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Galaxy interactions, and the starburst galaxies – AGN connection

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Abstract. Starbursts and Active Galactic Nuclei (AGN) are observed to preferentially occur in interacting or barred field galaxies. Galaxy interactions cause gas infall from the galactic disks, which may lead to the triggering of a central starburst which could then evolve to an AGN, or the gas infall may fuel a pre-existing central black hole in an AGN. Here, first the concept of galaxy interactions is introduced. Then the problem of fuelling of an AGN is discussed and it is shown that galaxy interactions or bars help in this process. Next, an overview of the physical properties of the starburst galaxies, including their tracers and the triggering mechanisms, is given. Some simple theoretical ideas regarding the physical, causal connection between starburst galaxies and AGN are discussed. Implications of the starburst–AGN connection for the evolution of the high redshift galaxies are mentioned. The current trends and future problems in these topics are briefly discussed.

Key words: starburst galaxies—AGN—quasars—interacting galaxies

1. Introduction

In this article, a brief overview of the physical, causal connection between starburst galaxies and active galactic nuclei (AGN) is presented. Galaxy interactions are shown to play a major role in the triggering of starbursts, which could evolve to AGN. Alternatively, the interaction could provide fuel to a pre-existing central black hole in the galaxy.

Section 2 contains a brief review of the physical properties of AGN. Next, the concept of interacting galaxies is introduced and their importance is discussed. The observational evidence for galaxy interactions in AGN is presented. The main physical issues concerning the fueling of an AGN are discussed and it is shown that galaxy interactions and bars help in this process. In Section 3, physical properties of starburst galaxies are discussed. Some simple theoretical ideas regarding the evolution of starburst to AGN, and the observational evidence for these, are presented in Section 4. Both phenomena are expected to be more effective at high redshifts. Starbursts evolving to AGN can therefore explain the evolution of the quasar luminosity function, as discussed in Section 5.

Both starburst galaxies and AGN are vast and extremely active areas of research today. Hence, it is not possible to give a complete coverage of these in this article. Instead, an attempt is made here to highlight the basic physics of the starburst galaxies, the starburst-AGN connection, and the fuelling of AGN driven by galaxy interactions. The current status in this area is discussed. Also, some open, theoretical problems in this area are pointed out at the end of Sections 2,3,4 and 6.

2. AGN, and their fuelling

2.1 *Brief overview of AGN*

The title AGN has by now come to denote a bewildering zoo of objects, see e.g. Woltjer (1990) for a nice summary of the phenomenology of AGN. Although the various AGN seem dissimilar at a first glance, there are several common physical characteristics which unify these (*e.g.*, Begelman 1988, Netzer 1990). These are:

1. *Compact, central energy source*: This is evident from the short time–scale variability, especially in the X-ray region. The size of an AGN is dependent on the wavelength at which it is observed with the more energetic emission being more centrally concentrated.

2. *Large rates of energy output*: The large central rate of continuum energy output seen often far surpasses other (stellar) energy sources within the host galaxy.

3. *Non-thermal central energy source*: The central continuum source shows a non-thermal, flatter or a harder spectrum as compared to the standard thermal spectrum from stars. Thus, in an AGN a larger percentage of energy is emitted in the high frequency range. Superposed on this, there are optical emission lines excited by a non-stellar source.

4. *Large line widths*: The central gas moves rapidly as inferred from the large line widths of the gas emission. This implies motion in a deep potential well.

These characteristics have now come to define an AGN. Of course, there is a tremendous variation in the values of these parameters amongst the various types of AGN. However, these properties show a smooth variation, with overlap amongst the various classes. This means that these properties do represent basic physical characteristics, and hence can be used as meaningful classification parameters.

For example, if one were to categorize the AGN on the basis of their total central luminosities (L_t), then the AGN can be divided into the following three groups (Netzer 1990): (1). Quasars and QSO's (radio-quiet quasars) with $L_t \sim 10^{45} - 10^{47}$ erg. sec^{-1} $\sim 10^{12} - 10^{14} L_{\odot}$.

These are the most energetic AGN. (2) Mini-quasars: Seyfert 1, and Seyfert 2, with $L_t \sim 10^{43} - 10^{45}$ erg. sec^{-1}. (3) Micro-quasars: Liners, with $L_t \sim 10^{41} - 10^{43}$ erg. sec^{-1}. The infrared luminosity values for the starburst galaxies (Section 3) overlap with the L_t values for the micro-and mini-quasars. The number of Quasars and QSO's is much smaller than that of the Seyferts which in turn are much less numerous than the Liners. In fact, almost all large, barred, early type galaxies show evidence for the phenomenon of Liners (line ionization nuclear emission regions).

Although the detailed physics of AGN is complex and not well-understood, their basic characteristics described above can be best explained by the following *standard model*. The central, non-stellar power source of an AGN is believed to be a massive black hole, powered by release of gravitational energy from accretion of gas from the surrounding host galaxy (e.g., Blandford 1990). This can explain the main AGN characteristics—namely, the compact nature of the central source, the high rates of energy output (since the conversion from mass to energy is very efficient in the relativistic potential as compared to that in the star formation process), the non-thermal central energy spectrum, and the large linewidths. Providing a steady source of fuel to the central source is a major problem. The fuelling process is helped by galaxy interactions, as discussed in Section 2.4.

2.2 *Galaxy interactions*

What does one mean by a galaxy-galaxy interaction? This is not a trivial question since galaxies interact via gravitational force which is a long-range force. There is no hard or unique rule to define interacting galaxies. However, if the gravitational tidal force due to the interaction between a galaxy pair is a non-trivial fraction (say, at least a few percent) of the gravitational force within an isolated galaxy, then the galaxy may be said to be undergoing an encounter.

For example, the Andromeda galaxy (M31) and our Galaxy are not interacting strongly, since their sizes (and masses) are roughly equal and their separation is ~ 700 kpc which is about 30 times the diameter of each galaxy. In contrast, the Large Magellanic Cloud (LMC) and our Galaxy are clearly interacting. The LMC is about (1/10) as massive as our Galaxy and the two are separated by a distance of only 50 kpc. This is about twice the diameter of our Galaxy, and about five times the diameter of the LMC. Hence each galaxy has a significant gravitational tidal effect on the outer regions of the other. The LMC is, in fact, believed to be a satellite of our Galaxy and its orbit is evolving dynamically and the LMC is slowly spiralling into the Milky Way.

Various definitions for 'interacting' galaxies are used in the literature. These are as follows:

1. A pair of galaxies is said to be interacting if the two galaxies lie close spatially and have similar line-of-sight velocities, and in fact this is how groups and clusters of galaxies are defined. A group typically has a size of ~ 1 Mpc, and contains a few large galaxies and several smaller galaxies.

2. Interacting galaxies exhibit morphological features such as tidal tails in the outer parts where the effects of perturbation due to the gravitational encounter would be the strongest (see *e.g.* Arp 1966; Schweizer 1986). A tremendous amount of diversity and complexity is possible due to a variety of the sizes and shapes of galaxies and the orientation of their orbits, and disk planes.

3. An extreme case of interacting galaxies would be when a pair is in an obvious physical collision or a merger as for example is the case in Arp 220, or in NGC 6240. Here two merging disks and two nuclei can be seen with strongly perturbed outer regions. Such mergers lead to ultraluminous starburst galaxies, which are believed to be precursors to AGN (see Section 4).

