*The Starburst–AGN Connection*
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# The Extreme Nuclear Environments of Sgr $A^*$ and Arp 220

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**Abstract.** The dense ISM which is the fuel for both nuclear starbursts is believed to be accreted to the nucleus by stellar bars and galactic interactions. In this contribution, I summarize the observational results for two galactic nuclei at the extreme ends of starburst/AGN activity – our own Galactic nucleus with SgrA$^*$ and the ULIRG Arp 220. I discuss theoretical considerations for the properties of the ISM – it's density and scale height, whether it is likely to clump into gravitational bound GMCs – and the self-regulation of SB and AGN fueling due to radiation pressure support of the ISM. The latter yields an Eddington-like limit on the activity for both SB and AGN, corresponding to approximately 500 $L_\odot$ /$M_\odot$for optically thick regions in which the radiation has been degraded to the NIR.

## 1. Introduction

Interaction and merging play a fundamental role in the evolution of galaxies – producing the most luminous starburst galaxies and very likely luminous AGN. The dynamical effects of the interactions are most dramatic in the ISM since it is dissipative and has high filling factors. The torques and increased velocity dispersions due to the galactic encounters lead to rapid transport of the dense molecular ISM to the nuclear regions and high rates of cloud-cloud collisions. In many of the ultra-luminous IR galaxies, over $10^9$ $M_\odot$of $H_2$ gas is found at radii $<<$ 500 pc (comparable with the Galactic ISM mass, but within an area 50 times smaller). Within the central region, it now appears this gas dissipatively settles into a thin disk. These ultra-massive nuclear gas disks are presumably the sites of the nuclear starburst activity which may be regulated by a balance of self-gravity and radiation pressure support.

It is natural to think of evolutionary connections between starbursts and AGN in the sense of an ageing starburst leading to a luminous, optical AGN once the interstellar matter is dispersed or used up. In the following, I summarize some cogent characteristics of the nuclear regions of two extreme cases – Sgr A$^*$ and Arp 220 and follow by a discussion of the ISM properties in these galaxies.

## 2. Sgr A$^*$ – an Extraordinary ISM

Given the very limited spatial resolution of observations of distant AGN, it is most instructive and cautionary to look at the properties of the ISM in our own Galactic nucleus. The massive black hole in Sgr A$^*$ has a mass of $4\times10^6 M_\odot$as derived from the motions of stars within the central 1 pc (Genzel 2006, Ghez et al. 2008). A circumnuclear disk (CND) at radii out to $\sim$ 3 pc contain both ionized and dense molecular gas. Fig. 1 shows the ionized gas as probed in the

HI P$\alpha$ line at 1.87$\mu$m (false color, Scoville et al. 2001) in a structure termed the mini-spiral and the dense molecular gas as probed in the 3mm HCN line (contours; Christopher et al. 2004) in a clumpy ring at $1-3$ pc radius. The ionized gas in the min-spiral may be infalling or outflowing while that at the edge of the disk (the southeastern arm) probably originates from photoionization of the inner edge of the rotating molecular cloud ring.

The total mass of the molecular gas within 3 pc of the blackhole is variously estimated at $1-5\times10^5 M_\odot$and has an orbital time $\sim 10^5$ yrs. Given that the blackhole is only $\sim$ 10 times more massive it is clear that very little of the nearby ISM will actually make it to the blackhole, unless we are viewing an extremely atypical epoch in SgrA$^*$ and certainly the ISM is not being accreted on an orbital timescale (the luminosity of SgrA$^*$ is $< 10^6 L_\odot$ ).

It is clear that our intuition about the properties of the ISM in the disk of our galaxy should not necessarily be applied to the ISM in the inner nucleus. The molecular gas clumps in the CND have extraordinary properties! Their sizes are < 1 pc but densities $10^{7-8}$ cm$^{-3}$ (Christopher et al. 2004). (By contrast, a typical Galactic $10^5 M_\odot$GMC has a diameter 40 pc and mean density 300 cm$^{-3}$ (Scoville & Sanders 1978)) The higher densities are required if the clumps are to be self-graviating and stable against tidal disruption at their distance from the central point mass. If the dust-to-gas ratio in the clumps is similar to the standard Galactic value, then the inferred column densities of $10^{25}$ cm$^{-2}$ imply an extinction of $A_V \sim 10^4$ mag. Since the molecular ring/torrus is clearly not appearing edge-on, it is reasonable to believe that it resulted from the accretion event of a single cloud rather than smooth accretion over time from the larger nuclear disk. If such a cloud arrived at the point where it was tidally disrupted with a non-zero z height the resulting fragments might end up as clumps in an orbital plane inclined relative to the Galactic plane, as is observed for the CND.

