism to end the starburst phase. It was also realised that such a starburst phenomenon can explain certain blue-excess galaxies (Larson & Tinsley, 1978). Very soon, the launching of the IRAS satellite revolutionised the subject by the discovery of many thousands of infrared excess galaxies (Neugebauer et al., 1984), which otherwise would be classified as normal galaxies from their optical appearance (by normal galaxies, we refer to those which do not possess an AGN and are also not undergoing a starburst). The starburst phenomenon is now believed to be fairly ubiquitous among gas rich galaxies.

A starburst galaxy is defined as one undergoing sufficiently intense star formation that the gas present would be depleted over a timescale much smaller than the lifetime of the galaxy itself. It is found that in such systems, the bolometric luminosity is essentially dominated by the IR luminosity (specifically, a quantity L_{FIR} , defined using the four IRAS band luminosities), prompting Allan Sandage to ascribe a particular frequency of the electromagnetic spectrum to the residential abode of a possible theos (Soifer, Houck & Neugebauer, 1987). Higher this FIR luminosity, stronger is the starburst deemed to be. However, it should be noted that a high FIR luminosity alone is not sufficient to classify a galaxy as a starburst. The above two conditions, high L_{FIR} and high SFR together, usually imply that the current star formation dominates over the background quiescent (non-starburst) star formation in almost all wavebands (except those which arise from old stellar populations). The depletion time, which defines the starburst, is then given by $t_d = M_{\text{gas}}/\text{SFR}$. The SFR, of course, is a function of time. For a constant SFR, t_d corresponds to the actual duration of the starburst phase. If the SFR per unit mass is constant, then t_d is the e-folding time for star formation. For starburst galaxies, the depletion time can be as short as 10^7 - 10^8 years, whereas for the Galaxy, it is a few times 10^9 years. The SFR of the Galaxy is about $1 M_{\odot}/\text{yr}$. For starburst galaxies, this is greater than about $3 M_{\odot}/\text{yr}$, but this star formation occurs in a region of size less than 1 kpc. Hence the SFR density is much higher than in the Galaxy. SFRs as high as $1000 M_{\odot}/\text{yr}$ can occur in extreme starbursts. The time dependence of the SFR, or its history, in the starburst phase is not known. Instantaneous, constant as well as exponentially decaying SFR histories have been derived for various galaxies. It has been shown that the star formation rate is proportional to the total FIR luminosity. A reduced gas depletion time for starbursts is equivalent to an enhanced star formation efficiency, or SFE, defined as being proportional to the star formation rate per unit gas mass, and measured as $L_{\text{FIR}}/M_{\text{H}_2}$. The value of SFE ranges from about $2 L_{\odot}/M_{\odot}$ for normal galaxies to about $200 L_{\odot}/M_{\odot}$ for extreme starbursts. The SFE can also be expressed as the ratio between the stellar mass participating in the starburst and the molecular gas mass and this ratio is $<5\%$ for normal galaxies but can be as high as 50% for starbursts.

Since starburst galaxies have a high star formation rate, they also consist of a large number of OB stars, which dominate the optical continuum and line emission. Hence, those starbursts which are not almost completely enshrouded by dust have bluer colours than normal galaxies, which is why a substantial fraction of the galaxies in the Markarian and Byurakan Surveys are starbursts. As we will see below, starburst galaxies possess huge amounts of molecular gas compared to normal galaxies and hence associated dust as well. This dust absorbs the UV radiation from OB stars and is heated to temperatures of 30-80 K. The dust then reradiates

thermally in the infrared, peaking in the 60–100 μm region of the FIR. The molecular gas reservoir also gives rise to strong molecular lines in the mm and sub-mm. The OB stars ionize the gas around them, forming HII regions, which emit optical and IR nebular lines and also free-free emission in the radio band. Additionally, the ionized gas emits recombination lines in the radio, which forms the subject of this thesis. However, the radio continuum emission is dominated by the non-thermal synchrotron emission by relativistic electrons accelerated in shocks in SNRs. Since in a starburst galaxy, the number of stars $>8 M_{\odot}$ and hence the supernova rate is large, the radio emission is also enhanced compared to normal galaxies. The radio continuum and FIR emission are known to be tightly correlated for all star forming galaxies, including starbursts. This will be discussed in detail in section 4.6.

It is known that the star formation rate is proportional to the gas surface density, also referred to as the Schmidt law (Schmidt 1959. See Kennicutt 1998 for a recent review). Since the SFR for starburst galaxies is higher than normal, this implies that these galaxies also have a higher molecular gas density. Such an enhancement of gas density over other non-starbursting galaxies is indeed observed. Since the starburst phase is a short-lived phenomenon which requires a higher gas density than average, a mechanism which can efficiently concentrate gas into a small region is needed. Concentration of gas will occur under the influence of external torques. Torques can be produced by a non-axisymmetric potential, sources for which are bars, galaxy-galaxy interactions and galaxy mergers. It has been observationally seen that the starburst fraction is much higher among these classes of galaxies than among non-interacting unbarred solitary galaxies (see for example Arsenault 1989). Also, stronger the interaction, stronger is the starburst in that galaxy. We will discuss the issue of starburst triggers in more detail further on. However, a mechanism to concentrate gas in a small region is not sufficient. Any such mechanism should also be capable of doing so within a short timescale. Star formation is known to be a highly regulated process with negative feedback being provided by a variety of sources. The most important of these (mainly because this has a shorter timescale than other such processes) is the ionization of surrounding gas by newly formed OB stars, thus preventing this gas from further forming stars. The relevant timescale is therefore a few million years, which leads to the observed SFE in normal galaxies of 1-5%. Hence, in a starburst, the bulk of the star formation, and hence also the concentration of gas in a small region, should occur on timescales smaller than this.

As mentioned earlier, starburst galaxies are IR bright, and the nearby ones are therefore to be found in the IRAS catalogue. However, the converse is not true, i.e., not all IRAS galaxies are necessarily starbursts. The IR luminosity can have contributions due to dust emission from the large-scale star forming disk which need not be undergoing a starburst. It can also have significant contributions from ‘cirrus’, from dust heated by evolved stars, and from dust heated by a central AGN. Since the spatial resolution of IRAS is poor, differentiating between these various sources of infrared emission, based solely on the total IRAS fluxes, is difficult. It has, however, been established that higher the FIR luminosity, higher is the probability that the galaxy is undergoing a starburst. The observed FIR luminosity ranges from about $10^6 L_{\odot}$ (in normal galaxies like the Galaxy) to $>10^{12} L_{\odot}$ (in extreme starbursts). Strongly starbursting galaxies are classified as Luminous Infrared Galaxies or LIGs ($L_{\text{FIR}} > 10^{11} L_{\odot}$) and UltraLuminous Infrared Galaxies or ULIGs ($L_{\text{FIR}} > 10^{12} L_{\odot}$) and almost all galaxies with $L_{\text{FIR}} \gtrsim 10^{11} L_{\odot}$ are observed to be starburst galaxies. Among galaxies whose bolometric luminosity is greater than

$10^{12} L_{\odot}$, ULIGs constitute the dominant population, comparable in space density to even optically selected quasars. The merger fraction is also seen to increase with FIR luminosity, from 5 % for $10^9 L_{\odot} < L_{\text{FIR}} < 10^{10} L_{\odot}$ and 50 % for $10^{10} L_{\odot} < L_{\text{FIR}} < 10^{12} L_{\odot}$ to 100 % for $L_{\text{FIR}} > 10^{12} L_{\odot}$. Hence all strong starbursts seem to occur in mergers, but it is also known that not all mergers of equal strength result in a starburst. Though a high value of the FIR luminosity does not imply, in principle, a starburst, the ratio of this luminosity to the optical luminosity, $L_{\text{FIR}}/L_{\text{B}}$, is a good indicator of the presence of a starburst. This ratio is about 0.1 for normal galaxies, >10 for moderate luminosity starbursts, and >100 for ULIGs.

The above discussion dealt with global properties of a starburst. In a particular galaxy, though, where exactly a starburst occurs depends of the type of galaxy, the kind of trigger, local gas parameters and also the global disk properties. Since the dynamical timescale for concentration of gas by torques is least for galactic centres, strong starbursts occur preferentially in the nuclear regions of gas rich spirals and these are called SBNG, or StarBurst Nuclear Galaxies, where the starbursting region is typically a few hundred parsecs across. On the other hand, strong starbursts are also seen in dwarf irregulars, called BCDGs or Blue Compact Dwarf Galaxies, where the entire few kpc-sized galaxy is seen to undergo a starburst. Between these extremes, we also see disk galaxies with starburst regions extended over a kpc. Since spiral density waves can compress the gas and hence enhance star formation locally, weak starbursts are also seen along spiral arms (for eg, M 51). Related to this are mini-starbursts, which resemble scaled-up versions of HII regions, seen in many galaxies. These are known as GEHIIR or Giant Extragalactic HII Regions. NGC 3603 and the centre of the Galaxy are examples of such mini-starbursts in our own galaxy, and so is 30 Dor in the LMC. There also exist ‘ring starbursts’, where a starburst occurs in a ring, usually of diameter less than 1 kpc. This can either take the form of a circumnuclear starburst around Seyfert II nuclei, or a ring of star formation corresponding to a Lindblad resonance of a bar. In a handful of cases, like the Cartwheel galaxy, a starburst ring with a diameter of a few kpc is also seen, the large size explained by galaxy interactions. Though most starbursts tend to occur at galactic centres, it is possible for gas to accumulate in the overlap region between two interacting galaxies, where there are no pre-existing stars. This may lead to a starburst in the overlap region, which could even be stronger than any concurrent starburst occurring at the galactic nuclei (for eg., Arp 299 and Stephan’s Quintet).

