# Fueling Nuclear Star Clusters: Gas Dynamics in the Central 100pc

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**Abstract.** Our high resolution observations of the $^{12}$CO line emission in the central 300 pc of two late type galaxies IC 342 and NGC 6946 revealed the presence of abundant molecular material in the form of central gas disks with diameters of $\sim 30$ pc. These nuclear gas disks appear to coincide with star formation at the very center. Analysis of the gas kinematic in the nuclear gas disk of IC 342 finds evidence for non-circular motion. If interpreted as gas inflow to the center of IC342, crude estimates of the inflow rate are sufficiently high to replenish the fuel supply for future star formation events. We infer a gas inflow rate between 0.003 and 0.14 $M_\odot yr^{-1}$, based on the observed surface density of the nuclear gas disk and estimates of the radial velocities of the surrounding gas. Inflow rates of this order can support repetitive star formation events in the nucleus of IC 342 on timescales much smaller than a Hubble time. The distribution and kinematics of the CO(2-1) line emission in NGC6946 were recently mapped with the PdBI interferometer at 0.6" resolution. The observed molecular gas properties are in agreement with the inner 200pc long NIR bar feeding the ongoing nuclear star formation.

## INTRODUCTION

Recent observations with the Hubble Space Telescope (HST) at both optical and near-infrared wavelengths (e.g. Phillips et al.1996; Carollo, Stiavelli, & Mack 1998; Böker et al.1999; Matthews et al.1999) have revealed that a compact ($\sim$ few pc diameter), photometrically distinct star cluster is often present at the photocenter of spiral galaxies of all Hubble types. Surprisingly, most of the nuclear star clusters studied in detail so far turn out to be young: our Galaxy has a central stellar cluster of only $\sim 3$ Myr years (Krabbe et al.1995; Najarro et al.1997), and both M31 and M33 have blue nuclei that are very likely young star clusters (Lauer et al.1998). From ground-based spectroscopy, Böker et al.(2001) have recently measured a nuclear cluster age of $6-10$ Myr in NGC 4449. Clearly, these galaxies must recently have had significant inflow (of up to $10^8\,M_\odot$) of molecular gas into their central regions in order to trigger the formation of these young clusters.

To form a nuclear stellar cluster, which typically has a mass around $10^6\,M_\odot$, at least $10^7\,M_\odot$ of molecular gas must be available within the central few parsecs. As recently shown by Sakamoto et al. (1999) and Sheth et al. (2004), large-scale bars can efficiently move large quantities of molecular gas down to the inner kilo-parsec. However, as in the case of active galactic nuclei (AGN), the exact mechanism which can transport gas from a few 100 parsec down to a few parsec is still unclear. In numerical simulations (e.g. by Athanassoula 1992), the molecular gas often gathers in a stable configuration at the position of the inner Lindblad resonance (ILR) at a typical distance of a few 100 parsec (Buta & Crocker 1993). Recently, Englmaier & Shlosman (2000) and Maciejewski et al. (2002) showed that a density wave can exist inside the ILR which provides further inflow. However, the derived inflow rates are of the order of $(0.5-15)\times 10^{-2}\,\mathrm{M_\odot yr^{-1}}$ implying that it would take at least $\sim 10^8$ Myr to gather the necessary amount of gas for the formation of a massive nuclear cluster. In addition, the existence of a density wave also strongly depends on the sound speed and the shape of the ILR (Englmaier & Shlosman 2000, see also Maciejewski 2004a,b). Therefore, more observational data are needed to further constrain the numerical simulations.

We have embarked on a study of the molecular gas in the central few 100pc of the proto-typical late-type spirals IC342 and NGC6946 to investigate possible fueling mechanisms.

## OBSERVATIONS

The center of IC 342 was observed in the $^{12}\mathrm{CO}(2-1)$ line in January 2002 with the six-element Owens Valley Radio Observatory (OVRO) millimeter interferometer. Obtained in the L and H configurations with baselines between 15 and 115 m, the data have a spatial resolution of $\sim 1.2''$ (10 pc) with robust weighting. The noise per 2.601 $\mathrm{km\,s^{-1}}$ wide channel is 40 mJy per beam in the combined data of both tracks.