The next question is how frequent, and therefore important, are galaxy interactions? Even as recently as 20 years ago, it was believed that galaxy interactions are rare within the lifetime of a galaxy. However, over the last 10 years it has been realized through dynamical studies that take account of the massive halos of galaxies, and also through infrared observations, that a galaxy-galaxy interaction is a very common phenomenon. From the fraction of merging of colliding pairs in the NGC catalogue, and the duration of a merger (= 5×10^8 yr) compared to a galaxy lifetime of 10^{10} yr; it can be argued that ~ 5% of galaxies undergo physical collisions or mergers in their lifetime (Toomre 1977). Recent estimates give an even higher value for the merging fractions (Schechter 1990). The percentage of mergers could be higher at earlier epochs. Further a much larger fraction would undergo a distant or a tidal encounter. Thus a galaxy interaction is a common phenomenon in the lifetime of a galaxy. Hence, the effects of galaxy interactions on the evolution of galaxies must be taken into account. This is analogous to the 'nature plus nature' idea as in psychology. Galaxy interactions significantly affect the evolution of galaxies and especially the gas in them. The increased gas viscosity leads to an increased gas infall, which may trigger starbursts or fuel a pre-existing black hole as will be discussed in Sections 2.4 and 3.

2.3 *Evidence for interactions in AGN*

It was first suggested theoretically that galaxy interactions may be responsible for providing fuel for AGN, via redistribution of angular momentum and the resulting deeply plunging stellar orbits (Toomre & Toomre 1972). However, clear observational evidence for this idea has only become available in the last 10 years. This is a difficult observational problem since a large dynamic range is required to detect a 'fuzz' representing a host galaxy around an AGN and to study its (disturbed) morphology. Also, for the distant AGN, one needs to obtain redshifts for two apparently faint objects in order to rule out a chance projection. Despite this, however, it has now been shown that AGN occur preferentially in interacting pairs of field galaxies or groups of galaxies as discussed next.

About 70% of low redshift QSO's have close neighbours, or have peculiar morphologies, and tidal tails and multiple nuclei as indicators of galaxy interactions (Smith *et al.* 1986 Hutchins *et al.* 1984; Stockton 1990). Also, powerful radio galaxies are shown to be associated

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with morphologically disturbed galaxies (Heckman *et al.* 1986). Seyferts show evidence for interactions as seen from the fraction with nearby neighbours (Dahari 1984), and from their disturbed, amorphous morphology (MacKenty 1990). A high fraction of a sample of interacting/disturbed galaxies with companions show Seyfert type of activity (*e.g.* Vorontsov-Velyaminov 1977; Balick & Heckman 1982; Keel *et al.* 1985). This is by no means a complete list and significant progress is expected in the coming years—for example from the high resolution imaging observations, say from the Hubble Space Telescope, to image the QSO host galaxies to low surface brightness. Thus, there is clear observational evidence for galaxy interactions to be occurring in AGN. Therefore the formation and/or fuelling of the central black hole in an AGN must be made possible by galaxy interactions in field galaxies or in groups of galaxies.

There are, however, two caveats to this result as stressed by Stockton (1990). First, the criteria used to denote interaction are somewhat arbitrary or subjective. More importantly, there is no suitable sample of non-interacting galaxies. This is particularly true for the QSO's which are seen mostly at high redshift, z. That is, the only galaxies visible at high z may be the luminous, interacting ones (Stockton 1990).

It should be noted that the AGN do not seem to favour a cluster location (*e.g.* Balick & Heckman 1982). Only ~ 1% of cluster galaxies show Seyfert type emission lines versus ~ 5% of field galaxies showing a similar behaviour (Dressler, Thompson & Shectman 1985). Further the AGN in clusters seem to lie in the outer, clumpy and unevolved regions. Only in looser clusters is the frequency of Seyferts the same as in field galaxies (Petrosyan 1982). Clusters of galaxies have deeper potential wells than the field case, hence the galaxy encounter timescale is short compared to their internal dynamical timescale (*e.g.* Sarazin 1986). Such fast galaxy encounters may not lead to a significant gas infall (see Section 2.4). In contrast, in the outer, clumpy and unevolved regions of a cluster, the dynamical conditions are similar to that in a field case, and hence presumably suitable for AGN formation and fuelling via galaxy interactions.

2.4 *Fuelling of AGN and galaxy interactions*

The fuelling of the central black hole in an AGN is major theoretical problem. The problem can be divided into the availability of gas fuel in the galactic disk, and the transport of this fuel from the disk to the central regions. It turns out that the total amount of available fuel is more than adequate. The net luminosity L_t from a black hole of mass M_{BH} is related of mass infall (=dm/dt) as follows:

$$L_t = \approx 10^{45} \frac{\epsilon}{0.1} \frac{dm/dt}{(0.2 M_{\odot} \mathrm{yr}^{-1})} \frac{M_{BH}}{10^8 M_{\odot}} \mathrm{ergs}^{-1}$$

where ϵ is the efficiency of conversion from mass to energy. (The black hole mass would increase following the infall and this could well be the formation mechanism for the black hole).

Thus, in order to support luminoisty of even the most luminous AGN – that is, quasars and QSO's (with $L_t \sim 10^{45} - 10^{47}$ erg sec^{-1}), one would need a gas accretion rate of about 1-100 $M_\odot$ yr^{-1} onto a canonical black hole mass of $\sim 10^8 M_\odot$ (*e.g.*, Shlosman, Begelman & Frank 1990). At this rate, the gas in a typical spiral galaxy can easily support the central AGN luminosity for about $\sim 10^7 - 10^{10}$ yr.

Therefore, the main problem is how to transport this material from the galactic disk into the central regions. For a typical central black hole mass of $\sim 10^8 M_\odot$, the maximum radius up to which the gravitational effect dominates over the stellar gravity is ~ a few pc. The standard discussion of central accretion disks invokes an even smaller region of $\sim 10^{-4}$pc (Blandford 1990). Hence it is important to explain how the gas as fuel can be transported from the galactic disk region (of about ~10 kpc) to deep into the central regions close to the black hole.

In a gravitating, differentially rotating disk, the specific angular momentum or the angular momentum per unit mass increases with the radial distance. Hence the gas infall from a region of high specific angular momentum at high radial distances to the central regions has to be associated with an outward transport of angular momentum in the disk. This is a standard problem in the evolution of differentially rotating systems encountered in a number of contexts in astronomy, *e.g.*, in planetary rings. One way the gas infall is made possible is via the gas viscosity. The viscosity in the gas motion tends to damp out its differential motion in the disk. The gas looses energy and sinks deeper into the central gravitational potential. The rate of gas infall is thus set by the rate of viscous dissipation. This evolution was worked out by Lynden-Bell & Pringle (1974) in a classic paper, who showed that a viscous, differentially rotating disk evolves in such a way that most of the mass falls in and a small amount moves out to the region of high specific angular momentum so that the net angular momentum is conserved. Even when there is an external tidal torque as in interacting galaxies, the net evolution of the dissipational component, namely gas, follows the same qualitative behaviour (*e.g.*,Icke 1985, or Barnes & Hernquist 1991).