There is no reason to suppose that a starburst is coeval over the entire starbursting region. Since star formation involves multiple positive and negative feedback processes, each with different timescales, the temporal sequence of star formation in a given region is complex. A fair description of this process is given by Stochastic Self-Propagating Star Formation, or the SSPSF model (Gerola & Seiden, 1978). Since after about 10^7 years, ionization of cold gas by OB starlight is expected to halt star formation in the neighbourhood, one would naively expect this time period to be the extent of the starburst phase as well, whereas the starburst phase in individual galaxies is observed to have a span as long as $\sim 10^8$ years. Spatial dating of star formation ages in these galaxies shows that star forming sites of different ages (ages $< 10^8$ years) are found to be spatially separated, which can be explained by SSPSF in combination with the detailed dynamics of the specific starburst trigger for that galaxy. For example, in an interacting system, if the two galaxies are known to have made multiple close approaches to each other (perigalacticon), then a starburst can be expected at every pass, with a suitable time lag. This

has been verified in a few starburst systems. Apart from SSPSF, a natural temporal progression of gas into smaller radii is expected due to a bar potential. Interestingly, there are systems which have a nuclear starburst and a surrounding starburst which is much older, an example of a starburst propagating outside-in (for eg, NGC 4314, NGC 6764). An inside-out progression of a starburst is also known, for instance, in NGC 1614. In some galaxies with multiple star forming regions with different ages, there is a clear spatial progression, i.e., there is a well defined spatial direction along which the age of the star formation increases, (for eg., NGC 5253). This is an example of sequential star formation. Though a definite progression of star formation is seen in some galaxies, especially in barred and ringed ones, it is expected that most starbursts, particularly BCDGs, are recurrent, or episodic. Evidence for an episodic starburst comes both from starburst modelling of spectrophotometric data as well as metallicity evolution models of observations, though there are uncertainties in the history of metal outflow from the system. This episodic star formation is due to the self regulation of star formation. Multiple encounters and mergers throughout the history of a massive galaxy are also expected to cause multiple starbursts.

It is clear from the above discussion that interactions and mergers are the preferred methods of triggering extreme starbursts. In a classic paper, Toomre & Toomre (1972) explained the presence of observed galaxy bridges and tails in interacting systems as transient kinematic effects of gravitational forces. Since then, many detailed simulations (see Barnes & Hernquist 1992 for a review) have been carried out, which describe the process of rapid funneling of cold gas into the centres of the interacting galaxies, increasing the volume density of the gas by more than two orders of magnitude, which is what is needed to trigger a starburst. It is no surprise then, that a very high fraction of the Arp galaxies are indeed starburst systems. These merger systems have now been studied at high resolution at various frequencies and detailed dynamical simulations exist which can reproduce the observed morphology of tidal tails and other disturbed structures. The strength of the interaction and hence the strength of the starburst depends on the relative orientation of the spins of the two gas rich disk galaxies, being maximum for parallel spins. Hence strong starbursts occur in interaction between galaxies with similar orientations. Starbursts can be induced in one or both of the interacting or merging galaxies. The ratio of the masses of the two galaxies plays a part in determining the relative tidal stripping of gas and hence the relative starburst strength. It is believed that when two gas rich spiral galaxies merge, they undergo a vigorous starburst which exhausts most of the gas and the merged system evolves dynamically into an elliptical galaxy. A de Vaucouleurs $r^{1/4}$ radial profile has been seen in evolved mergers and post starbursts, which supports this hypothesis. One of the main objections to this scenario, that the specific frequency of globular clusters of ellipticals is much higher than of spirals, can be circumvented by the enhanced production of super star clusters in situ, which is discussed later. Moderate starbursts, though, are known to occur in isolated galaxies as well. One of the main causes of a starburst in such systems is the formation of a stellar bar, which provides a non-axisymmetric potential. Lindblad showed that in such a potential, there exist resonance radii and that gas tends to flow towards these resonances. This provides a natural explanation of ring starbursts in barred galaxies and indeed, these rings of star formation do occur at the radii of Lindblad resonances calculated based on the parameters of the observed bars. The gas flows inwards along the edge of the stellar bar and after dissipative collisions, settles down into the non-intersecting inner $x1$ or $x2$ orbits. There is evidence

that the fraction of barred galaxies is larger in starburst samples as against samples of normal galaxies, though there are also opposing evidences in the literature. The strength of the starburst, though, is probably not correlated with the strength of the bar. However, the fraction of starbursts among barred galaxies is more than those among unbarred galaxies. The presence of bars would prevent gas infall within a certain radius and hence explaining isolated SBNGs is not possible in this scenario. One possible way out is to invoke an additional smaller bar within a larger stellar bar, which would then funnel the gas further inwards. This ‘bar within a bar’ has now been seen in a few galaxies. Non-axisymmetry of a much smaller amplitude due to lopsidedness or due to spiral arms is also known to increase star formation, though these produce global starbursts which are much weaker. It should be noted however, that there exist a large number of apparently isolated galaxies which are seen to undergo strong starbursts whose trigger is not yet known. However, in some cases, deep HI imaging has revealed the presence of extremely low surface brightness dwarf companions which could perturb the disk and trigger star formation.

Let us now return to one of the global properties of star forming galaxies, namely, Schmidt law. It has been found that on large scales, Schmidt law is obeyed, with an exponent of 1.4, i.e., $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4}$. Unfortunately, this does not yield clues about the cause of the star formation as a variety of processes can be invoked to yield a Schmidt-type law. In fact, existing data on global star formation is equally well explained by the relation $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}} \Omega$, where Ω is the angular frequency of rotation in the galaxy, for which sufficient theoretical motivation exists as well. For large scale gravitational instabilities of the disk, for shear induced accretion due to differential rotation, as well as for coagulation by cloud-cloud collisions, an exponent of 2 is expected, since the timescales for these phenomena all scale as Σ_{gas}^{-1} . If the local timescale for star formation in a GMC is the free fall time, however, then an exponent of 1.5 is expected. Non-linear feedback, of course, will change the value of the exponent in any model. The above discussion is valid for large scales and a local scale Schmidt law is not yet known and might not even exist. An enhanced gas density enhances the SFR. However, an enhanced SFE in starbursts also needs to be explained. Heuristically, if the timescale of star formation scales inversely as gas density, and is therefore smaller in starbursts, then a larger mass of gas can convert to stars before negative feedback sets in, hence giving rise to a larger SFE.

1.1.2 Stars and the ISM in starburst galaxies

In this section, we discuss the properties of the stellar component and also the interstellar medium (ISM) in starburst regions.

Stars form from molecular gas and hence the evolution of this component of gas is crucial in determining the nature of a starburst. Torques acting on the gas concentrate the gas into a smaller region, thus increasing its density. The surface density of molecular gas in starburst regions is observed to be as high as a few times $10^4 \text{ M}_{\odot}/\text{pc}^2$, a factor of 50-250 times higher than seen in normal galaxies. This corresponds to a mass of few times 10^8 to few times $10^{10} \text{ M}_{\odot}$ within a kpc. The molecular gas mass is calculated from the observed CO luminosity. The conversion factor from CO to H_2 is notoriously uncertain within a factor of a few to ten. Nevertheless, it has been established that M_{H_2} correlates with L_{FIR} , though this ratio itself, defined as SFE, increases with L_{FIR} . However, the SFE does not seem to depend on the Hubble type of the galaxy, though the SFR does show such a correlation. Gao & Solomon (1999)

find that for a sample of interacting galaxies with a range of separations of the two galactic nuclei, the CO luminosity is positively correlated with the separation, thus implying that as the interaction becomes stronger, more molecular gas is presumably used up in the starburst. They also find that this correlation breaks down for advanced mergers and UltraLuminous Infrared Galaxies (ULIGs). In merging LIGs, it is found that the SFE is correlated inversely with the separation between the nuclei. Though the above results have been based on CO studies, it is known that the actual process of star formation happens in dense cores of GMCs and hence it is to be expected that the dense gas traces star formation better than the global CO distribution. Observations of dense gas in starburst centres using lines of CS, HCN, HCO^+ , show that the mean molecular temperature of the central regions of LIGs is high, with $T_{\text{kin}}=60\text{-}90\text{ K}$ and so is the density, with $n(\text{H}_2)\sim 10^5\text{-}10^7\text{ cm}^{-3}$, conditions similar to the cores of Galactic GMCs. Since the average volume density of the molecular gas in the central starburst regions is high, even the intermolecular cloud medium could indeed be molecular, evidence for which has been seen in a few cases. This has been successfully used to produce a high SFE in the case of massive GMCs in starbursts (Jog & Das, 1992, 1996). It was mentioned earlier that the ratio between L_{FIR} and M_{H_2} increasing with increasing L_{FIR} is interpreted as an increase in the SFE with L_{FIR} , the former quantity reaching about 50% for ULIGs. A sample of ULIGs, or ‘extreme starbursts’ were observed by Solomon (2001) in the HCN line, which traces dense gas due to its higher critical density. The ratio of HCN luminosity to the CO luminosity was found to be higher for ULIGs than for normal spirals, indicating that a larger fraction of molecular gas in these galaxies is at a high density, and in fact, at a density corresponding to a galactic GMC core. He also found that L_{FIR} and L_{HCN} (which is proportional to the mass of dense gas) are correlated for all starbursts and that the ratio between the two is constant for a wide range of L_{FIR} as opposed to that between L_{FIR} and CO luminosity. This indicates that star formation depends more on the dense gas and more interestingly, that the SFR per unit *dense* gas mass is constant in all kinds of star forming galaxies.

Apart from CO and dense gas tracers like HCN, other important molecular gas tracers are the 18 cm OH maser lines. The typical 1667 MHz isotropic line luminosity is about $10^4 L_{\odot}$ and hence starbursts which exhibit these lines are known as OH megamaser galaxies, in comparison with the luminous Galactic OH maser sources. OH megamasers are seen preferentially in galaxies with large SFE. Indeed, it is known now that the OH luminosity is proportional to L_{FIR}^2 . These megamasers occur in those ULIGs with a strong radio continuum, a gas column density exceeding 10^{22} cm^{-2} and warm IRAS colours. Along with copious amounts of molecular gas, large amounts of neutral HI gas is also present in starburst regions. The ratio of molecular to neutral gas mass is higher in starbursts, with a value of about unity, and there is tentative evidence for a possible increase with $L_{\text{FIR}}/L_{\text{B}}$. The line widths of HI absorption profiles towards starburst nuclei are extremely large, ranging from a few hundred km s^{-1} to 1000 km s^{-1} . The HI column densities are $\gtrsim 10^{21\text{-}22}\text{ cm}^{-2}$ in the inner few 100 pc. The HI profile is found to be consistently redshifted compared to the optical line profiles for a number of starbursts; the interpretation of this effect is complicated by dust extinction.