The $^{12}\mathrm{CO}(1-0)$ and $^{12}\mathrm{CO}(2-1)$ line emission from the central 500 pc in NGC 6946 were simultaneously observed using the IRAM Plateau de Bure interferometer (PdBI) in its AB configuration in early 2003. The achieved spatial resolution is 0.6” (1.2”) using uniform weighting for the $^{12}\mathrm{CO}(2-1)$ ($^{12}\mathrm{CO}(1-0)$) line with a spectral sampling of 5 km/s wide channels.

## RESULTS FOR IC 342

The central region of IC 342 has been mapped with intermediate resolution (2.5-4”) in several molecular lines such as the $^{12}$CO, $^{13}$CO, C$^{18}$O and HCN(1-0) transitions (e.g. Ishizuki et al. 1990, Turner, Hurt & Hudson 1993, Meier et al. 2000, 2001, Downes et al. 1992). The molecular gas ring of about 10” diameter is evident in all maps, and shows signs of strong streaming motions. Our recent 1.2” resolution observations of $^{12}$CO(2-1) revealed for the first time a 30 pc diameter molecular gas disk coinciding with the nuclear stellar cluster (Schinnerer, Böker & Meier 2003; see Fig.1). This disk connects via two faint CO bridges to the circumnuclear ring. Its gas kinematics show evidence for non-circular motion.

The nuclear star cluster in IC 342 has a mass of $6\times 10^6\,\mathrm{M_\odot}$ and experienced a major burst of star formation $\sim 60$ Myr ago (Böker et al. 1999). For the moment, we will assume that the most recent burst produced 30% of the cluster mass, i.e. about $2\times 10^6\,\mathrm{M_\odot}$. Assuming a star formation efficiency of 20%, about $10^7\,\mathrm{M_\odot}$ of molecular

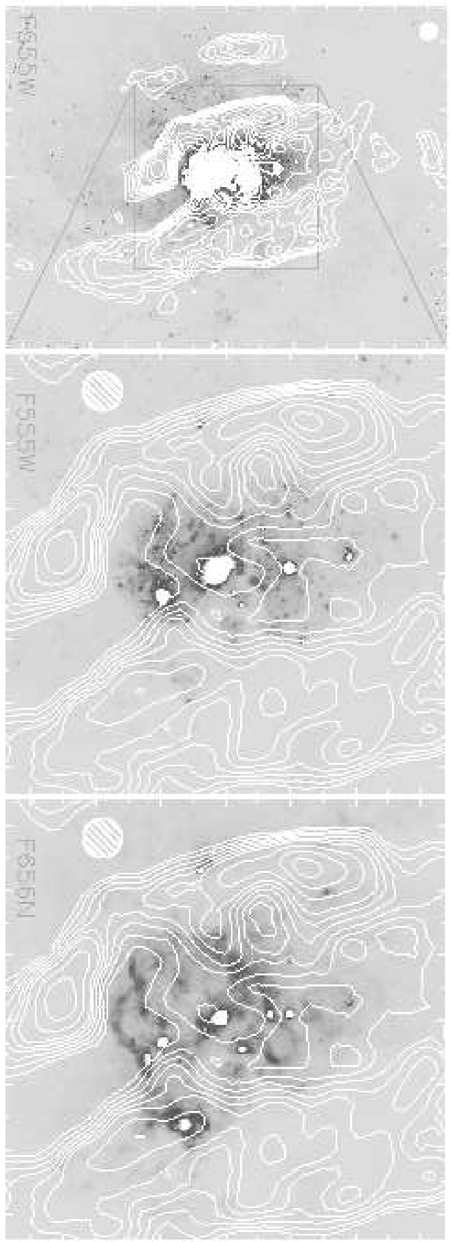


**FIGURE 1.** IC342: The distribution of the $^{12}$CO(2-1) line emission overlaid in contours onto HST/WFPC2 V band image (*left* and *middle*) and H$\alpha$ image (*right*). The molecular gas generally seems to avoid regions of star formation. However, a small 30 pc nuclear gas disk has been detected which appears to be connected to the outer spiral arms via two bridges.

gas are needed in order to produce such a starburst event. This is 50 times more than the present-day mass of the nuclear CO disk ($M_{H_2} \sim 1.7 \times 10^5\,M_\odot$). In the following, we use our CO observations to constrain the inflow rate of molecular gas and to estimate how long it might take before another such starburst event can occur.