The above discussion was applicable for a particulate disk where the standard kinematic viscosity due to physical collisions is applicable. The same physical behaviour also results when the origin of viscosity is more subtle. In another classic paper, Lynden-Bell & Kalnajs (1972) have shown that in the presence of a non-axisymmetric potential as associated with spiral features, there is an exchange of energy between particles and the wave at resonances. This is analogous to Landau damping in plasma physics. This results in a similar outward transport of angular momentum associated with an infall of material in the disk. The details of these dynamical effects of the non-axisymmetric perturbations are too involved technically to be covered here.

Norman (1992) has studied the evolution of clouds with dissipational collisions in such a non-axisymmetric potential. The treatment of two body, dissipational collisions including the estimate of two-body collision rate in a sheared disk is a complex subject (*e.g.*, Petit & Henon 1987; Gammie, Ostriker & Jog 1991 – and references therein). This collision rate is simply denoted by a constant parameter γ, by Norman. Norman has shown that the infall time is proportional to the dynamical time and the total potential energy and is inversely proportional to the cloud collision rate γ, times the perturbation potential. Physically what this means, is that the infall time is always greater than or equal to the dynamical time in the region under study; and the stronger the perturbation or the non-axisymmetric potential, the closer the infall time is to the dynamical timescale. Thus, for merging galaxies with large distortions ~ 30%, infall times as short as 3 x 10^8 yr are possible – see Norman (1992) for details.

A barred morphology of a galaxy has a similar effect on the gas cloud motions, and results in a steady rate of gas infall. The basic idea is that the gas gets shocked in the bar potential, looses its kinetic energy and falls in. This complex problem mostly has to be worked out numerically (*e.g.*, Sellwood & Wilkinson 1993 and references therein). A large fraction of starburst galaxies do indeed show a barred morphology (Hawarden *et al.* 1986). The criterion for the onset of a bar instability requires that the ratio of the total rotational kinetic energy to the absolute value of the total potential energy be > 0.14 (Ostriker & Peebles 1973). Gas infall into the central regions would thus tend to make the system more unstable to a bar instability. Hence, this is a self supporting/ accelerating process (*e.g.*, Norman 1992).

Galaxy interactions can help in causing gas infall from galactic disk to the central regions as follows. A galaxy interaction can perturb cloud orbits and thus increase the cloud collision rate. The increase in dissipation via cloud collisions would then lead to a higher gas infall rate. A gravitational perturbation due to a galaxy interaction can also cause the formation of temporary spiral features in the disks (*e.g.*, Toomre & Toomre 1972). The stronger the gravitational perturbation due to the galaxy interaction, the stronger are these effects. The resultant increase in the effective viscosity in the disk leads to a smaller gas infall time and hence a higher gas infall rate (*e.g.*, Norman 1992). Further, gas infall driven by galaxy interactions can cause/strengthen a bar instability in the galaxy, thereby further increasing the gas infall rate as discussed above.

Thus galaxy interactions are clearly important in causing gas infall from the galactic disks to their central regions. This could then trigger central starbursts (Section 3), which evolve into AGN (Section 4); or it could fuel a pre-existing central black hole.

2.5 *Future work*

The various dynamical aspects of gas infall from 10 kpc to 1kpc, and especially from 1 kpc to 1 pc, have yet to be worked out completely. Some of these are as follows:

1. The non-axisymmetric perturbations are generally not important in causing gas inflow to below 1 kpc, since a very close encounter is needed to get the gas to ≤ 1 kpc of the galactic centre (*e.g.*, Icke 1985). Lin, Pringle, & Rees (1988) have suggested that gravitational instabilities in the central gas may result in increased cloud collisions and hence increased viscosity, and would therefore cause gas infall. However, they start out with a very large amount of gas mass ($\leq 8 \times 10^9 M_\odot$) in the central 1 kpc.

2. A general problem is that the infall time is proportional to the local dynamical timescale which is smaller at lower radii. Hence, establishing a steady supply of gas all the way into the central 1 pc is difficult (Frank 1990).

3. The rate of central accumulation of gas also depends on the initial distribution of gas. Most starbursts and Seyferts are barred galaxies with central gas holes, and yet theorists doing infall calculations generally use a centrally peaked gas distribution which leads to a higher gas infall rate, as pointed out by Shlosman *et al.* (1990).

4. The specific angular momentum in a galactic disk increases linearly with the radial distance square, r^2, in the central region of solid body rotation, versus its linear dependence on r in the outer regions of a flat rotation curve. Hence the problem of outward angular momentum transport required to get the gas in from 1 kpc to 1 pc is more severe than to get it in from 10 kpc to 1 kpc. Thus the fuelling of AGN is harder than getting the gas infall to the central 1 kpc as required for starburst galaxies. Note, however, that given the higher efficiency of conversion of mass into energy around a black hole, a much smaller gas infall rate is necessary to support an AGN compared to a starburst of the same total luminosity.

5. The resulting starbursts or the radiation from the AGN may cause gas outflow. This negative feedback on the host galaxy may hinder further gas fuelling (see Section 4.2 for details).

6. For the sake of simplification, work on gas infall in the literature so far has been mainly confined to spiral (disk) galaxies.

Thus there are many challenging, and well-defined physical problems that need to be solved to fully understand the important question of fuelling of AGN.

3. Starburst Galaxies

The subject of starburst galaxies is a very active and exciting field of research today. In this section, the basic properties of starburst galaxies are discussed. The possible connection between the starburst galaxies and AGN is presented in the next Section.

3.1 *Introduction*

Starburst galaxies are characterized by very high luminosity ~ $10^{10} - 10^{12}\, L_{\odot}$ in the far-infrared (~ 30 – 300 μm), seen typically over the central region of ~ 1 kpc diameter. This is about 10 – 10^3 times the central infrared luminosity from a quiescent galaxy like our Galaxy. A major part of luminosity in these galaxies is in the infrared region. A star formation rate (SFR) of ~ $10 - 100 M_{\odot}\ \mathrm{yr}^{-1}$ is required to explain the above high luminosity values. At this rate, the gas in a galaxy would be exhausted in $\leq 10^8$ yr – which is much smaller than the lifetime of a galaxy. Hence the luminous phase must be a transient phenomenon and therefore, galaxies showing high infrared luminosity are said to be undergoing a starburst. The infrared luminosity is believed to be from young, massive stars which are therefore still near the sites of formation, namely, the gas clouds. Hence, the stellar radiation is absorbed by the dust in the clouds, and re-radiated thermally in the far-infrared.

Starburst galaxies are often seen in interacting field galaxy pairs. A large fraction of the IRAS IR-bright galaxies show evidence for recent interaction as indicated by the presence of nearby neighbours, or from their disturbed morphology and tidal tails (*e.g.,* Jospeh *et al.* 1984; Lonsdale, Perssons & Matthews 1984, Telesco 1988). A large fraction (~ 70%) of interacting galaxies show starburst phenomenon (*e.g.* Bushouse 1986). Due to their relative proximity to us, the evidence for interaction in starburst galaxies is on a far surer footing than that for the AGN, especially for QSO's, discussed in Section 2.3. Thus, galaxy interactions play a major role in triggering starbursts. A galaxy-galaxy interaction has a dramatic effect on the dissipational component (gas) in the galaxies. A galaxy interaction leads to an increase in the effective viscosity of gas clouds and hence an infall of gas from the galactic disk to the central regions (Section 2.4), which then may result in a starburst. Thus gas is an excellent diagnostic for the study of galaxy interactions. The realization that galaxy interactions are common (Section 2.2) and that they strongly affect gas, has led to the tremendous research activity in this area.