Associated with this gas, of course, is dust. Assuming a constant dust-to-gas ratio, one can readily see that for typical gas column densities in nuclei of starbursting disks and ULIGs, the visual extinction A_{V} is 50-100 magnitudes for LIGs and even a few 100 magnitudes in extreme cases. Such high values of extinction imply that the heart of the starburst in StarBurst Nuclear

Galaxies (SBNGs) is essentially unobservable in the UV and optical and maybe even in the NIR. These highly obscured regions are now becoming accessible primarily due to MIR imaging and spectroscopy. Therefore, atleast for centrally concentrated starbursts like UltraLuminous Infrared Galaxies (ULIGs) and SBNGs, estimation of the total SFR from $H\alpha$ measurements will underestimate the real SFR by probably an order of magnitude. Indeed, it seems that a $H\alpha$ or a UV image of such a region is more a map of sites of low extinction and less a map of true star formation. An accurate estimate of the total SFR in highly obscured starburst regions seems impossible using optical and in some cases, even IR data. Radio continuum and FIR emission yield an extinction-independent estimate of the SFR though they suffer from other uncertainties. Recently, it has emerged that radio recombination lines might be a viable tool to estimate the SFR, which is indeed extinction free and is also free of biases inherent in using the radio continuum luminosity. However, modelling such lines is not straightforward and more importantly, since these lines are weak, they provide access to only the much denser parts of the starbursting regions which emit stronger lines. Analysis of the various uncertainties and development of these lines as a tool to estimate the SFR forms part of the work described in this thesis. Dust, in any case, is the most important constituent of LIGs and ULIGS since its FIR emission dominates the bolometric luminosity. The dust mass can be calculated from L_{FIR} to be greater than $10^{8-9} M_{\odot}$ for these galaxies. The dust temperature can be obtained from the infrared Spectral Energy Distribution (SED) and the derived values in starbursts range from 30-60 K. The SFE, or L_{FIR}/M_{H_2} , correlates with the dust temperature, measured by the IRAS colour $F_{60\mu m}/F_{100\mu m}$. Assuming the dust to be at a single temperature is an approximation, and is not really valid in most galaxies. SEDs obtained over a wide range of frequencies from NIR to mm, indicate that a multi-temperature model, or atleast, a two-temperature model is necessary. Most of the observed emission can be explained by invoking a cold dust ($T_d < 40$ K) and a warm dust ($T_d > 40$ K) component. Recently, measurements of the dust emission at $\lambda > 100 \mu m$ using the ISO satellite have shown that previous studies which used only shorter wavelength data underestimate the cold dust mass by up to a factor of 3. Though this result has been obtained primarily for nearby normal disk galaxies, the total dust mass of starbursts too will have to be revised upwards. An additional complication in studying dust in starbursts is that of the extinction curve A_{λ} . The galactic extinction curve is well described by a value of $R_V = 3.1$ and a certain dust grain size distribution. A characteristic feature is also the presence of the prominent 2175 Å graphite bump. The extinction curve for starburst galaxies was computed from observations of a sample of nearby UV bright starbursts and it was found that these curves were much greyer than the Galactic curve and they also lacked the 2175 Å bump (these curves are described by the Calzetti law), and hence resembled closely, the LMC extinction curve. However, the difference between the Galactic and the LMC extinction curves is attributed to the low metallicity of the LMC whereas these starburst galaxies have metallicities comparable to the Galactic value. One explanation put forth to explain this puzzle was that the intrinsic grain size distribution is different in starburst regions. On the other hand, the Calzetti law can also be explained using the Galactic dust properties, but by assuming a very patchy dust-gas distribution (Natta & Panagia, 1984; Witt, Thronson & Capuano, 1992; Calzetti, Kinney & Storchi-Bergmann, 1994) and this latter explanation seems to be favoured. It should be noted that ULIGS (which are not UV bright) exhibit a normal galactic extinction law instead.

We now discuss the nature of the stellar component of starbursts. The optical spectrum

of starbursts is dominated by emission from young massive stars (and the ionized gas around them). Up to a few thousand O stars are present in strongly starbursting regions. If significant star formation had occurred more than 3 million years ago, then a substantial population of Wolf Rayet (WR) stars will also exist at the present time. Galaxies which exhibit prominent WR spectral features are called WR galaxies. Slightly older star formation also gives rise to a large population of Red SuperGiants as well. The effective temperature T_{eff} of the ionizing stars can be estimated from the various optical and infrared line ratios. Though most studies indicate an average T_{eff} of about 30 000-35 000 K for StarBurst Nuclear Galaxies (SBNGs) and slightly higher for Blue Compact Dwarf Galaxies (BCDGs), significant observational biases are known to exist. The value of T_{eff} is important mainly in determining the most massive star that can be produced in a starburst. It is not necessary that the Initial Mass Function (IMF) of the stars formed in a starburst is the same as that in normal galaxies, since the details of the IMF (upper and lower mass cutoffs and the slope) are expected to depend on the environment. Detailed study of a few nearby starbursts has consistently shown that the lower mass cutoff in these regions is higher than in the galaxy and is probably as high as 1-5 $M_{\odot}$. However, this result depends on the value of the assumed upper mass cutoff, which is not well known. Hence the question of whether the starburst IMF is different from the galactic IMF is still unanswered. However, there have been recent attempts at directly constructing the IMF of a few star clusters in nearby starbursts using the HST by counting individual stars at high angular resolution.

That starburst regions are not linearly scaled up versions of quiescent star formation is perhaps best illustrated by a class of objects now known as Super Star Clusters, or SSCs (discovered first, and also termed as such, by van den Bergh 1971). These are unique to starburst environments and are massive and bright, sometimes numbering a few hundred in some starbursts. SSCs are extremely luminous objects, some of which have absolute visual magnitudes M_V exceeding -14 to -15 . These are also very compact, with an effective radius of ~ 4 pc, and the total stellar mass is $>10^4 M_{\odot}$, up to $5 \times 10^6 M_{\odot}$, implying a large stellar density. The ages of the SSCs which have been observed range from 2 million years to 500 million years. Based on these properties, it has been hypothesized that SSCs are proto globular clusters, i.e., globular clusters (GCs) in formation. Since these starbursts are seen to possess an older GC population as well, the suggestion that atleast some of the GCs are produced in strong starbursts will also explain the observed bimodality of GCs in old galaxies. It should be noted that if GCs form out of typical GMCs, the SFE needed is few tens of percent which makes a starburst the most probable birthplace for these objects and SSCs seem to be those GCs in formation. However, the formation process of such massive clusters is not yet understood. Recently, the youngest SSCs (much younger than 3 million years) have been discovered in two nearby galaxies. These are optically completely obscured and were discovered through optically thick thermal radio emission (Turner, Beck, & Ho, 2000; Kobulnicky & Johnson, 1999). These have also been detected in radio recombination lines (Mohan et al. 2001, chapter 4 of this thesis). SSCs are found in a variety of starburst environments: mergers, ULIGs, SBNGs and even tidal dwarf galaxies. van den Bergh (2000) has noted that the specific cluster frequency (the number of clusters per unit luminosity or per unit mass of the parent galaxy) of SSCs is higher for stronger starbursts.

A starburst occurs over a finite period of time and can have a complex history of star formation (SFR as a function of space and time) within that span, determined by global and local gas properties as well as feedback. This makes the interpretation of the starburst SED compli-

cated. The problem is further compounded by a possible background quiescent star formation and low spatial resolution data covering regions of different stellar ages. Nevertheless, the SFR history can be derived to within reasonable modelling accuracies by the method of stellar synthesis. Pioneered by Larson & Tinsley (1978) and later developed by Bruzual & Charlot (1993) and others, this method involves the theoretical computation of the continuum SED, line strengths and line widths as a function of SFR history, time and metallicity. These results are then matched with the measured values of these parameters to derive the SFR history and the ‘age’ of the starburst. One of the most accurate and constantly updated models is Starburst 99, that of Leitherer and co-workers (Leitherer et al., 1999), which includes the latest non-LTE stellar atmosphere models and stellar wind characteristics and is capable of predicting the SED from far-UV down to NIR. Though a global fit to the measured SED will yield the required parameters, certain observables like the H α equivalent width can be used to directly derive the ‘age’ of the starburst. Quantitative descriptions of starburst regions, as a function of space even, are now possible due to these various fairly sophisticated models. However, the interpretation is not always unique and usually, multiple solutions can be found to fit a given dataset. Extending the wavebands for which data are modelled is one of the ways to eliminate this degeneracy.

Due to the high SFR density in starburst regions, the effects of feedback from the stars to the ISM is much more than in normal galaxies and is, in fact, non-linear. Apart from short term local effects which effectively limit local star formation due to negative feedback, long term effects dominate the ISM in these galaxies, and in fact determine the duty cycle in episodic starbursts which we now discuss briefly. The total ionization rate in starbursts is very high, with a Lyman continuum photon flux ranging from $>10^{52}$ photons s^{-1} to few times 10^{55} photons s^{-1} . Therefore, a large part of the surrounding molecular and atomic gas is ionized and also, a significant fraction of the ionizing photons escape into the surrounding large scale ISM as well. However, the most important effect of a starburst region on the ISM of the galaxy is caused by supernovae and stellar winds. It is known that total kinetic energy released in a stellar wind over the lifetime of a O star is comparable to that released in a single supernova explosion. Since the supernova rate (proportional to the SFR) is much higher than in normal galaxies, the mechanical energy imparted to the ambient medium is also much higher, with the rate of supplied energy being $\sim 1\%$ of the bolometric luminosity. Strong shocks penetrate the surrounding ISM, with velocities reaching 400-800 km s^{-1} (deduced from shock ionized infrared lines). The kinetic energy imparted by a collection of O stars and WR stars through their supernovae and stellar winds leads to an overpressured cavity of gas. This gas then expands into the ambient ISM, causing massive fast outflows preferentially along the minor axis of a disk galaxy, with outflow speeds reaching few thousand km s^{-1} . Galactic scale outflows occurring due to an almost constant supply of kinetic energy is called a superwind. The outflowing material contains hot X-ray emitting gas, warm ionized gas, cold gas, dust and also cosmic rays and magnetic fields. Hence such starburst induced superwinds are believed to be the primary source for supplying the Inter Galactic Medium (IGM) with heavy elements as well as kinetic energy. Large HI supershells with diameters of a few kpc are also observed to erupt out of the plane of disk galaxies. The effect of these processes is so intense that it is believed that probably a significant fraction of the ISM in Blue Compact Dwarf Galaxies (BCDGs) escapes from the galaxy in such a starburst phase.