At present there is no evidence of star formation within the molecular clumps despite their very high densities and internal dynamical timescales $\sim 10^4$ yrs. However, the very high extinctions suggested above would preclude detection of embedded young stars and the only means of detecting them might be via radio detection of ultra-compact HII regions or maser emission. The unusually high densities of the molecular clumps must reflect the fact that at lower density they would not be tidally stable and therefore would exist for long (see Sec 6).

## 3. Arp 220 – A 'Prototypical' ULIRG

Mm-wave imaging provides a unique capability to probe the starbursts in dusty ULIRG nuclei. More than 20 luminous ($\geq 10^{11} L_\odot$) infrared galaxies have now been imaged, primarily at OVRO and IRAM (Scoville, Yun & Bryant 1997, Downes & Solomon 1998, Bryant & Scoville 1999, Tacconi et al. 1999). Virtually all display massive concentrations of molecular gas in the central few kpc.

Arp 220, at 77 Mpc, is one of the nearest and the best known ultra-luminous merging systems ($L_{8-1000\mu m}$ =1.5 $\times$ $10^{12}$ $L_\odot$). Visual wavelength images reveal two faint tidal tails, indicating a recent tidal interaction (Joseph & Wright 1985), and high resolution ground-based radio and near-infrared imaging show a double nucleus (Baan & Haschick 1995, Graham et al. 1990). The radio nuclei are separated by 0.″98 at P.A. $\sim$90° (Baan & Haschick 1995), corresponding to 350