A lower limit can be calculated by assuming that it took the full 60 Myr since the last starburst for the nuclear CO disk to form. In this case, the inflow rate is $\sim 0.003\,M_\odot$/yr or about 3 Gyr are needed before a new starburst event could occur. We derive an upper limit to the inflow rate by taking the observed gas surface density of $\Sigma \sim 500\,M_\odot/pc^2$ together with the width of the two dust lanes seen in the V-band image ($\sim 0.2''$). This yields an estimate of the gas inflow rate onto the nuclear disk of $\sim 2000\,M_\odot/\,pc \times v_{rad}$. We find that radial motions of up to $v_{rad} \sim 70\,km\,s^{-1}$ can be present in the molecular gas next to the nuclear cluster, depending on the exact shape of the gravitational potential. These rough estimates result in an inflow rate of $\sim 0.14\,M_\odot$/yr. Such an inflow rate would accumulate about $10^7\,M_\odot$ of molecular gas in the nucleus within 70 Myr.

These two estimates probably bracket the actual inflow rate, but a number of uncertainties remain. For one, the $H_2$ mass in the center of IC 342 might be overestimated by a factor of 4-5 due to the use of a Galactic conversion factor, as discussed in Meier et al. (2001). In addition, the non-circular motions can be overestimated due to the unknown shape of the underlying gravitational potential. Nevertheless, the inflow rates discussed here are not unreasonable to support repetitive nuclear starbursts in IC 342. Moreover, the inflow rate is likely to vary over time with lower inflow rates in the past, and could increase in the future as more mass is accumulated at the center

Our analysis of new high-resolution maps of the $^{12}CO(2-1)$ emission in the center of IC 342 has revealed the following main results. We detect molecular gas coinciding with the nuclear stellar cluster. This, and the presence of streaming motions close to the nucleus, suggests that gaseous matter is currently accumulating at the nucleus of IC 342. These findings provide support for in-situ formation of nuclear clusters and repetitive nuclear starbursts. Rough estimates of gas inflow rates suggest that massive ($10^6\,M_\odot$) nuclear starbursts in IC 342 can be supported with duty cycles between a few hundred Myrs and 1 Gyrs.

## RESULTS FOR NGC 6946

NGC 6946 is a prime example for a late-type spiral galaxy with a prominent nuclear starburst. The starburst history of the inner $8''$ ($\approx 230pc$) can be described by two recent events (about 5 Myrs and 15 Myrs ago) that each converted about $(5-10) \times 10^7\,M_\odot$ of molecular gas mass into stars (Engelbracht et al. 1996). These authors infer a high extinction of $A_V \approx 10$ towards the nuclear region which is surprising given the almost face-on geometry. As one of the closest ($d = 5.5$ Mpc, Tully 1988) galaxies with intense nuclear star formation, NGC 6946 offers a unique opportunity to study the dynamics of its circumnuclear molecular gas disk (e.g. Ishizuki 1990, Regan & Vogel 1995, Sakamoto et al. 1999). At this distance, the $0.6''$ spatial resolution afforded by the PdBI at 1mm samples spatial scales of only 15 pc.