A nuclear starburst and an AGN have one thing in common: both need huge amounts of gas

to be funnelled into a small region in space, of the order of a few hundred pc in the case of a SBNG and a few pc in the case of an AGN. Therefore it is natural to expect that these disparate phenomena are related in some way but the exact nature of the relationship still remains unclear. There are various theories and some of the proposed scenarios include a concurrent formation of the starburst and the AGN, either the starburst or the AGN acting as a trigger for the other, and an actual evolution from one to the other. However, even the direction of evolution, if any, is not clear. A significant fraction of low luminosity AGNs are observed to possess circumnuclear starbursts, mostly in the form of a ring. Seyfert IIs are known to have an excess of star formation in the form of star clusters, molecular gas and associated FIR emission compared to normal galaxies (and even compared to Seyfert Is, which questions the validity of the strong unification principle). The typical accretion rate needed to sustain a low luminosity AGN can be explained by stellar winds from a nuclear massive cluster or by tidal disruption of stars in low angular momentum orbits. The gas which fuels this circumnuclear starburst could be concentrated in the galactic centre due to multiple nested bars. Powerful AGNs, like QSOs, also exhibit evidence for associated starbursts near the centre. The much higher accretion rate required by QSOs can be supplied only by strong external triggers like interactions or mergers. A significant fraction of FR II sources show evidence for interaction in the form of tidal tails. There is also evidence of ongoing interaction in nearby QSOs from HST imaging; their host galaxies exhibit disturbed morphologies. These objects also have huge amounts of molecular gas within the central few kpc region. Almost all UltraLuminous Infrared Galaxies (ULIGs) show evidence for both an AGN and a nuclear starburst. The detection of molecular gas in radio quiet quasars at high redshift with masses similar to that found in ULIGs, is further evidence linking the two phenomena. However, the exact chronological and causal relation between them is yet to be known. On a different note, a non-standard kind of unification between the two has been attempted by Terlevich and co-workers (see Terlevich et al. 1995 and references therein). These authors construct pure starburst models in an attempt to explain all the observed characteristics of AGNs without invoking a central black hole. Though this model has severe difficulties in the case of powerful AGNs, it is a viable model for low luminosity AGNs and is probably the correct explanation for a subset of these.

Lastly, we turn to starbursts at high redshift and their cosmological significance. The typical duration of a starburst phase and the number of detected starbursts taken together imply that probably every galaxy went through a starburst phase in its past. Since interactions and mergers trigger strong starbursts, the number density of starbursts is expected to be larger at high redshifts since the merger rate increases rapidly with redshift (probably as steep as $[1+z]^4$ or higher; see Darling & Giovanelli 2002 for a summary). Since a significant fraction of the star formation in the universe must have occurred in starburst environments, the redshift dependence of the SFR volume density is closely related to the redshift dependence of the starburst volume density. This ‘star formation history of the universe’ is not yet unambiguously known. It has been well established that the co-moving volume density of SFR increases from $z=0$ to $z\sim 1$. At redshifts greater than one, models range from a decline (Madau plot), to a constant value (from sub-mm continuum data using the SCUBA instrument on the James Clark Maxwell Telescope), to a further increase with redshift (from reionization models and HDF analysis). The star formation history is intimately related to the AGN history of the universe. Both of these seem to peak at $z\sim 2$ and there are theoretical models which link the evolution histories of the two

phenomena. The recent discovery of the correlation between the bulge mass and the black hole mass also indicates that the high redshift formation of the spheroidal stellar component, presumably in a burst of star formation, and that of the AGN are connected. The epoch of the first star formation also assumes cosmological significance. The discovery of fully formed galaxies with near solar metallicity and a population of old stars at higher and higher redshifts provide a strong constraint on various structure formation models. There have even been attempts at deriving cosmological parameters from the derived starburst age of high redshift galaxies, though not successfully. Also, the epoch of first star formation is important for a variety of reasons. These primordial starbursts probably played a significant and as yet unknown role in reionizing the universe. Superwinds from these galaxies would have provided the mechanism of initial enrichment of collapsing gas and especially the IGM with heavy elements processed in stellar interiors and supernovae. These objects are probably at redshifts of 7-10 and may be detected by the Next Generation Space Telescope (NGST). The strongest starbursts at redshifts of 1-4 are now being detected for the first time by SCUBA on the JCMT and also by the bolometer array (MAMBO) on the 30-m IRAM telescope (see Omont et al. 2001 and references therein). These galaxies, most of which lack optical counterparts, not only account for most of the high redshift star formation but can also explain the far infrared background. Detection of $>10^{10} M_{\odot}$ of molecular gas through its CO emission from objects at redshifts greater than 4 (see for example Guilloteau et al. 1999) is another important advance in this field. Chandra and XMM-Newton have discovered a population of highly obscured X-ray hard AGNs which could be sites of extreme starbursts, though this hard X-ray population and the sub-mm detected SCUBA sources seem to have little overlap. In summary, new instruments are now providing us access to extreme starbursting systems at high redshifts, which may have profound implications for both structure formation theories as well as explaining present day normal galaxies we see around us.

1.2 Radio emission from galaxies

The broadband luminosity (νL_{ν}) of galaxies, with or without an AGN, is the weakest in the radio region. Nevertheless, radio emission has proven to be an important diagnostic of galaxies. The radio luminosity function (RLF) of galaxies can be described by a Schechter function. The local RLF has been decomposed into contributions from AGNs and from starbursts (see, for the most recent RLF which is obtained from the 2dF survey, Sadler et al. 2002). AGNs dominate the RLF (number per logarithmic interval of luminosity per Mpc^3) at high luminosities and the starbursts dominate the RLF at low luminosities. The two luminosity functions cross over at $P_{1.4 \text{ GHz}} \simeq 10^{23.2} \text{ W Hz}^{-1}$. This cross-over value corresponds, for a galaxy at a distance of 10 Mpc, to a 1.4 GHz flux density of 13 Jy. The typical nearby strongly starbursting galaxy has a flux density of a few Jy. The flux density from the region of active starburst, usually of size ~ 1 kpc, is a few hundred mJy. This, of course, is continuum emission, which is composed of both non-thermal and thermal radiation. There is also substantial line emission in the radio, primarily the 21 cm HI line emission. Apart from a few molecular lines (like OH at 1.6 GHz, HCHO at 4.8 GHz, NH_3 at 23 GHz etc), we also expect radio recombination lines (RRL) throughout the radio band. The details of RRL emission and its detectability will be discussed later in this chapter.

The radio continuum (and RRL) emission traces two different emission processes; non-thermal synchrotron emission from supernovae near star forming regions and from AGNs, and thermal emission, predominantly from gas ionized by OB stars, with some contributions from an AGN as well. The main advantage in studying radio emission is the absence of dust obscuration. The extinction of radio waves due to dust is extremely insignificant (scattering goes as λ^{-4} and pure absorption goes as λ^{-1}) and hence we can access highly dust obscured regions easily. The emission by dust does however extend up to the radio band but only for wavelengths shorter than mm.

1.2.1 Radio continuum

1.2.1.1 Synchrotron emission

Synchrotron emission is the radiation emitted by a charged relativistic particle moving in a magnetic field. The main contributors to the synchrotron emission from galaxies are relativistic electrons. These relativistic electrons are commonly produced by Fermi acceleration in supernova shocks and subsequently diffuse out to $\sim$ kpc scales over a few 10^7 years. This causes the non-thermal emission in galaxies to be diffuse and far removed from the supernovae and hence star formation sites. However, a significant fraction of the total synchrotron emission from a galaxy arises from young radio supernovae. For a single electron at energy E , the synchrotron power (dE/dt) is proportional to E^2 and hence the synchrotron lifetime goes as E^{-1} . For a collection of particles with an energy distribution function $N(E) \propto E^{-p}$, the synchrotron intensity goes as $I_\nu \propto \nu^{-(p-1)/2}$. The observed galactic diffuse non-thermal radiation can be described, on the average, by $I_\nu \propto \nu^{-0.7}$. The low frequency behaviour of synchrotron radiation is determined by synchrotron self-absorption and the high frequency behaviour is determined by the upper cut-off to the energy spectrum of electrons. However, in practice, the low frequency galactic non-thermal emission is determined by free-free absorption by thermal gas. The high frequency part of this radiation will depart from the simple power law given above due to synchrotron as well as inverse-compton losses (primarily the latter for typical radiation fields present in starburst regions) and also ionization and relativistic bremsstrahlung losses. It is worth noting that, limited by the opacity (mainly self-absorption), the brightness temperature ($T_B \propto I_\nu \nu^{-2} \Omega^{-1}$) can be very much higher than $\sim 10^4$ and hence can be distinguished from thermal emission (see below).

The main sources of synchrotron emission in a galaxy are (1) diffuse relativistic electrons, (2) emission from young supernovae and (3) an AGN. Young SNRs are pc-sized and can be resolved by VLBI techniques whereas AGNs remain unresolved. Also, the brightness temperatures of AGNs are much higher than that of diffuse synchrotron or young SNRs. However, to detect high brightness temperatures and hence to unambiguously detect AGNs, high resolution observations are necessary.

1.2.1.2 Thermal emission

Thermal emission in the radio is due to bremsstrahlung or free-free radiation of non-relativistic electrons. Thermal dust emission is significant only at mm wavelengths. Free-free emission is dominated by the electron-proton scattering process. The emissivity is determined by collisions and hence by the gas density. Hence free-free emission can be used to determine the gas density.