The non-interacting starburst galaxies tend to be barred (Hawarden *et al.* 1986), where the bar may be responsible for causing the gas inflow required for the starburst to occur (Section 2.4). The starbursts are seen in interacting field galaxies and in groups of galaxies, but not in clusters at the present epoch (*e.g.,* Kennicutt, Bothun & Schomer 1984; Jog & Solomon 1992 for details). Perhaps the fast encounters that occur in the cluster potential do not affect the gas significantly, as discussed in Section 2.3. This point is further discussed in Section 3.3.

Starburst galaxies are interesting objects in themselves as sites of high rates of formation of massive stars and high star formation efficiency. Moreover, they also have important implications for a number of fields in astronomy. First, since preferentially massive stars are formed (Section 3.2), as these evolve and die they cause a metal enrichment of the host galaxy. This is especially important for the early, chemical evolution of the primordial galaxies and also for the inter-galactic medium. Second, the supernovae resulting as the end states of massive stars are expected to lead to a substantial energy input into the dynamics of the interstellar medium. Third, ultraluminous starburst galaxies are believed to be progenitors of AGN – see Section 4.

It is instructive to briefly review the vast literature on the history of development of this subject. The initial work on the morphological and dynamical properties of interacting galaxies was done by Arp (1966), and Toomre & Toomre (1972) respectively. Larson & Tinsley (1978) first studied the enhanced star formation in interacting galaxies. They noticed that the interacting/peculiar galaxies are bluer and show a large scatter or dispersion in their UBV colours. Their study of chemical evolution of galaxies showed that the above observed features of interacting galaxies could be explained by bursts of star formation. The bursts required would have a duration of $\geq 2 \times 10^7$ yr each, involving up to ~ 5% of the galaxy mass.

Observationally, galactic nuclei were studied with good resolution from around 1960's. Around 1970's the near infrared detection techniques improved considerably which were used to study star-forming regions in our Galaxy. Observations showed that many galactic nuclei emit large infrared luminosity (Rieke & Lebofsky 1979), and have spectra similar to the galactic star-forming regions with peaks in the far-IR. Thus the high luminosity from galactic nuclei was attributed to young, massive stars. The stars are still enshrouded by clouds and hence the entire stellar radiation is absorbed and re-radiated thermally in the infrared. Since then spectrophotometric studies in near-IR and optical have yielded more data on hot gas in star-forming regions in galaxies. The subject of starburst galaxies was truly launched after data from the Infrared Astronomy Satellite (IRAS) became available in the mid-1980's. This has in turn led to a spurt of activity in the theory of dynamics and evolution of interacting galaxies. Thus the feedback from observers and theorists to each other has led to a fast growth of and understanding in this field.

The IRAS data was limited to four wavebands centred at 12, 25, 60, and 100 μm. The infrared (IR) domain covers the wavelengths from 1-300 μm, with the near-IR, mid-IR, and far-IR range covering 1 - 10 μm, 10 - 30 μm, and 30 - 300 μm respectively. If the emission is treated as a black-body radiation, then by Wien's displacement law, the peak emission would be seen around a wavelength of 10 μm when the dust temperature is about 300 K, and so on.

The discussion in the Section covers normal-size starburst galaxies, but not the blue compact dwarf galaxies. The latter are nearly always isolated, and are believed to have undergone a number of episodes of bursts of star formation (Thuan 1992).

3.2 *Tracers of starbursts*

The main observational features of starbursts are now fairly well understood, and are as follows. For the various parameters given below, the lower values in the range in each case is typical for tidally or weakly interacting galaxies, such as M82, while the higher values represent the evolved mergers such as Arp 220 (= IC 4553). See *e.g.*,Telesco (1988), and Jog & Solomon (1992) for details. These features are:

1. *High Central Infrared Luminosity*, $L_{\mathrm{IR}} \sim 10^{10} - 10^{12}\, L_{\odot}$: The high values of L_{IR} indicate a high SFR as discussed above at the beginning of Section 3.1. A subset of galaxies with $L \geq 10^{12}\, L_{\odot}$, called ultraluminous galaxies, are believed to be progenitors of AGN (Section 4).

2. *High values of* $L_{IR}/M_{gas} \sim 1 - 30 L_{\odot}/M_{\odot}$: L_{IR}/M_{gas} is an indicator of the star formation efficiency (SFE). While a large L_{IR} could simply be a result of a large size and hence the large gas mass content of a galaxy, the large value of L_{IR}/M_{gas} implies a high SFE. SFE in starburst galaxies is estimated to be ~ 10–30% (e.g., Rieke et al. 1980) versus a few % as observed in a quiescent galaxy like our Galaxy.

3. *Infrared excess*, $L_{IR}/L_B \sim 0.1 - 60$: This ratio represents the ratio of recent, massive star formation to the earlier, average star formation. The high value of L_{IR}/L_B (>1) implies that most of the luminosity from the galaxy is in the infrared, and is due to the recent formation of massive stars. For the ultraluminous galaxies, this ratio could be very high (>>1)–for example, for Arp 220, this is equal to 60. In such cases, a significant fraction of the IR luminosity is believed to be of AGN origin (see Section 4).

4. *High* H_α *luminosity* $\sim 10^{40} - 6 \times 10^{42}$ erg sec^{-1}, *and strong optical emission lines*: The strong, narrow optical recombination lines arise in hot, ionized gas–these are either permitted lines from Hydrogen, or forbidden metal lines only seen in regions of high temperature and low gas density. The various line ratios give a handle on the physical conditions such as the temperature and the gas density (*e.g.*, Osterbrock 1989). These ratios show that these lines arise in hot gas, ionized by massive stars as in the galactic H II regions. In fact these line ratios are the best diagnostics to distinguish between starburst versus AGN as the main central ionizing source (see Section 4.1 for details).

From the H_α luminosity, the required photoionizing flux, and hence the mass of young, massive stars required to explain this luminosity can be deduced. Hence H_α luminosity is a good tracer of young massive stars.

5. *High* H_α *equivalent widths*: This quantity is proportional to the ratio of the number of young, massive stars to the total number of older stars, and hence is physically similar to the parameter L_{IR}/L_B. The equivalent width of H_α line, $\omega\,(H_\alpha)$, is higher for interacting galaxy pairs than it is for isolated galaxies (Bushouse 1986), indicating that the % of massive stars formed is higher in the interacting galaxies.

6. *Unusual (redder) colours*: The near –IR, spectrophotometric studies (*e.g.*, Joseph *et al.* 1984) indicate that $K - L$ colours are redder for the interacting galaxies as compared to those for isolated galaxies, while the $H - K$ colours are the same in both samples. H, K, L filters are respectively centered around 1.6, 2.2, and 3.6 μm. The above result indicates that most of the luminosity is in far-IR. This can be explained by the addition of a blackbody spectrum at a temperature of ~ 25-50 K, corresponding to the dust emission, superposed on the blackbody emission from the older stellar population.

7. *Spatial distribution of starbursts*: For a pair of galaxies undergoing a tidal/distant gravitational encounter, as well as for the isolated barred galaxies, the starburst in a galaxy is distributed over a central region of ~ 1 kpc diameter. For colliding galaxies, on the other hand, the starbursts occur over a larger central region of ~ several kpc size (*e.g.*, Joseph & Wright 1985, see Jog & Solomon 1992 for other references).