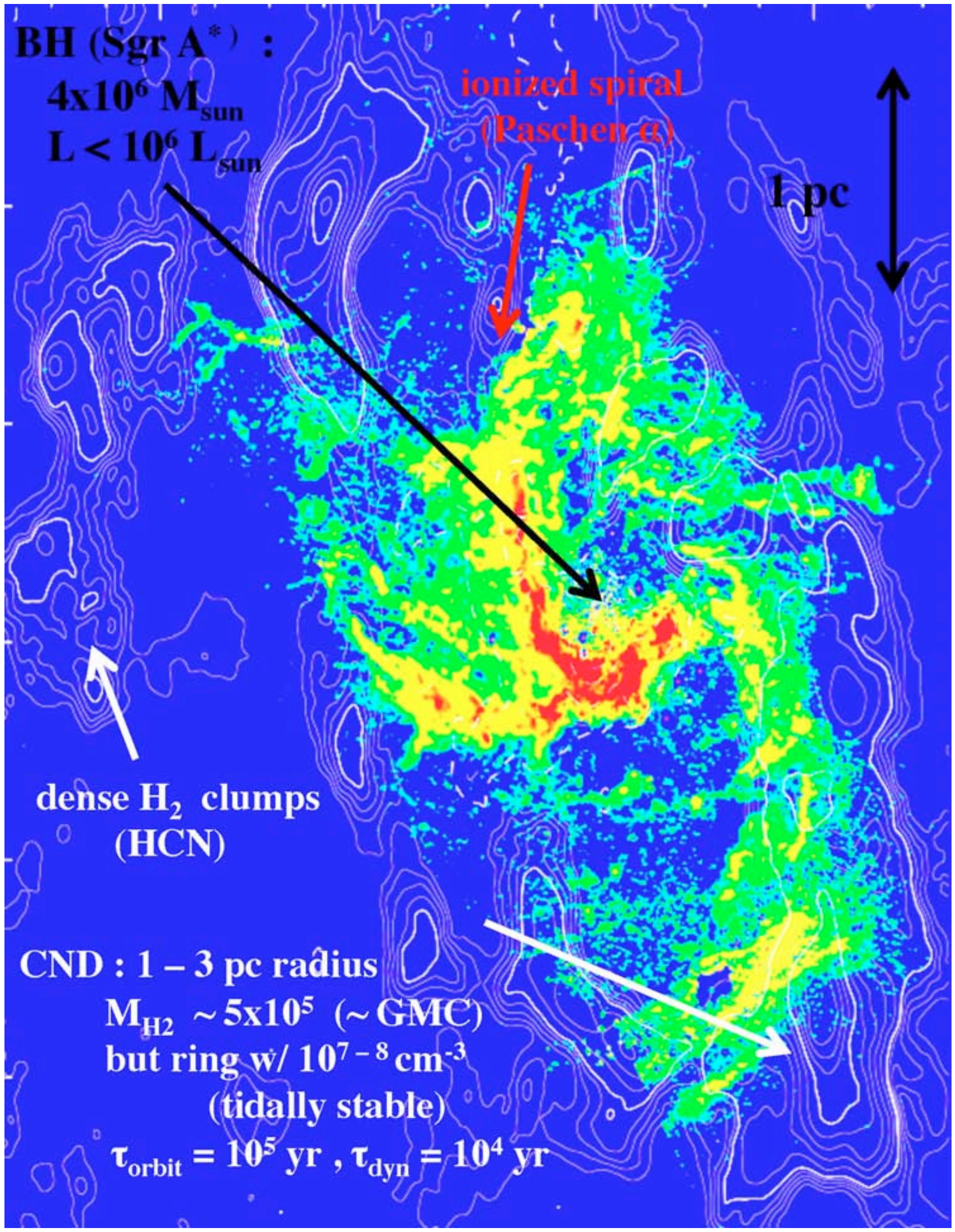


Figure 1. The circumnuclear disk (CND) in the Galactic nucleus disk in ionized gas (false color) imaged in the HI P$\alpha$ line at 1.87$\mu$m and the dense molecular gas (contours) probed by HCN emission (Christopher et al. 2004). The ionized gas is seen in a spiral pattern and from the inner surfaces of the neutral molecular clumps. The densities in the molecular gas are $\sim 10^7$ cm$^{-3}$ and the clumps are orbiting at 1-3 pc radius.

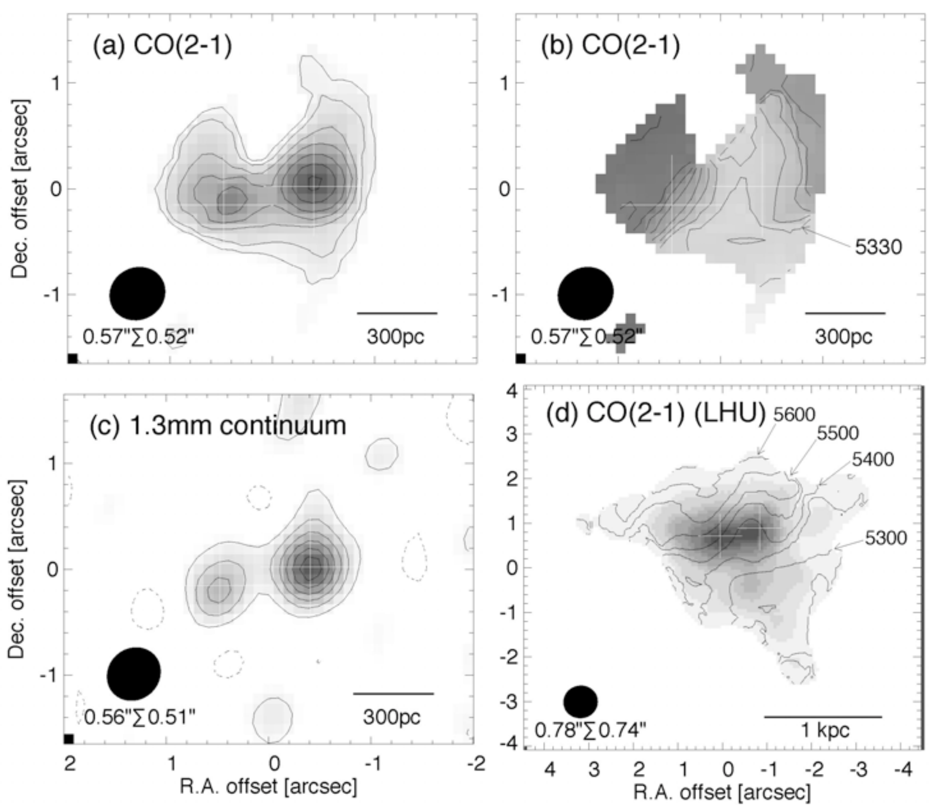


Figure 2. The merging nuclei of Arp 220 are shown in 0.5″resolution imaging of the CO(2–1) and dust continuum emission (Sakamoto etal 1999). These data clearly resolve the two nuclei and reveal for the first time counter-rotating disks in each nucleus. The panels show : a) continuum-subtracted CO(2–1) (using only high resolution data), b) the CO mean velocities, c) the 1.3 mm dust continnum, and d) the total CO emission including both low and high resolution interferometry. Crosses indicate the 1.3 mm continuum positions of the nuclei.