The optical depth for thermal gas, i.e., gas with a Maxwell-Boltzmann velocity distribution function, is

$$\tau_c = 0.03014 \left(\frac{T_e}{\text{K}} \right)^{-1.5} \left(\frac{\nu}{\text{GHz}} \right)^{-2.0} \left(\frac{\text{EM}}{\text{pc cm}^{-6}} \right) \left[\ln \left(\frac{0.04955}{(\nu/\text{GHz})} \right) + 1.5 \ln(T_e) \right] \quad (1.1)$$

wherein the last expression in parenthesis is an approximation to the gaunt factor for radio wavelengths, and the emission measure EM is given by $\int n_e^2 dl$ where n_e is the electron density and l is the path length through the gas. The solution of the radiative transfer equation for a thermal gas with electron temperature T_e and a background intensity I_{bck} is given by

$$T_B = \left(\frac{c^2}{2 k_B \nu^2} \right) I_{\text{bck}} e^{-\tau_c} \left(\frac{\Omega_{\text{source}}}{\Omega_{\text{beam}}} \right) + T_e (1 - e^{-\tau_c}) \left(\frac{\Omega_{\text{source}}}{\Omega_{\text{beam}}} \right) \quad (1.2)$$

where Ω_{source} and Ω_{beam} are the solid angles subtended by the source within the synthesized beam and the solid angle of the synthesized beam respectively. The background source is assumed to have the same lateral extent as the thermal gas. Since the latter two expressions inside parenthesis in eqn. 1.2 are always ≤ 1 , we find that, for $I_{\text{bck}}=0$, T_B is always $\leq T_e$. The value of T_e for HII regions ionized by stars with a reasonable upper mass cut-off of $\sim 80 M_\odot$ will lie between 5000–12000 K for a metallicity of $Z_\odot$ to $Z_\odot/5$. Hence, though with high resolution observations, one can obtain brightness temperatures $> 10^5$ K for non-thermal emission, thermal gas photoionized by stars will always yield $T_B < 10^4$ K. When the gas is optically thin, the free-free flux density goes as $\sim \nu^0$ and for optically thick gas, the emission is given by the beam-diluted blackbody emission and hence goes as $\sim \nu^2$. Observations of the free-free emission at multi-frequencies will yield an estimate of the gas density. However, this inferred value is the ‘rms’ electron density and is related to the true electron density by

$$n_e^{\text{rms}} = \sqrt{f} n_e^{\text{true}} \quad (1.3)$$

where f is the volume filling factor of the thermal gas within the beam of the instrument. Free-free absorption by thermal gas in front of non-thermal radiation is the primary opacity for the latter and limits the observed brightness temperature at low frequencies.

Dust absorbs UV and optical radiation, is heated, and reradiates thermal radiation corresponding to its temperature. This emission from a dust cloud is that of an optically thin blackbody, i.e., the emission from individual grains is blackbody radiation, but the optical depth for dust absorption of this radiation is negligible. The emission is characterised by an emissivity which scales as ν^1 - ν^2 and hence the R-J part of this emission scales as ν^3 - ν^4 . Therefore, dust emission is significant, even for starburst galaxies, only at mm wavelengths and shorter and can be completely neglected below ~ 30 GHz.

1.2.2 Radio recombination lines (RRLs)

The possibility of observing lines due to transitions between highly excited levels of atoms was considered by Van de Hulst (1945) in his classic paper and later by Wild (1952). Both authors concluded, due to an incorrect treatment of Stark broadening, that these lines would not be observable. Independent of these efforts, Kardashev (1959) correctly calculated the line intensities and predicted that these lines would indeed be observable. The first successful observations of Radio Recombination Lines (RRLs) were by Dravskikh & Dravskikh (1964), who detected

the H104 α towards the Omega nebula from the Pulkova Observatory and by Sorochenko & Borodzich (1965), who detected the H90 α line towards the same object from the Puschino Observatory. Since then, innumerable RRLs of hydrogen as well as other atoms like helium, carbon, sulphur, etc have been detected in galactic HII regions. We now describe the theory of RRL formation and derive the necessary expressions to be used later in this thesis.

1.2.2.1 RRL – line formation and transfer

Plasma in ionization equilibrium will necessarily have the ionization rate balancing the recombination rate. Specifically, in the case of a HII region, the recombination of free electrons with protons must balance the photoionization by the stellar UV-photons. Most of this recombination is directly to low- n levels (where n is the principle quantum number of the level, hereafter termed as n level or level n). Nevertheless, there is a small non-zero probability of an electron recombining to a high- n level, called a high Rydberg level. The probability for this electron to make a downward radiative transition with $\Delta n=1$ is maximum, and decreases for increasing values of Δn . For large n , these transitions result in line emission in the radio wavebands. The Bohr radius of these high- n atoms is macroscopic and their lifetimes are fairly large ($A_{m,n} \propto n^{-5}$). Hence, in terrestrial conditions, these atoms are usually collisionally ionized or collisionally de-excited. Radiative de-excitation is significant only in the low density gas found in interstellar space. The radio recombination lines for high- n levels are denoted by Eng where n is the value of the lower n -level of the transition, g is α, β, γ , etc for values of Δn of 1, 2, 3, etc and E is the atomic symbol of the element whose transition is observed. The $n=102$ to $n=97$ transition of hydrogen, for example, is denoted as H97 ϵ . The frequency of emission for a transition from level m to level n is given by

$$\nu = R_{\infty} \left(1 + \frac{m_e}{M_a}\right)^{-1} \left(\frac{1}{n^2} - \frac{1}{m^2}\right) \text{ MHz} \quad (1.4)$$

where $R_{\infty}=3.28984195 \times 10^9$, m_e is the mass of the electron and M_a is the atomic mass of the element considered. For large values of n and m , $\nu \propto 1/n^3$. Large n transitions occur at low frequencies.

Consider an electron undergoing a downward radiative transition from level m to level n in a hydrogen atom. For large n , the resulting line radiation at frequency ν_{mn} will fall in the radio, called an RRL. The transfer of this line radiation depends on the continuum radiation field, the optical depth at ν_{mn} and the velocity field of the ionized gas. We ignore the effect of the latter in this analysis. For the simple case of thermal gas with a background continuum source of intensity I_o , the solution to the radiative transfer equation for a ray normal to the emergent surface of the thermal gas is

$$I_c = I_o e^{-\tau_c} + S_v^c (1 - e^{-\tau_c}) \quad (1.5)$$

$$I_l = I_o e^{-\tau_c} (e^{-\tau_l} - 1) + [S_v^{l+c} (1 - e^{-\tau_c - \tau_l}) - S_v^c (1 - e^{-\tau_c})] \quad (1.6)$$

where I_c and I_l are the observed continuum and line intensities, τ_c and τ_l are the continuum and line optical depths. The source function S_v is defined as the ratio of the emissivity to the absorption coefficient; S_v^{l+c} is the source function at frequency ν_{mn} and S_v^c is the source function responsible for the continuum radiation. If κ and j are the absorption coefficient and emissivity

respectively, then

$$S_{\nu}^c = \frac{j_c}{\kappa_c} ; \quad S_{\nu}^{l+c} = \frac{j_l + j_c}{\kappa_l + \kappa_c} \quad (1.7)$$

By thermal gas, we refer to gas whose particle velocities obey the Maxwell-Boltzmann distribution function and can therefore be described by a single kinetic temperature T_K . In most cases, the continuum radiation from the RRL emitting gas is free-free emission, which is a thermal process. Hence the continuum source function $S_{\nu}^c = B_{\nu}(T_K)$, where $B_{\nu}(T_K)$ is the Planck function at frequency ν and temperature T_K . In general, for a radiative transition between two levels, κ_l at a frequency ν is given by

$$\kappa_l = \frac{h\nu}{4\pi} \phi(\nu) (N_n B_{nm} - N_m B_{mn}) \quad (1.8)$$

where N_m and N_n are the level populations, B_{nm} and B_{mn} are the Einstein's coefficients, and $\phi(\nu)$ is the line profile function, normalised such that $\int \phi(\nu) d\nu = 1$. We assume that the absorption and emission line profiles are identical. Hence, with the knowledge of the level populations and the profile function, eqn. 1.6 can be solved. The profile function has contributions from doppler broadening, ϕ_D , and pressure broadening, ϕ_P . Doppler broadening is caused by the doppler shifts due to the motions of atoms along the line of sight. The main components of doppler broadening are thermal motions and turbulence. Thermal broadening will cause the line profile to be a gaussian. Turbulence is also expected to produce a gaussian line profile. Hence the combined profile function will be a convolution of thermal motions and turbulence, which is a gaussian whose width is given by the two contributing widths summed in quadrature :

$$\phi_D(\nu) = \frac{1}{\sqrt{\pi} \Delta\nu_D} e^{-\left(\frac{\nu-\nu_o}{\Delta\nu_D}\right)^2}, \quad (1.9)$$

$$\text{where } \Delta\nu_D = \frac{\nu_o}{c} \left[\frac{2 k_B T_K}{m_p} + \frac{2}{3} \langle V_t^2 \rangle \right]^{1/2} \quad (1.10)$$

ν_o is the central frequency, $\langle V_t^2 \rangle^{1/2}$ is the r.m.s. turbulent velocity, and m_p is the mass of the ionized species, in this case, the proton. In the case of pressure broadening, the line shape can be approximated by a lorentzian,

$$\phi_P(\nu) = \frac{\Delta\nu_P}{2\pi} \frac{1}{(\nu - \nu_o)^2 + \frac{\Delta\nu_P^2}{4}} \quad (1.11)$$

For typical interstellar densities, Griem (1967) showed that pressure broadening is mainly due to collisions (impact effect), as opposed to quasi-static electric fields (Stark effect). Also, collisions with electrons is more important than collisions with protons. For hydrogen which is not at too low a temperature, he obtained

$$\Delta\nu_P = \frac{5}{3\sqrt{2\pi}} \left(\frac{\hbar}{m_e} \right)^2 \sqrt{\frac{m_e}{k_B T_K}} n_e n^4 \left[\frac{1}{2} + \ln \frac{k_B T_K \lambda}{3\hbar c n^2} \right] \quad (1.12)$$

where n_e is the electron density. In general, the net line profile is a convolution of the doppler broadened and the pressure broadened profiles, and the resultant function is called a Voigt profile. However, it can be seen that the ratio of pressure broadening to doppler broadening, $\Delta\nu_P/\Delta\nu_D$, is proportional to n^7 and hence pressure broadening is important primarily at low frequencies and is observable at high frequencies only for very high densities.. In any case, we

shall see that in the extragalactic context, the observed line width is determined almost solely by the bulk velocity gradients in the ionized gas within a synthesized beam area. Hence, as opposed to galactic RRL studies, we cannot use the observed line profiles to derive the physical properties of the gas like turbulence and density.