Thus, the high values of L_{IR}, L_{IR}/L_B, H_α luminosity, H_α equivalent widths; the strong emission lines, and the redder colours indicate a recent burst of formation of massive stars.

To summarize, starbursts are characterized by a high SFR, a high SFE and a preferential formation of massive stars. That is, the initial mass function (IMF) is biased towards massive stars (with an index smaller than the standard Salpeter index 2.35), or the minimum mass of stars formed is ≥ a few $M_{\odot}$ each. This is confirmed by theoretical models for the IMF and the duration of starbursts (Rieke *et al.* 1980). A preferential formation of massive stars allows the gas reservoir to support a burst of a given luminosity for a longer duration. This is because the luminosity per unit mass is non-linear, increasing function of the stellar mass, and hence the same net luminosity can be produced by a smaller rate of star formation and gas consumption if the stars formed are massive.

The details of physics for the origin of the high SFE and the preferential formation of massive stars in the high density shocked gas are discussed in Jog & Solomon (1992). The high SFR resulting in the high density, shocked gas results in a small time for star formation over which the restrictive UV-feedback can occur. This then results in a high SFE (Larson 1987; Jog & Solomon 1992). The high SFE, and the high density in the shocked gas which allows for a good gas-duct coupling, results in a higher gas temperature and hence a higher critical or minimum Jeans mass for the stars formed (Larson 1986; Jog & Solomon 1992).

While these tracers indicate a high rate of massive star formation, and is accepted by all workers in the field (*e.g.,* Norman 1992, and the various articles in that book) it should be mentioned that so far there is no direct, conclusive observational proof for this. An indication of high mass star formation is given by the radio observations of supernovae hotspots in starburst galaxies. These have been observed for example in M82 (Kornberg, Bierman & Schwab 1985), in NGC 253 (Turner & Ho 1985), and in NGC 1808 (Saikia *et al.* 1990). However obtaining a rate of supernova formation from these is model-dependent (*e.g.,* Condon 1992). Van Buren & Norman (1988) have proposed a search for a number of near-IR and mid-IR lines, including the Co (Cobalt) II line at 10.52 μm, and study their variation with time. Cobalt is formed as a by-product of a type II supernova, and is predicted to have a half-life of 77 days. Thus the above line is expected to show variation on this time scale which is sufficiently small for this to be a viable idea observationally.

3.3 *Triggering of starbursts*

Surprisingly,the origin of the triggering of starbursts has not received much attention in the literature. Most of the theoretical work in the literature so far has been concentrated on the dynamical problem of showing that galaxy interactions can lead to gas infall from the galactic disk to the central ~ 1 kpc region (*e.g.,* Noguchi & Ishibashi 1986; Hernquist 1989; Barnes & Hernquist 1991). But the detailed physical treatment for the triggering of starbursts is mostly missing. Hence these earlier models do not yield quantitative results such as $L_{\rm IR}$.

In these models, the increased gas density is assumed to lead to an increased star formation. More specifically, the increased central gas concentration is assumed to lead to an increase in cloud collisions which then result in an enhanced formation of massive stars (*e.g.,* Noguchi & Ishibashi 1986; Sanders *et al.* 1988). While this is a plausible triggering mechanism, there are several problems with this approach - see Jog & Das (1992) for details. For example, theoretical hydrodynamical simulations show (Lattanzio 1990) that high velocity and/ or off-centre cloud collisions lead to their overall disruption rather than compression - the latter would lead to star formation. Second, if cloud collisions were the main triggering mechanism, the SFR and hence the ratio of IR luminosity per unit cloud mass should be larger for the smaller mass clouds, since the smaller clouds would have a higher collision frequency. This is not seen at least in the molecular clouds in our Galaxy (Mooney & Solomon 1988). Third, one should see a global increase in the star formation rate in the tidally interacting galaxies as cloud orbits are perturbed and the clouds collide prior to falling in. This is contrary to what is seen. Thus cloud collisions cannot be the main triggering mechanism for enhanced star formation.

An alternative triggering mechanism that is based on the detailed evolution of a realistic, multi-component interstellar medium in a galaxy has been proposed by Jog & Das (1992), and Jog & solomon (1992). The basic idea is that in an isolated galaxy, the giant molecular clouds GMCs) are barely stable, and are sites of massive star formation, with a low SFR. If the ambient pressure around a pre-existing GMC were to increase, this overpressure could drive a radiative shock into the cloud, thus triggering the onset of a starburst.

Jog & Das consider a galaxy with pre-encounter interstellar gas (ISM) parameters as in our Galaxy. Then the evolution of the multi-component ISM is studied as the galaxy undergoes an encounter. A galaxy interaction causes gas clouds from the disk to tumble into the central region (Section 2.4). Further, recent observations by Bally *et al.* (1987, 1988) have shown the existence of a fairly uniform molecular, intercloud medium (ICM) in the central 1 kpc of our Galaxy. Jog & Das note that the average pressure in this central ICM is greater by a factor of 30 compared to the effective turbulent pressure (>> thermal pressure) within an incoming disk GMC. Therefore, as a pre-existing disk GMC tumbles into the central region following a galaxy interaction, it thus arrives in the pre-existing high-pressure central gas reservoir. The GMC is barely stable to begin with. The overpressure due to the central gas (the molecular intercloud medium) then causes a radiative shock compression of the outer shell of the GMC. The compression continues until the crossing time is larger than the growth time of gravitational instabilities in the shocked shell. This shocked shell then fragments and forms massive stars.

The resulting luminosity depends on the fraction of cloud mass compressed, the efficiency of star formation in the shocked gas, and the rate of gas infall from the disk to the central region. The resulting lower limits on L_{IR} ~ a few x $10^9 L_\odot$ and L_{IR}/M_{gas} ~ a few $L_\odot / M_\odot$ agree fairly well with the observed values for central starbursts in tidally interacting galaxies - see Jog & Das (1992). The evolved mergers of galaxies, where the graviational perturbations are strong, are expected to have higher central gas concentrations (Section 2.4). This is indeed observed to be the case (*e.g.*, Scoville *et al.* 1986). The mergers yield higher values of $L_{IR} \leq 10^{12} L_\odot$, and $L_{IR}/M_{gas} \leq 100\, L_\odot/M_\odot$ respectively, which agree with the observed values from the central regions of evolved mergers. This quantitative analysis was made possible because realistic, observed pre-encounter gas parameters as in our Galaxy were used. Future work must include even more detailed gas dynamics such as the effects of clumpy nature of the clouds (see Section 3.4.2).