pc. To power the energy output seen in the infrared by young stars requires a star formation rate of $\sim 10^2$ $M_\odot$ $yr^{-1}$. Arp 220 has been the subject of a number of OVRO and IRAM interferometer studies imaging in the 2.6 mm CO line (Scoville, Sargent & Sanders 1991), 3 mm HCN (Radford et al. 1991), and 1.3 mm CO (Scoville, Yun, & Bryant 1997, Downes & Solomon 1998, Sakamoto et al. 1999). The CO (2–1) line emission, mapped at $1''$ resolution, showed two peaks separated by $0.9''$, and an inclined disk of molecular gas (Scoville, Yun, & Bryant 1997, Downes & Solomon 1998). These peaks correspond well with the double nuclei seen in near-infrared and radio continuum images. The $0.5''$ resolution CO and 1.3 mm continuum maps obtained by Sakamoto et al. (1999) using OVRO are displayed in Fig. 2. These reveal **counter-rotating** disks of gas in each of the nuclei. The kinematic data clearly require very high mass concentrations in each nucleus, consistent with their being individual galactic nuclei. The fact that they are counter-rotating is consistent with the concept that more complete merging may be associated with counter-rotating precursor galaxies in which there can be greater angular momentum cancellation. The masses in each nucleus are apparently dominated by the molecular gas – a common finding of the ULIG galaxy studies (Bryant & Scoville 1999).

The western nucleus in Arp 220 exhibits hard x-ray emission and very high velocity CO emission. The inner dust emission source seen at $\lambda \sim 1$ is extremely compact with $10^9$ $M_\odot$within R $<$ 35pc (Downes & Eckart 2007). Downes & Eckart also argue that the inferred dust temperature of $\sim$ 175K implies a higher radiation energy density for its heating than could be provided by a compact starburst and therefore that this nucelus might harbor a luminous and massive blackhole.

## 4. AGN – Starburst : Observational Connections

Evidence has also accumulated for an evolutionary link between merging ultraluminous IR galaxies and UV/optical QSOs as suggested by Sanders et al. (1988) : similar local space densities for ULIRGs and QSOs; continuity of FIR SEDs smoothly transitioning between the two classes (Sanders et al. 1988 & Neugebauer et al. 1986); the occurrence of AGN-like emission lines (Veilleux et al. 1999) and significant point-like nuclei (less than 0.2 $''$ – Scoville et al. 2000) in 30-40% of the ULIRGs ; and the association of both ULIRGs and some QSOs (MacKenty & Stockton 1984, Bahcal et al. 1997) with galactic interactions. Whether the entire QSO population had precursor ULIRGs (implying that galactic merging is the predominant formation mechanism for AGNs) is not yet settled. Two possible scenarios linking the ULIRG and AGN phenomena are : 1) that the abundant ISM which fuels the starburst also feeds the central black hole accretion disk; or 2) the post starburst stellar population evolves rapidly with a high rate of mass-return to the ISM in the galactic nucleus – leading to sustained fueling of the black hole (e.g. Norman & Scoville 1988).

## 5. AGN – Starburst : Theoretical Considerations

The largest potential sources of fuel for active galactic nuclei (AGNs) are the nuclear interstellar medium (until it has been cleared out) and the mass-loss stars in the galactic nucleus. Commonly, most discussion recently has focussed on the former sources; so in this section, I would like to emphasize the latter possibility. For a galactic nucleus with mass $10^9 M_\odot$ situated at the center of the stars in a nuclear starburst cluster, approximately 20% of the initial stellar mass will be lost via red giant mass-loss winds within the first $2 \times 10^8$ years (Norman and Scoville 1988). In two papers (Scoville and Norman 1988, Scoville and Norman 1995), we have examined critically the fate of this mass-loss material – specifically to account for both the broad emission lines and the broad absorption lines seen in AGNs.

The physics of the dust shed by the stars in their stellar winds, particularly its evaporation, is critical to determining whether the mass-loss material accretes inwards to an accretion disk or is blown outwards by radiation pressure. This consideration leads naturally to a division of the central cluster environment into an inner zone (at $\leq$1 pc) where the dust is evaporated and the gas falls inwards and an outer zone (r $\geq$ 1 pc) where the dust (and gas) survives and is driven outwards at high velocity by radiation pressure.