1.2.2.2 RRLs under *LTE* conditions

If a gas cloud is in perfect thermodynamic equilibrium (*TE*), then the entire medium, including matter and radiation, can be described by two variables, say, the absolute temperature T and density, n . The velocity distribution function of the particles will be given by the Maxwell-Boltzmann law at temperature T , the relative level populations in atomic species will be given by the Boltzmann law, with an excitation temperature T , the ionization states will be given by the Saha formula, and the radiation field will be a Planckian at a temperature T . Detailed balance will hold for every process. It is quite rare for all these properties to be simultaneously satisfied in most astrophysical systems. Usually, a slightly more restrictive situation called Local Thermodynamic Equilibrium or *LTE* holds. Under *LTE* conditions, the occupancy of various levels, both bound and free, is assumed to be described by a single locally defined temperature $T(\mathbf{r})$ and the thermal radiation will also be a Planckian at the same temperature $T(\mathbf{r})$. However, there could exist large scale gradients in temperature, density and radiation but *LTE* implies that *locally*, matter is in thermal equilibrium, i.e., excitation temperature T_{exc} equals the kinetic temperature $T_K = T(\mathbf{r})$, and hence there is no long range interaction between matter and radiation. This equality will hold if all collisional processes are in detailed balance. For example, almost the entire volume of the sun except the outer parts, can be described by *LTE* though there is a net outward temperature, radiation and density gradient. However, even *LTE* is a rather restrictive condition and is not usually valid. One example where it breaks down is the low density regime, or the nebular case, discussed in the next section. Since the effect of collisions and radiation on the occupancy of levels is dependent on the level considered, it can well happen that in a particular gas cloud, some levels can be described by *LTE* and some cannot.

Under *LTE* conditions, the relative level populations are given by the Boltzmann equation and the actual values can be computed from the gas density using the Saha formula. *LTE* values for variables are denoted by a superscripted asterisk. From eqn. 1.8, the *LTE* line optical depth for hydrogen can be derived to be

$$\tau_l^* = \frac{\pi e^2}{m_e c} \left(\frac{h^2}{2\pi m_e k_B} \right)^{3/2} T_e^{-1.5} n^3 \frac{f_{mn}}{n} e^{\chi_n} \phi(\nu) \left(1 - e^{-h\nu/(k_B T_e)} \right) EM_l \quad (1.13)$$

where T_e is the kinetic temperature, f_{mn} is the oscillator strength, χ_n is the ionization energy of level n divided by $k_B T_e$ and EM_l is the line emission measure, defined as $EM_l = \int n_e(l) \times n_{H^+}(l) dl$. Hereafter, we assume that the continuum and line emission measures are identical (neglecting ionized Helium). The factor $(1 - e^{-h\nu/(k_B T_e)})$ is the correction due to stimulated emission, which is not negligible in the radio regime, as opposed to the optical waveband. In the radio waveband, the above expression reduces to

$$\tau_l^* = 1.92 \times 10^6 \left(\frac{EM}{\text{pc cm}^{-6}} \right) \left(\frac{T_e}{K} \right)^{-2.5} \exp \left(\frac{1.58 \times 10^5}{T_e n^2} \right) \left(1 + \frac{3}{2n} \right) \times \frac{1}{2.665 \Delta\nu_D \left(1 + 2.46 \frac{\Delta\nu_D}{\Delta\nu_P} \right)} \quad (1.14)$$

Under *LTE* conditions, Kirchoff's law will hold and hence the source functions S_ν^{l+c} and S_ν^c equal the Planck function $B_\nu(T_e)$. Therefore, eqn. 1.6 can now be solved to calculate the *LTE* line intensity.

Both τ_c and τ_l are positive and hence, in the absence of a background source, the line intensity is always in emission. It can be seen that the ratio $\tau_l/\tau_c \propto \nu$, i.e., $\propto 1/\sqrt{\tau_c}$. Since the line intensity is proportional to $e^{\tau_c}(1-e^{-\tau_l})$, it can be easily seen that when $\tau_c \geq 1$, the line emission drops sharply with increasing continuum optical depth and soon becomes unobservable at lower frequencies. Increased line width due to pressure broadening also contributes to a lower peak line flux. Hence, low frequency hydrogen RRLs are usually not detectable from classical HII regions in the Galaxy.

1.2.2.3 RRLs under non-*LTE* conditions

Most recombination line emission occurring in the ISM cannot be described by *LTE* processes and non-*LTE* calculations are necessary. For typical interstellar gas, the distribution function of free electrons and ions is still a Maxwell-Boltzmann law at a temperature T_K , the kinetic temperature. However, the occupancy of different bound levels in an atom populated by recombination will not be described by a Boltzmann distribution at temperature T_K , i.e., the excitation temperature T_{exc} is not equal to T_K and in fact, the value of T_{exc} is different for different levels of the atom. If the occupancy of two particular levels is determined primarily by collisions with the gas particles, then T_{exc} for the transition between these two levels will equal T_K and the ratio of the two level populations will be given by the Boltzmann law. If collisions do not dominate over radiative processes in determining the occupancy of a level, then the occupancy departs from the *LTE* value and this departure is parametrised by the departure coefficient b_n . If the population of level n is N_n^* in *LTE* conditions and is N_n under non-*LTE* conditions, then b_n is defined by $N_n = b_n N_n^*$. The value of b_n for a level n is unity in the case of *LTE* and is less than unity for non-*LTE* conditions. The collision rate is higher for gas at higher density. Therefore, denser the gas, closer is the value of b_n to unity, for a given n . Likewise, since the collision cross section is higher for larger n -levels, it is expected that for a given gas density, larger n -levels have b_n closer to unity. Since the primary process which populates high- n levels is recombination which is a purely radiative process (neglecting collisional recombination), low- n level populations in a low density gas will be determined by various radiative processes alone. The lower envelope of b_n vs. n is decided by these processes in the zero density limit, and is called the radiative limit. The upper envelope, of course, reaches unity asymptotically. The intermediate levels are affected comparably both by radiative and collisional processes and the range of ns so describable is determined by the gas density. The value of b_n for a given n is decided by the gas density, kinetic temperature and radiation field. The procedure for calculating the values of b_n is described in detail by Salem & Brocklehurst (1979) and will not be discussed here. The value of b_n vs. n is plotted for different densities in figure 1.1. The values plotted here and further used in this thesis are obtained from a program due to Salem and Brocklehurst, modified by Walmsley and further modified by Payne and Anantharamaiah.

It was shown by Goldberg (1966) that the correction for stimulated emission in the case of non-*LTE* is given by $(1 - \frac{b_m}{b_n} e^{-h\nu/(k_B T_K)})$. He defined a factor β_{mn} , which is the multiplicative

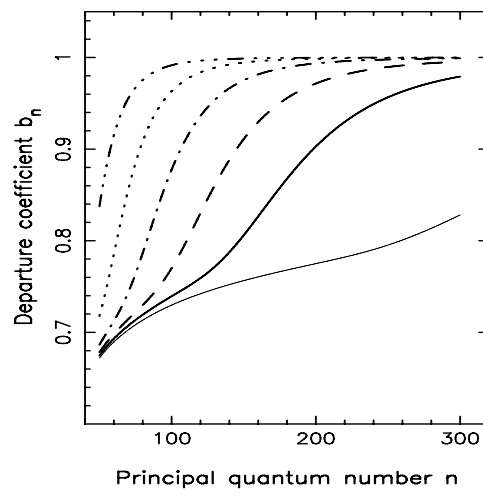


Figure 1.1: The non-*LTE* departure coefficient b_n vs. n for various densities for $T_K=7500$ K. The thick solid, dashed, dash-dotted, dotted and dot-dot-dashed curves are for gas densities of 10^{-1} , 10^0 , 10^1 , 10^2 , and 10^3 cm^{-3} . The thin solid curve at the bottom denotes the radiative limit. The value of b_n tends towards unity for higher densities and for larger n .

correction factor to be applied to eqn. 1.13, as

$$\beta_{mn} = \frac{1 - \frac{b_m}{b_n} e^{-h\nu/(k_B T_K)}}{1 - e^{-h\nu/(k_B T_K)}} \quad (1.15)$$

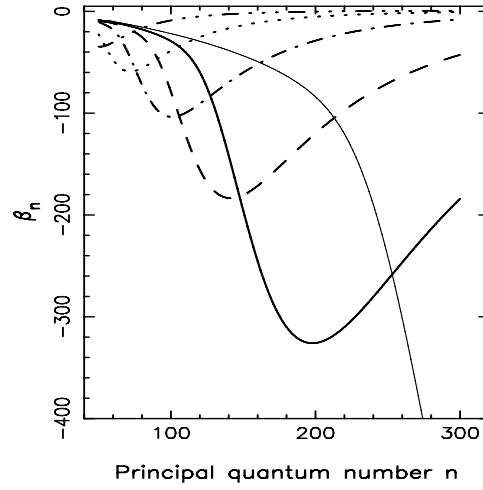


Figure 1.2: The non-*LTE* correction factor β_{mn} vs. n for various densities for $T_K=7500$ K and $m = n + 1$. The thick solid, dashed, dash-dotted, dotted and dot-dot-dashed curves are for gas densities of 10^{-1} , 10^0 , 10^1 , 10^2 , and 10^3 cm^{-3} . The thin solid curve at the bottom denotes the radiative limit. The value of β_{mn} tends towards unity for higher densities and for larger n .

For low frequency lines ($\frac{h\nu}{k_B T_K} < 1$),

$$\beta_{mn} \simeq \frac{T_K}{T_{\text{exc}}} \quad (1.16)$$

Since we are concerned only with $(m =)n + 1 \rightarrow n$ transitions, we will denote β_{mn} by β_n hereafter. Figure 1.2 shows the variation of β_n with n for various densities. It is seen that the value of β_n is

negative and large ($\ll -1$) for a range of densities and n . β_n is a measure of the slope of the b_n vs. n curve and hence of the population inversion of the upper level relative to the lower level. Hence, though $b_n < 1$ signifies that the actual populations of the two levels m and n are less than the *LTE* values, $\beta_n < -1$ implies that the level m is relatively overpopulated.