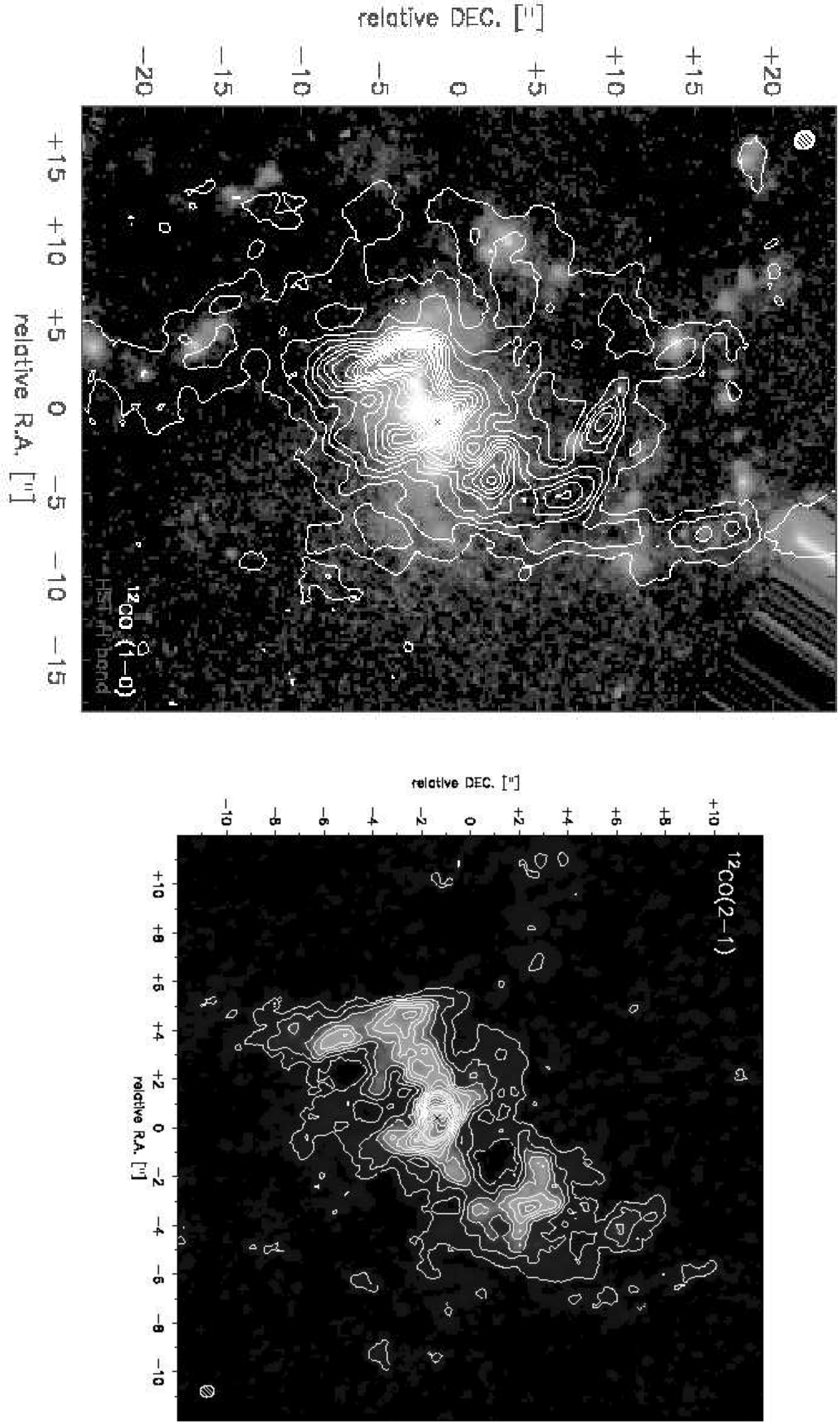


**FIGURE 2.** NGC 6946: Abundant molecular gas is present in the central kiloparsec of this late type galaxy as seen in the distribution of the $^{12}$CO(1-0) (*left* in contours overlaid onto HST Pa$\alpha$ emission image in greyscale) and $^{12}$CO(2-1) (*right*, shown in contours and greyscale). The molecular gas distribution in the inner 300 pc shows an $S-$shape reminiscent of the dust/gas lanes seen along large-scale bars.

The central molecular gas distribution has been resolved by our new PdBI observations into an $S-$shape structure. The CO(1-0) line emission probes the larger scale distribution in the central arcminute showing that in general the molecular gas distribution is similar to the pattern of young star formation. Although, the molecular gas and the young HII regions are not cospatial. In the central 300 pc the distribution of the molecular gas is very reminiscent of the gas/dust lanes seen along large-scale kiloparsec bars. The nuclear stellar bar detected by Elmegreen et al. (1999) in the NIR could be a possible explanation for this. Preliminary analysis of the molecular gas kinematics suggests that indeed gas is fueled to the central $\sim 30$ pc via shocks along the leading sides of this NIR bar. More analysis is needed to obtain an estimate of the possible inflow rates to the very center. However, the presence of high extinction and several young star forming sites within the central 100 pc make this galaxy an ideal target to study the interplay between gas dynamics and star formation.

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