For standard grain opacities, the equilibrium temperature of the grains is given by (cf. Scoville and Norman 1995)

$$T_D(r) = 1800 \left( \left( \frac{L_{UV}}{5 \times 10^{12} L_\odot} \right) \left( \frac{1}{r_{pc}} \right)^2 \right)^{\frac{1}{5.6}} \text{ K.} \quad (1)$$

If the grains sublimate at 1800 K, then the closest distance for grain survival is

$$r_0 = \left( \frac{L_{UV}}{5 \times 10^{12} L_\odot} \right)^{\frac{1}{2}} \text{ pc,} \quad (2)$$

It is interesting to note that the density required for tidal stability of a broad emission line cloud at 1 pc radius requires that such clouds must have extremely high internal densities – perhaps arguing for a stellar origin rather than interstellar. At 1 pc from a $10^9$ $M_\odot$black hole, the Roche limit density is $3\times10^{11}$ cm$^{-3}$.

## 6. Physical Considerations Regarding the Nuclear ISM

For both Sgr A and Arp 220 which have luminosities differing by over $10^6$, the accreton rates (suggested by both the blackhole masses divided by the Hubble time and by the observed luminosities) are order of magnitude less than the mass of nearby ISM divided by their respective orbital timescales. For the Sgr A$^*$ and Arp 220, $M_{ISM}/\tau_{orbit}$= few $M_\odot$per yr and $10^4$ $M_\odot$per yr, respectively. Thus it is apparent that : either the fraction of material actually accreted is very small or the accretion timescale is $\sim 10^4$ orbital periods.

One very effective means of restricting the accretion (or even ejecting the dense ISM) is via the radiation pressure of the AGN acting on the associated dust. For a self-gravitating gas and dust mass, the effective 'Eddington' limit is approximately 500 $L_\odot$ /$M_\odot$, similar to the overall mass-to-light ratio measured in the Arp 220 nucleus ($10^{12} L_\odot$ / $3 \times 10^9 M_\odot$. For higher luminosity to mass ratios, the ISM is blown out of the region.

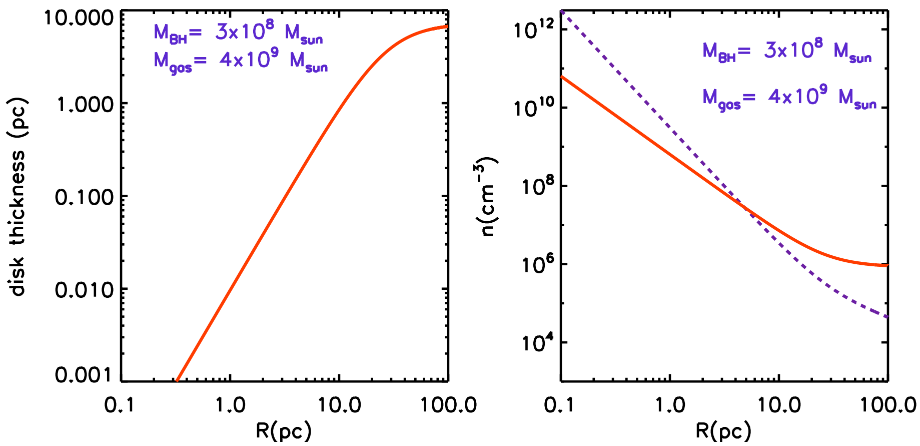


Figure 3. A very crude model for the disk in gas-rich merging systems like Arp 220 is shown. We assume a central point mass (blackhole) and a uniform gas surface density disk extending to 100 pc radius. The turbulent velocity dispersion within the disk is taken to be 50 km/s (based on Arp 220; Scoville et al 1997). The disk thickness as a function of radius for hydrostatic equilibrium is shown in the right panel and the mean gas density in the left panel (solid red line). The critical density required for stability of a self-gravitating object (e.g. a cloud) in the disk is shown by the dashed (blue) curve. The right panel shows the extraordinarily high gas densities expected for these very simple assumptions and underscores the fact that self-graviating clouds should not form in the inner disk due to tidal disruption.