The line optical depth τ_l for non-*LTE* conditions is given by

$$\tau_l = b_n \beta_n \tau_l^* \quad (1.17)$$

The non-*LTE* line optical depth is negative for negative values of β_n , implying maser-like emission. The source function in this case can be derived to be

$$S_v^{l+c} = \frac{(b_n \tau_l^* + \tau_c)}{(b_n \beta_n \tau_l^* + \tau_c)} B_v(T_K) \quad (1.18)$$

Goldberg (1966) showed that when $\beta_n < -1$, there is an enhancement of the recombination line strength, by a factor of a few. However, for maser amplification with a gain $\gg 1$, it is not enough that $\beta_n < -1$. The net optical depth ($\tau_l + \tau_c$) should also be negative, which is satisfied in some cases. For typical HII region parameters, the line enhancement due to non-*LTE* effects is considerable. Figure 1.3 shows the expected ratio of non-*LTE* to *LTE* line strength for a typical HII region.

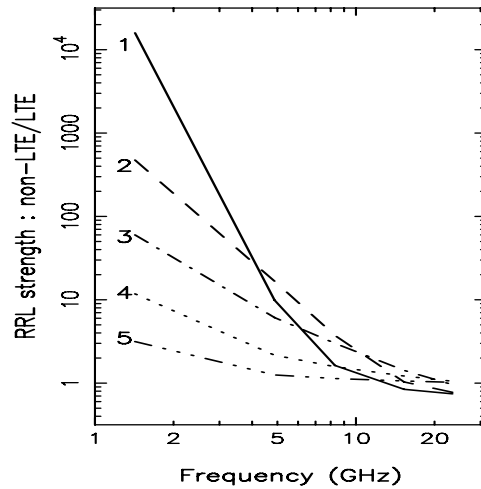


Figure 1.3: The non-*LTE* to *LTE* line ratio vs. frequency for various densities for $T_K=7500$ K and $EM=10^7$ pc cm $^{-6}$. The curves marked 1,2,3,4 and 5 are for densities of $5 \times (10^0, 10^1, 10^2, 10^3 \text{ and } 10^4 \text{ cm}^{-3})$.

All calculations discussed above assume that the collisions are strong enough to thermalise the various l sub-levels of all n levels, i.e., the populations of the various l sub-levels are in the ratio of their statistical weights. Though this is a good approximation in most cases, it is not so for small n across a range of densities. This ‘unblurring’ of l levels leads to an interesting effect called overcooling or the dasar effect. The above effect, along with a few other phenomena, primarily for high frequency RRLs, have been described in detail in a classic paper by Strel'nitski, Ponomarev & Smith (1996).

Another important consequence of large negative β_n and hence a negative τ_l is the following. Consider the case when the continuum optical depth becomes large ($\tau_c > 1$). As described in

the previous section, the *LTE* line strength is greatly reduced (primarily by the factor $e^{-\tau_c}$). However, since the non-*LTE* τ_l can be large and negative, for combinations of n and density, the value of $|\tau_l|$ becomes comparable to τ_c . Hence $(\tau_l + \tau_c) < \tau_c$ and the line intensity is much larger than in the *LTE* case. Therefore, it is possible to probe moderately optically thick regions using RRLs in non-*LTE* and derive gas densities, which are otherwise inaccessible using lines produced under *LTE*. In other words, for moderately thick regions, we can see deeper into the gas through RRLs than through radio continuum. This behaviour can be seen in figure 1.4 where, by increasing τ_c by increasing the path length, the non-*LTE* line enhancement is also increased.

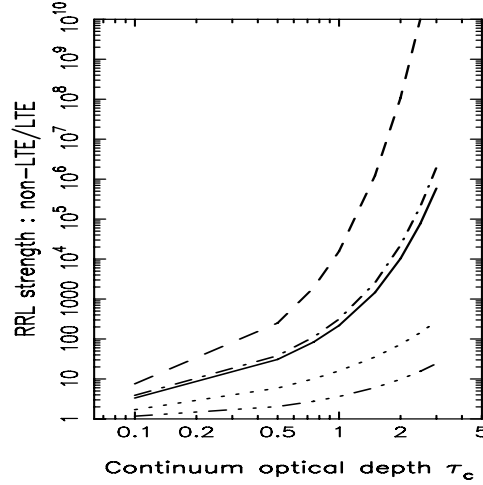


Figure 1.4: The non-*LTE* to *LTE* line ratio vs. τ_c for various densities for $T_K=7500$ K. The curves, from top to bottom, are for gas densities of 10^3 , 10^2 , 10^1 , 10^4 and 10^5 cm^{-3} .

It can be seen based on figures 1.1 and 1.2 that the line optical depth is a strong function of local electron density under non-*LTE* conditions. This is the primary advantage of using RRL emission, though the line strengths are orders of magnitude less intense than optical and IR recombination lines. By modelling the line formation process as well as the subsequent radiative transfer, the local gas density can be derived. The procedure and its limitations are discussed in detail in chapter 2. It was pointed out by Shaver (1975) that for a given RRL, the line emission is emitted predominantly by gas over a small range in densities. Lower the frequency of the observed line, lower is the density the line is sensitive to and vice versa. Hence high- n lines are sensitive to low density gas and low- n lines are sensitive to high density gas. Figure 1.5 shows the density dependence of five RRLs and it can be seen that there is a noticeable peak in the line flux and this peak shifts towards higher densities for higher frequency lines.

From the above discussion, it seems that non-*LTE* effects change the line formation process drastically and a simple *LTE* analysis is inadequate. Assuming *LTE* conditions, the electron temperature can be derived from the line to continuum ratio, denoted by T_K^* . This would deviate from the true temperature T_K which can presumably be obtained with a full non-*LTE* analysis. However, Shaver (1980) showed that, for a given emission measure EM, there exists a particular RRL at a frequency ν such that the value of the temperature derived assuming *LTE* is within a few percent of the true temperature, i.e., $T_K \approx T_K^*$. This result has been applied to galactic studies but is not very useful for extragalactic systems.

The final property of RRLs we will discuss in this section is the behaviour of the two terms in

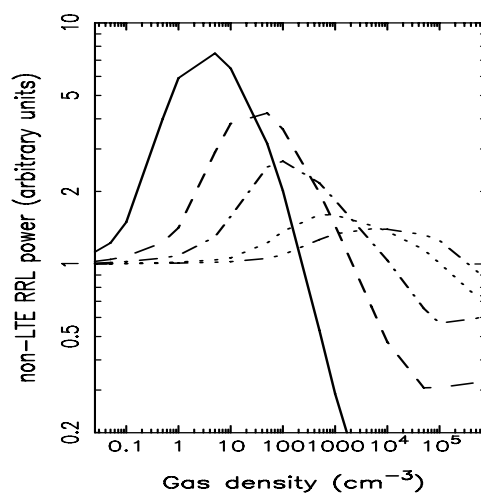


Figure 1.5: The non-*LTE* RRL power in arbitrary units vs. gas density for $T_K=7500$ K and $EM=10^7$ pc cm $^{-3}$. The solid, dashed, dot-dashed, dotted and dot-dot-dashed curves denote the H148 α , H110 α , H92 α , H75 α and H65 α lines respectively at 2.0, 4.9, 8.3, 15.3 and 23.4 GHz.

eqn. 1.6. The first term describes the contribution to the line emission due to stimulated emission by a background radiation field. This background is usually dominated by non-thermal radiation which tends to have a higher brightness temperature than any background thermal emission. The second term is the line emission from the ionized gas itself, which was discussed above in detail. This is primarily spontaneous emission at low continuum optical depths. For moderate optical depths though, the line emission is dominated by stimulated emission by the continuum emission of the gas itself. Both these processes will be referred to jointly as internal emission hereafter. Note that if the ionized gas has a non-zero emissivity for non-thermal emission (i.e., non-thermal emission mixed with thermal emission), then this radiation will also contribute to stimulated emission, but its behaviour will be different from that of the first term in eqn. 1.6 (by a factor $\tau e^{-\tau}/(1 - e^{-\tau})$, approximately). Consider a background radiation whose flux density has a spectral index of -0.7 . Under *LTE* conditions, and if $\tau_c \ll 1$ and $\tau_l \ll 1$, the RRL power corresponding to the first term of eqn. 1.6 has a dependence of $\sim \nu^{-0.7}$. The internal emission, however, has a dependence of $\sim \nu^2$. When the gas becomes optically thick, or at least when $\tau_c \sim 1$, or when non-*LTE* conditions apply, the exponents for the frequency dependence will change. Under non-*LTE* conditions, these exponents will also acquire a density dependence.

In this section, we have discussed various properties of RRL emission, taking into account various non-*LTE* effects. Though these properties necessarily complicate any line modelling, they are also precisely those properties which allow us to derive local electron densities and sizes from these lines, thus making such observations worthwhile in their own right. The details of the modelling procedure will be described in detail in section 2.3.

1.3 RRLs from starburst galaxies

1.3.1 Past work

In this section, we briefly describe the history of extragalactic RRL observations carried out up to 1996. The first RRL detected outside the galaxy (and the Magellanic Clouds) was the H166 α

line at 1.4 GHz seen in the nearby starburst galaxy M 82 by Shaver, Churchwell, & Rots (1977) using the Westerbork Synthesis Radio Telescope. In their paper, the authors claimed that this line is probably due to stimulated emission by the thermal gas due to the background continuum. They also predicted that using this phenomenon of stimulated emission, RRLs could be seen from high redshift quasars with strong radio continuum. The line from M 82 was confirmed by several observations undertaken in quick succession (Bell & Seaquist, 1977; Chaisson & Rodriguez, 1977; Shaver, Churchwell & Walmsley, 1978; Bell & Seaquist, 1978; Rodriguez & Chaisson, 1980). The second galaxy from which RRLs were detected was yet another nearby starburst NGC 253 (the H102 α line at 6 GHz from the Algonquin Radio Telescope; Seaquist & Bell 1977). Soon after the first detections, there were a number of single dish and interferometer observations of various RRLs from these two galaxies in the cm, and later in the mm-band (Mebold et al., 1980; Puxley et al., 1989) as well. Modelling the low frequency RRLs from both these galaxies, especially in M 82, indicated that almost all of the line emission comes from externally stimulated emission (Shaver, Churchwell & Walmsley, 1978). However, higher frequency lines (Puxley et al., 1989), especially mm-wave lines, were much stronger than predicted by these models and hence these latter lines were explained as arising due to spontaneous emission (the analysis of these mm-wave RRLs in the literature, however, is flawed, since, contrary to what the authors assume, non-LTE effects in the form of stimulated emission due to the thermal emission of the line emitting gas is far more important than the LTE line emission, and hence cannot be ignored just because the background radiation is negligible, i.e., one cannot assume that $b_n < 1$ but $\beta_n = 1$, as the authors have done). Shaver (1978) calculated the expected RRL flux densities from high redshift quasars and derived a value of 1-10 mJy near 1 GHz. A number of such objects were observed (Churchwell & Shaver, 1979; Bell et al., 1984), though no line was detected (there were a couple of false detections which could not be subsequently confirmed). Possible reasons for the non-detection are large line widths, high density, small or zero emission measures (i.e., insufficient amounts of gas in front of the continuum source) and proximity to the non-thermal radiation field which saturates the maser.