The complementary case of early stages of mergers where the star formation occurs in situ in regions of overlap (as for example in Arp 244 or in Arp 299) can also be explained by the overpressure idea (Jog & Solomon 1992). Jog & Solomon (1992) consider a physical collision between two field spiral galaxies with pre-encounter, two-phase ISM in each galaxy as in our Galaxy. During a galaxy collision, the atomic hydrogen clouds from the two galaxies will collide while the GMCs, with their smaller volume filling factor, would not collide (except in the rare case of an edge-on collision). The overpressure in this case is thus provided by the remnants of collisions of atomic hydrogen clouds from the two galaxies. This is a dynamic problem and the duration of starburst is set by the galaxy disk crossing time ~ 4 x 10^7 years. Since the starbursts occur in regions of overlap, this model can thus explain the origin of the spatially extended starbursts covering several central kpc^2 as seen in colliding galaxies (Section 3.2). In particular, this model can naturally explain the origin of the starbursts in the overlapping disks as in Arp 299 (NGC 3690/ IC 694) - see Combes (1988), or in Arp 244 (NGC 4038/39) - see Stanford *et al.* (1990). Whether the IR emission from the central region or that from the extranuclear disk dominates depends on the geometry and the epoch of collision, and on the initial radial gas distribution. The resulting typical IR luminosity is ~ a few times $10^{11} L_\odot$, with the maximum upper limit of $10^{13} L_\odot$. The resulting value of L_{IR}/M_{gas} is typically ~ $20 L_\odot / M_\odot$. These results are in good agreement with observations for colliding galaxies. This model can also naturally explain the simultaneous presence of nearly normal CO luminosity and shocked H_2 gas observed in these galaxies - for the details of this and other results from this model, see Jog & Solomon (1992).

A fast collision expected between a pair of cluster galaxies would lead to a different evolution of the two-component intersteller medium (Valluri & Jog 1990). Following a fast collision, the colliding components from the two galaxies (i.e., the atomic hydrogen clouds) would loose their kinetic energy and will be left behind at the centre of mass of the system. Thus a fast collision would lead to a preferential removal of atomic hydrogen gas from the galaxies while leaving the molecular hydrogen gas unaffected, in agreement with observations (see Valluri & Jog 1990 for details). Thus a collision would not result in a luminous starburst in this case. This could be one reason why ultraluminous starbursts are not seen in clusters at the present epoch (Section 3.1; also Jog & Solomon 1992).

So far, the effectiveness of galaxy interactions in triggering starbursts has been highlighted. Note, however, that nearly 30% of interacting galaxies do not show starbursts (Bushouse 1986). Conversely, isolated, barred galaxies may show starbursts. In fact, most isolated starburst galaxies are barred (Hawarden *et al.* 1986). Thus a galaxy interaction is not always a necessary nor a sufficient condition for the onset of starburst. It is important to explain why this is so. Whether or not gas infall occurs in interacting galaxies depends on details of galaxy orbits and disk inclinations, and not all interactions lead to a large amount of gas infall (Mihos *et al.* 1991). Further, Jog & Das (1992) show that if the galaxy does not have a high pressure central gas reservoir to begin with, then despite gas infall due to a bar or an interaction, the galaxy would not display a starburst - as is the case in M33. Conversely, an isolated, barred galaxy such as IC 342 where the bar causes the gas inflow (*e.g.*, Section 2.4) may show a starburst if it has a high pressure central gas reservoir. Thus the parameters of the central, molecular intercloud medium are critical in determining whether or not a starburst will be triggered (Jog & Das 1992, also Section 3.4.2).

A non-starburst origin of the high IR luminosity starbursts starbursts has been proposed by Harwit *et al.* (1987), who claim that the IR emission comes from a direct collision between molecular clouds from the colliding galaxy pair. The main problem with this model is that it will only work for the rare case of an edge-on collision between galaxies (see the filling factor argument by Jog & Solomon 1992 described above). They also assume an extremely centrally concentrated gas which is not typical of a pre-encounter galaxy. Hence their model would require too high a collision rate between galaxies if it is to produce the observed percentage of IR-luminous galaxies.

3.4 *Current trends, and future work*

3.4.1 *Current trends*

The subject of starburst galaxies has reached a level of maturity now as clear from the detailed observational studies now under progress listed below. These will help clarify the theoretical picture better.

1. High resolution, interferometric mapping in CO, CS mm wave lines is being carried out to study the dynamics and chemistry of starburst galaxies. Such studies can also tell us about the geometry of interaction, and also can act as tests for starburst models. In Arp 244, for example, the CO emission is stronger in the region of disk overlap than in the nuclei (Standford *et al.* 1990). This can be explained naturally by the overpressure model for colliding galaxies by Jog & Solomon (1992).

2. Gas at large distances (~ 50 – 100 kpc) from the interacting galaxies, has been detected in optical emission lines (Heckman, Lehnert & Armus 1993); or as neutral atomic hydrogen gas (HI), or as ionized gas as traced by the H_α emission (Hibbard *et al.* 1993). This will allow a study of the SN/ISM interaction, and the relation between the inflow/outflow of gas and the central source.

3. Soft X-rays observations from ROSAT, and also radio studies to study the hotspots, will help us understand the contribution and evolution of massive stars.

4. Some related theory problems under study include the formation of elliptical galaxies (*e.g.* Barnes 1992), and bulges of spirals (Rich 1992), by mergers of spiral galaxies. The observations of evolved mergers such as NGC 2623 (=Arp 243), or Arp 220 do in fact show the $r^{1/4}$ de Vaucouleurs intensity profiles applicable for ellipticals (Wright *et al.* 1990). Thus the morphological evolution of even the 'normal' galaxies may have been affected by galaxy mergers in their past history.

3.4.2 *Future work*

Some of the theoretical problems in this topic are given below. Also see Sections 2.5 and 4.2 for related problems.

1. *Gas dynamics* : Future theoretical studies of starburst triggering and evolution must take account of details of gas dynamics, and should include a study of shocks in clumpy clouds (Section 3.3), and a hydrodynamic treatment of cloud collisions with radiative losses, and so on.

2. *Central gas properties* : The central molecular intercloud medium (ICM) appears to be a fairly general feature of spiral galaxies, as shown from the high spatial resolution studies of our Galaxy (Bally *et al.* 1988), and M33 (Wilson & Scoville 1990). The existence of ICM can be deduced from lower resolution observations in a number of galaxies (Solomon & Sage 1988; Aalto *et al.* 1993). The pressure of this component is crucially important in determining whether or not a galaxy interaction results in a starburst (see Section 3.3, also see Jog & Das 1992 for details). The energetics and evolution of the ICM need to be studied carefully.

Thus, the subject of starbursts has relevance for a number of fields such as the chemical and dynamical evolution of the ISM, and the IGM, the morphological evolution of the galaxies, and also evolution of startbursts into AGN, as mentioned in Section 3.1. The last point will be addressed in detail in the next Section.

4. The starburst – AGN connection

In this section, a simple unified model of AGN is assumed, that is, a central non-stellar source, i.e. a central black hole powered by accretion (Section 2.1). There are at least three possible causal connections between starbursts and AGN. These are:

1. *Starbursts evolving to AGN (i.e., Starbursts as progenitors of AGN)*: There is clear evidence for this case, and I will mainly concentrate on this in the rest of this Section.

2. *AGN triggering starbursts in the host galaxy* : It is often hard to separate out this case from case 1. Surprisingly, there is clearer evidence for starbursts triggered in the host galaxy by the AGN jets for the high redshift systems as seen from the alignment of their (continuum) radio and (line-emission) optical axes. (*e.g.*, MaCarthy *et al.* 1987; Chambers, Miley, & Van Breugel 1987). It is possible that galactic parameters such as the gas contents or the galactic environment are different early on (Rees 1989), which allow this connection to be established. Note, however, that recent observations in the near-IR (K-band) – which corresponds to the optical regime at the redshifts considered – show a less strong alignment (Rigler et al. 1992). This means that the starburst affects only a small fraction of the galaxy mass and not a large fraction as was implied by earlier observations.