A similar 'Eddington' limit applies for dust embedded starburst regions – the only difference being that the luminosity is from OB stars rather than blackhole accretion (see Scoville 2002, 2003, Murray et al 2005, Thompson et al 2005). It turns out that much larger scale nuclear starburst such as that in Arp 220 have approximately the same empirical limit of 500 $L_{\odot}$ / $M_{\odot}$, suggesting that nuclear starburst activity may also be regulated by a balance of self-gravity and radiation pressure support.

## 7. Considerations for Nuclear Starburst Disks

As a first step, toward understanding the massive gas disks like that seen in Arp 220, we consider an extremely simple model with uniform gas surface density out to radius 100 pc. A the center of the disk, we imagine a point mass of $4\times10^8$ $M_{\odot}$– either a central blackhole or a nuclear star cluster. The disk is assumed to be self-gravitating and in hydrostatic equilibrium with a sound speed of 50 km/s, representative of the turbulent velocity dispersion measured in Arp 220. Although this is meant only as an illustrative, *gedanken*, experiment, it clearly shows that the conditions are inescapably different from those of star forming clouds in the Galactic disk.

In Figure 3, the disk thickness and mean gas densities are shown as a function of radius out to 100 pc. The thickness of the disk is typically less than

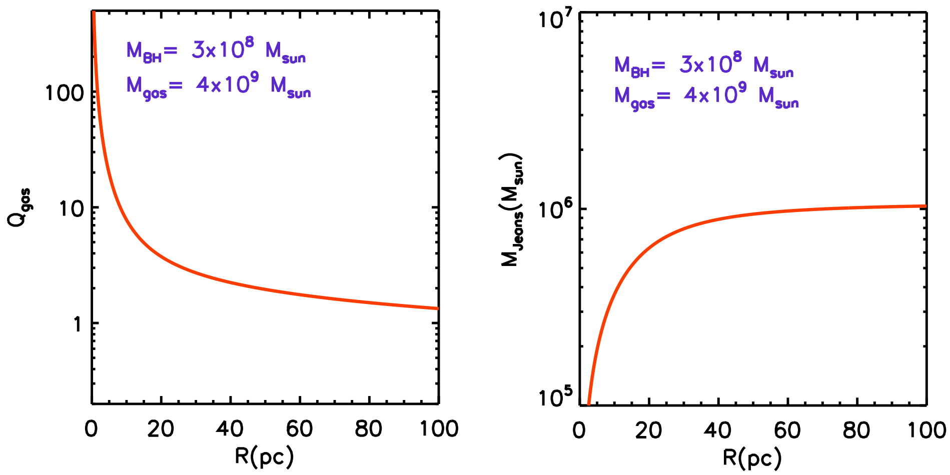


Figure 4. The left panel shows the Toomre Q stability parameter (Q < 1 unstable) for the disk parameters in the previous figure and the right panel shows the Jean mass for collapse/self-gravitation assuming a sound speed of 50 km/s and neglecting tidal shear.

10 pc and the mean densities are everywhere $> 10^6$, getting up to $10^{10}$ cm$^{-3}$ near the center. The right panel of Figure 3 also shows the gas density required for tidal stability (dashed line) – clearly demonstrating that it will be difficult to form stable clouds within the central 10 pc radius. Within this region, we should expect a more continuos gaseous disk structure, not a cloudy ISM as found in the center of our Galaxy.

The gravitational stability of the disk can also be seen from the Toomre Q parameter shown in Figure 4-left. Within the inner 10 pc, Q >> 1 and it is very hard to form self-gravitating structures in the ISM, such as clouds. On the other hand, outside 10 pc radius such clouds might form (if they are not disrupted by cloud collisions) but their masses are required to be very large, exceeding $10^6$ $M_\odot$.

## 8. Conclusions

In this contribution, I have tried to emphasize a number of considerations with respect to AGN and starbursts which I think are often overlooked. These include:

1) the very plausible links between starburst activity and fueling of AGN – specifically **both** the ISM and the mass-loss from the post starburst stars. The latter has the virtually of maintaining AGN fueling long after the ISM is cleared from the nucleus by the AGN.

2) the fact that dust in the neutral gas provide a much lower Eddington limit than the electron scattering assumed in the classical Eddington limit. This limit imposed by radiation pressure on dust may limit the highest levels of both starburst and AGN (se contribution by Thompson in this volume).

3) the fact that the ISM characteristics are inevitably very different from those of Galactic GMC which we know so well. Much higher densities are ex-

pected and in many cases it will also be difficult to form self-gravitating clouds. In the latter instance, we can expect a continuous disk-like structure for the dense ISM.

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