Shaver and others expected that extragalactic RRLs due to internal emission, which they termed spontaneous emission, will probably not be detected (apart from rather special cases of M 82 and NGC 253, and at that time, the nature of these two galaxies and their importance was not known either) since galaxies need to be nearby for these lines to be detectable. Ironically, it is precisely this kind of emission that has been detected from a number of nearby galaxies and till date, there has been no detection of any line from high redshift quasars and radio galaxies due to externally stimulated emission. The third galaxy from which RRLs were observed was NGC 2146 (Puxley et al., 1991). The authors modelled the line emission in detail in terms of a uniform slab as well as a collection of HII regions which provided the motivation for the modelling scheme developed in this work and earlier. Lines were also seen from 30 Doradus region in the LMC (see Peck et al. 1997 for the most recent observations and references therein). Following this, there were no new detections of extragalactic RRLs till the beginning of the nineties, when, utilizing the much improved receivers and correlators made available on the VLA and the ATCA, Anantharamaiah and co-workers started a programme to search for radio recombination line emission from a number of nearby starbursts galaxies. It was obvious by this time that only starbursts galaxies possess huge amounts of ionized gas with sufficiently large emission measure ($>10^7$ pc cm $^{-6}$) for their line emission to be detected. In total, 17

galaxies were observed with the VLA and seven with the ATCA in order to detect the H92 α line at 8.3 GHz. Out of these, line emission was detected from nine galaxies at the VLA and four at the ATCA. Seven of these were also observed using the IRAM and the SEST to search for mm-wave RRLs and five galaxies were detected in mm-RRL emission. The galaxies from which RRLs have been seen, excluding the work in this thesis, are NGC 253, M 82, NGC 2146, NGC 660, NGC 1365, NGC 3628, NGC 3690, M 83, Arp 220, NGC 4945 and Circinus, at cm-wavelengths, and NGC 253, M 82, NGC 4945, NGC 3628, NGC 4151 and Arp 220 at mm-wavelengths. Some of these observations along with models for the line emitting gas in these galaxies have been published (Anantharamaiah et al., 1993; Zhao et al., 1996, 1997; Phookun, Anantharamaiah, & Goss, 1998). The cm-wave lines, except for ~ 10 mJy lines from NGC 253, M 82 and NGC 4945, are observed to be ≤ 1 mJy in strength and 100-200 km s $^{-1}$ wide. The line emission as well as the associated continuum emission was modelled and the line emission in some galaxies could be explained as mainly internally stimulated emission from a collection of compact (few pc) high density ($\sim 10^4$ cm $^{-3}$) HII regions. Some galaxies could also be fit by a foreground uniform screen of low density (few 100 cm $^{-3}$) gas. Hence, both a high density class of solutions as well as a low density class of solutions were observed to be consistent with the observed data. The ionization derived in these galaxies was in excess of 10^{52} photons s $^{-1}$, thus probably accounting for a dominant portion of the total star formation in these starburst regions. The integrated RRL flux of the sample of galaxies observed was found to be correlated with both the Bry flux as well as the HCN/HCO $^{+}$ line strengths and weakly correlated with the total radio continuum. Resolved line emission was seen in a few galaxies and hence kinematics of highly obscured high density nuclear gas were also studied.

1.3.2 Motivation for our observations

Some of the key problems regarding the starburst phenomenon are fairly well understood. We know that starbursts have higher SFR and SFE and we know that this requires large gas densities, which is observed. Different mechanisms which can produce the required enhancement of gas density, like galaxy-galaxy interactions, spiral arms, bars etc, are also known. These mechanisms have been modelled in detail and their predictions agree well with observations. Various large scale correlations between star formation parameters have been discovered and simple models of star formation explain them fairly satisfactorily. However, all these processes are understood globally. Our knowledge of local small scale details (e.g., microphysics of highly efficient star formation) is not adequate. What is needed observationally are physical parameters of gas and star clusters at small scales, but such observations are hampered by large amounts of dust obscuration. Thus the centre of starburst regions, which is what needs to be studied in detail, is almost completely hidden from view in the UV, optical and sometimes even in the IR. Additionally, some of the wavebands important for studying the starburst process like the MIR, FIR and sub-mm, lack adequate spatial resolution (the situation has improved considerably for X-rays with XMM-Newton and now Chandra). It is in this light that the detection of radio recombination lines from a number of nearby starbursts assumes importance. Radio continuum emission is, like RRL, not affected by dust, and is also much brighter compared to RRLs. High resolution continuum images of starburst centres are available and they have led to a wealth of detail about the gas in these regions. However, it is usually difficult to separate the non-thermal part from the thermal part of the continuum radiation. Even if this is possible, thermal emission

will not yield very reliable local gas properties, viz., the derived density is only the rms density and is plagued by unknown filling factor uncertainties. Though radio continuum is still an important tool, some of its drawbacks are offset nicely by the properties of recombination lines - these lines arise only in thermal gas, and the line emission, using non-LTE effects, can yield the local electron density directly. Hence a combination of radio recombination lines and continuum can be used profitably to derive gas properties in highly obscured, otherwise inaccessible, starburst centres.

RRLs probe ionized gas and hence recent star formation. Since the location, geometry and dynamics of this gas is affected by the stars ionizing it, RRLs can potentially yield information about the geometry and amount of star formation in obscured regions, which molecular lines cannot do very well. Earlier observations of extragalactic RRLs, summarised in section 1.3.1, suggested the following. First, low frequency RRLs seemed to arise due to externally stimulated emission and high frequency lines seemed to arise predominantly due to internally stimulated emission. Therefore, a multiwavelength RRL study, can, in principle, be used to study the properties of both the background radiation as well as the properties of the thermal gas. Second, models of the cm-wave RRLs resulted in two classes of models : low density (gas at $\leq 10^3 \text{ cm}^{-3}$ with a size of tens of parsecs) and high density (gas at $> 10^3 \text{ cm}^{-3}$ with a size of a few parsecs). It is important to determine which of these components are responsible for the RRL emission and whether most of the ionized gas is at low or high density and this can be addressed by suitable multiline observations. We plan to address these issues in this thesis. Though it is known that high density molecular gas exists in starburst centres, the density of the ionized gas is not known. The only reliable estimate of gas densities come from ISO observations of the fine structure lines of heavy elements in the IR and these consistently yield densities of 100-500 cm^{-3} . However, a much higher density was derived using earlier RRL observations for most of the ionized gas. Either there are two distinct components of ionized gas, in which case, the extinction needs to be even higher than previously estimated, or the modelling of the IR lines or the RRL lines has ambiguities. This problem needs to be resolved. In any case, gas at different densities is expected to exist in any large enough region and the relative amounts of gas at various densities is as yet, completely unknown. Low density diffuse gas would probably be ionized by diffuse radiation which leaks out of HII regions and also by field stars, whereas, high density gas is expected to be compact and would be ionized by recently formed stars and star clusters. These clusters can be observed in the optical only when the surrounding dust is blown away, and by that time, most of the ionized gas is blown away as well. Hence, detecting young gas and dust enshrouded star clusters might be easier in the radio than in the optical. High resolution imaging in the MIR can also play an important part in this regard, and such observations are now being carried out. Though a given RRL, due to its line formation process (see section 1.2.2.3), is biased towards a certain range of densities and continuum optical depths, it is unbiased to extinction. In any case, it is an independent probe from which the SFR can be estimated. Also, by comparing the ionization requirements with other wavebands, a good estimate of extinction can be made. Note that, due to saturation at a A_V of a few magnitudes, an estimate of the extinction using progressively longer wavelength lines gives progressively higher values of A_V and hence RRLs, along with $\text{Br}\gamma$, for example, can be used to derive a more reliable estimate than, say, $\text{H}\alpha$ and $\text{H}\beta$. Additionally, radio interferometric observations are possible at subarcsecond resolution and in fact, the spatial resolution of RRL observations

is limited only by the sensitivity. Hence, the highest resolution observations of the ionized gas possible at present are through radio continuum and RRLs. We need to identify the actual sources of radio line emission. Then, along with resolved continuum data for such individual sources, accurate modelling of the properties of these objects can be carried out. Lastly, RRLs can also be used to obtain kinematic information about highly obscured gas in the form of velocity fields for spatially resolved line emission and also line widths for unresolved emission. Since starbursts are caused by dynamical triggering, studying the kinematics of the dissipative gas will yield clues about the actual triggering process.

So far, we have discussed the observation of RRLs from nearby galaxies which are emitted primarily by internally stimulated emission. Recall, however, that the first predictions of extragalactic RRLs were of externally stimulated emission from high redshift objects. Earlier attempts to detect such lines failed and the limits derived were about 10 mJy. Since we can do much better with present day instruments, it is worthwhile to revisit this area of research and hence, as a pilot study, we have also carried out observations of a gravitational lens. A search for RRLs from Damped Ly α Absorbers has also been undertaken (Anantharamaiah et al.; private communication), though with no success.

Apart from the various motivations for this project described above, an additional not exactly flippant reason is that extragalactic RRLs should be studied because they can be. We in astronomy are never in a position of having too much data and usually, most of the effort is in refining the sensitivity of the few observational techniques we possess. It is but rarely that a new observational tool appears, and in this case, has appeared solely because of advances in radio instrumentation. Though RRLs are not expected to solve all existing problems in the field of starbursts, it is of interest to see what physical information one can derive from this tool. What we would like to know is (1) what can we learn from observing RRLs from starbursts ? (2) What complementary and supplementary information does it provide to data from other wavebands ? (3) Which part of a starburst region and what stage of a starburst are RRLs preferential to ? (4) What kind of design parameters need to be introduced in future telescopes like LOFAR, SKA and ALMA so as to fully utilise the diagnostic powers, if any, of extragalactic RRLs ? It is to answer these questions, atleast partially, that we have undertaken this project.