3. *Startbursts mimicing AGN* : This is an alternative to the standard model. Here the central starburst with hot, 'bare-core Wolf-Rayet stars' is said to explain all the observed properties of an AGN (Terlevich & Melnick 1985). This is known as the 'warmers' model and is mentioned here for the sake of completeness. The main problems with this model are that it cannot explain the observed fast variability in X-rays, or the optical emission line ratios which are indicative of non-thermal emission, or the luminosity of the most luminous quasars (Osterbrock 1991; Heckman 1992).

Perry (1992) and collaborators have considered models which need both starburst and AGN to match the observations.

4.1 *Central starbursts as progenitors of AGN*

This is the case 1 mentioned above and will be discussed in detail next. Such a causal connection is expected because, first, both the phenomena are centrally concentrated in a galaxy – although the AGN phenomenon is much more centrally concentrated than the starbursts. Second, both phenomena are seen more often in interacting galaxies. Galaxy interactions could either fuel a pre-existing black hole, or lead to a central starburst which could then evolve into an AGN.

Weedman (1983) was the first to propose this causal connection although in retrospect it now seems obvious. He proposed that if a large number of massive stars form fast, in a small central volume - then the compact stellar remnants from these could act as accretors. These remnants could evolve via dynamical friction, and settle into a small nuclear volume. Thus the nuclear region would evolve to be an AGN, with a net luminosity as in a Seyfert 1 galaxy. All the above initial conditions required for the evolution of a central starburst to an AGN are satisfied in a typical starburst since they have a high SFR and a high SFE and show a preferential formation of massive stars (see Section 3).

Weedman further argued that the timescale required for dynamical equilibrium of the stellar remnants is smaller than the duration of starburst, hence starbursts and AGN may be seen simultaneously in some cases. There is clear observational evidence for such composite nuclei in some galaxies. The nearby Seyfert NGC 1097 can be optically resolved into a central AGN nucleus and an extended 3 kpc diameter central ring showing starburst activity (Keel 1985). The host galaxies of QSO's, such as 3C 48, also show evidence for starbursts as evident from their distorted morphology and unusual colours (Stockton 1990). However, it is not clear from the studies of these composite nuclei whether there is a serious causal connection between the starburst and the AGN phenomena or whether there is merely an overlap of these phenomena. In the latter alternative, the two phenomena may show correlations simply because both could be fuelled by the same processes - namely galaxy interactions or central bars.

It is useful at this point to briefly review the main observational diagnostics/characteristics used to distinguish between the starburst and the AGN components. Some of these have already been discussed in Sections 3 and 2 respectively. These features are as follows: (1) A starburst has a steep, black-body spectrum whereas an AGN has a flatter continuum spectrum indicating the higher percentage of energy emitted at the higher frequencies in an AGN (*e.g.*, Netzer 1990). (2) The optical emission lines, including the H_α line, are narrower for the starburst case with the FWHM ($\leq$ a few 100 km s^{-1}), while their width is much larger ($\geq$ 500 km s^{-1}) for the AGN. There is a large variation in this parameter depending on the type of AGN (Seyfert 1, QSO etc), and the region within each case (*e.g.*, the narrow line region or the broad line region) – see *e.g.*, Netzer (1990). (3) The best separation between the starburst and the AGN as sources is provided by the diagnostic diagrams made from the line ratios for the various optical emission lines – see Osterbrock (1989) for details. For example, consider the diagram of ([OIII] λ5007) / ($H\beta$ λ4861) versus ([OI] λ6300) / (H_α λ6563) – see Fig. 12.2 from Osterbrock (1989). In this diagram, the AGN occupy the upper right region while the starbursts or HII regions occupy the lower left region. Physically, the first ratio represents the mean level of ionization and temperature, while the second ratio indicates the relative importance of a large partially ionized zone produced by high energy photoionization. Hence this second ratio has a higher value for a harder spectrum observed in an AGN. This explains the relative location of the AGN with respect to the starburst galaxies in these diagrams. (4) The starbursts show steep radio spectra due to the supernova remnants in them, and are spatially extended over the central ~ 1 kpc region. The AGN, on the other hand, show flatter radio spectra and have very small spatial dimensions - as small as ~ 1 pc (Condon 1992) or are even unresolved. (5) The gas content, and the ratio L_{IR}/M_{gas} is high in starburst galaxies (see Section 3.2), and is even higher in AGN.

A clear evidence for starbursts as being precursors to AGN has been obtained by the classic study by Sanders *et al.* (1988). Sanders *et al.* studied a sample of 10 ultraluminous galaxies detected from IRAS. These are the most luminous of all the known IR-bright galaxies. The limiting luminosity for this sample was chosen to be $10^{12}L_\odot$ since this is the limiting (optical) bolometric luminosity of QSO's and since the authors wanted to see if there was any connection between starbursts and AGN. They systematically studied a number of diagnostics for physical parameters that would distinguish between a starburst and an AGN as the main power source - namely, the slope of the continuum spectrum, the optical emission line ratios, the linewidth for the H_α line, the IR luminosity to the gas mass ratio L_{IR}/M_{gas}, and the infrared excess L_{IR}/L_B.

Based on the above diagnostics, Sanders et al. (1988) found that 90% of their sample of ultraluminous galaxies showed clear evidence for an AGN (a Seyfert) as being the dominant power source. They also showed that as L_{IR} increases, these properties show a smooth progression from starburst-dominance to AGN-dominance-in terms of the strength of these properties and also the percentage of galaxies showing these properties. Also, the percentage of interacting galaxies increases with increasing L_{IR}.

Sanders *et al.* conclude that these ultraluminous galaxies represent a stage in the evolution of merging galaxies where the AGN (a Seyfert) is the dominant energy source, which was presumably formed and/or fed by the strong galaxy interactions. This result has now been extended for a distant, larger sample covering a redshift range up to $z \leq 0.3$ (see Sanders 1992 for details). However, these have not yet been mapped in detail to check if most of them are indeed interacting galaxies.

Sanders *et al.* (1988) further claim the ultraluminous galaxies to be dust-enshrouded or buried QSO's (in early stages of formation) with L_{IR} values ~ the total luminosity values seen in the optical in typical QSO's. They outline a simple picture of the evolution from an ultraluminous starburst to an AGN. A galaxy interaction is assumed to lead to gas infall followed by a central starburst. The supernova explosions resulting from the starburst, the stellar winds, and the radiation pressure from the AGN are claimed to remove the dust shroud- and the host galaxy then appears as a standard UV/optical dominated QSO. However, their model does not give energetics of the dust heating or removal, nor the effects of dust on the spectrum from an AGN. Further, gas could also be removed via the same processes (Chevalier & Clegg 1985) - see Section 4.2.

This picture of a starburst evolving into a QSO is explored in more detail by Norman & Scoville (1988). They assume that a galaxy interaction leads to the formation of a dense central star cluster of ~ 4 x $10^9 M_\odot$ in the central 10-50 pc. The stellar outflows from this feed the AGN. The radiation pressure from the AGN ionizes the stellar mass-loss envelopes which thus produce the BLR (broad line region) features as seen in QSO's. However, the central starburst is typically seen over the central 1 kpc, and not 10 pc as they assume (Frank 1990). Also, the rate of mass loss from stars is high and replenishing the supply of stars may be a problem (Osterbrock 1991).

4.2 *Future work*

Thus, the evolution of a starburst into a full-fledged AGN still remains an *open problem.* A self-consistent solution to this problem is complex, one reason being that the overall AGN phenomenon is not fully understood. However, there are a number of well-defined, challenging theoretical problems in this area that need to be done. In addition to the gas infall problems listed in Section 2.5, and the detailed gas dynamics problems in Section 3.4, these include:

1. *Feedback from the central starburst/AGN on the host galaxy* : Supernovae resulting from a starburst can set up a wind in the surrounding host galaxy with a wind velocity of ~1000 kms^{-1}, which can clear a hole of radius few 100 pc (Chevalier & Clegg 1985; Chevalier 1992). These superwinds have now been observed. Thus the fuelling of a starburst/AGN in presence of an interaction or a bar is a self-supporting and in the end also a self-limiting process. A very high star formation rate would lead to a fast removal of a large amount of the central gas via winds. The question then is whether one can have fuelling despite the disruptive feedback from the central region? The infall models so far have not taken account of this effect. The disk/halo connection for the ISM in a galaxy should also be taken into account while considering evolution of these superwinds.

The effect of AGN on the host galaxy is even more important given its energetic output over a large range of wavelengths. For example, Begelman (1988) has studied the effects of X-rays from a Seyfert on the ISM of the host galaxy.

The point is, what you see in an AGN is after all a net effect of fuelling via gas inflow, and the AGN outflow and its effect on the host galaxy. Hence unless the effect of the AGN outflow on the host galaxy is understood clearly, it would be hard to check if the starburst → AGN connection is indeed valid.

2. *Evolution of the central star cluster* : The dynamical evolution of the compact stellar remnants from the central starburst (Weedman 1983), possibly with the formation of the central massive black hole, has to be worked out in detail.

3. *Timescales* : What are the relative timescales for starbursts, AGN, and galaxy interactions? How do these affect the statistics of the fraction of starburst galaxies observed to be showing an AGN component? This chain of questions needs to be answered.

4. *Future observations* : Future high resolutions (*e.g.* by the Hubble Space Telescope) will yield the velocity dispersions in the central regions. This will allow us to distinguish between the starbursts from the AGN since the dispersions would be much higher in the deeper potential wells expected in the standard model of an AGN. Recent CO observations of QSOs (Alloin *et al.* 1992) allow us to check the availability of molecular gas fuel in these systems. Near-IR observations for high redshift objects will provide additional information on the evolution of galaxy morphology with redshift.

5. Implications for high redshifts

The above discussion on the starburst → AGN connection has important implications for high redshift galaxies. Both the phenomena are expected to be more frequent and more luminous early on. This is because the number density of galaxies is expected to increase with redshift, and the galaxies are expected to be more gas-rich early on. Hence both the frequency and the effectiveness of encounters are believed to be higher early on. This can naturally explain the observed evolution of the quasar luminosity function as argued next. The comoving cumulative number density of quasars and QSO's (radio-quiet quasars) above a certain limiting luminosity is called the 'quasar luminosity function' (*e.g.*, Weedman 1986).

It is well known that the quasar luminosity function rises dramatically with the redshift z and peaks at $z \sim 2$ and falls beyond that - see Schmidt (1989). This evolution of the quasar luminosity function with z, and in particular its fall-off beyond $z \geq 2$ is not a purely observational selection effect. If anything, the typical absolute luminosity of a QSO increases with z (Warren & Peacock 1990). This implies that either most quasars formed at higher redshifts (and were short-lived) or that they were more bright at higher redshifts. The evolution of the quasar luminosity function can be well explained qualitatively by the interaction/merger picture. It could be a pure luminosity evolution due to the higher fuelling rate likely at high z due to the galaxies being gas-rich then. Or it could be explained as a combination of luminosity and number evolution - since the frequency of encounters is expected to be higher early on as explained above. The decrease in numbers at $z > 2$ is taken to imply that galaxy formation occurred at around $z = 2$ or just before that (Schmidt 1989).

Several models have been proposed to explore this idea (*e.g.,* Roos 1985; Carlberg 1990). However, these have too many parameters by necessity and hence do not give a unique scenario. Apart from all the problems associated with the gas infall problem, here there are additional uncertainties, such as the epoch of galaxy formation, the number and duration of starbursts. Most importantly, the structure of galaxies at high redshifts is a big unknown. In this context, the recent near-infrared photomoetry work for high redshift galaxies is very important. At the high redshifts of 2-3, this corresponds to the rest-frame optical wavelengths. Hence the near-IR photometry of these (nearly dust-free) galaxies will give information on the underlying structure of high redshift galaxies, which will act as important constraints for these models.

At the end it is worth mentioning the recent discovery of an interesting, distant object, IRAS 10214 + 4724, which is at a redshift of $z = 2.286$ (Rowan-Robinson *et al.* 1991). This has an extremely high IR luminosity, $L_{IR} = 3 \times 10^{14} L_{\odot}$, similar to the values for the most luminous (radio-loud) quasars known (see Section 2.1). It has a high molecular hydrogen gas mass content of $M_{gas} \sim 2 - 6 \times 10^{11} M_{\odot}$. Thus it is a system with the highest value of $L_{IR}/M_{gas} \sim 10^3 / L_{\odot} / M_{\odot}$ known so far. An AGN component has been deduced from the large width of the H_{α} emission. Due to its large gas content, it has been termed a 'primeval molecular galaxy', undergoing a burst of star formation (Solomon, Radford & Downes 1992). Yet it has a normal dust to gas ratio implying that at $z = 2.286$ it has already undergone a substantial formation of heavy elements. Thus, it is an extremely intriguing object, and it raises the question of what is the relation between starbursts, AGN, and galaxy formation and evolution. It is not yet known if this is a one-of-a kind object or is a typical example.

6. Discussion

A number of open problems have been listed at the end of Sections 2, 3 and 4. In addition, there are a number of related, and interesting topics which are not covered above, due to lack of space and also because the current understanding on them is fairly hazy. These include:

1. How do evolved starbursts appear? The ultraluminous galaxies have been found to evolve to AGN (Sanders *et al.* 1988). The evolved merging starbursts are found to have a $r^{1/4}$ de Vaucoulers intensity profile as in ellipticals. How do the lower luminosity starbursts appear as they evolve? This has been addressed by various authors (*e.g.,* Norman 1992); and there is no clear answer yet to this question.

2. Where are the dead quasars? Are they now dormant because of lack of fuel? Rees (1990) has addressed these questions, and shown that the recent discovery of black holes in the centres of nearby galaxies can tell us about the demography of quasars including their mean lifetimes etc.

3. What is the connections between an AGN and the centre of our Galaxy? Although the galactic centre is a dynamic region compared to the rest of our Galaxy, it is a very weak emitter

of IR radiation. From the central gas motions, the galactic centre is estimated to have a small central (black hole) mass of $\leq 3 \times 10^7 M_\odot$ (Rees 1990). Thus the galactic centre at present cannot be termed either a starburst or an AGN–even a weak AGN such as a liner.

Clearly, all these problems are not independent, and a better understanding on one of these may help shed light on the others as well.

Thus the fields of starbursts and AGN both promise to remain active and challenging for quite some time. Hopefully, the starburst–AGN connection, and the role played by galaxy interactions in this connection, will become clearer in the next few years.

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