

SELF-REGULATED FUELING OF GALAXY CENTERS: EVIDENCE FOR STAR FORMATION FEEDBACK IN IC 342'S NUCLEUS¹

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ABSTRACT

Using new, high-resolution interferometric observations of the CO and HCN molecules, we directly compare the molecular and ionized components of the interstellar medium in the center of the nearby spiral galaxy IC 342, on spatial scales of ≈ 10 pc. The morphology of the tracers suggests that the molecular gas flow caused by a large-scale stellar bar has been strongly affected by the mechanical feedback from recent star formation activity within the central 100 pc in the nucleus of the galaxy. Possibly, stellar winds and/or supernova shocks originating in the nuclear star cluster have compressed, and likely pushed outward, the infalling molecular gas, thus significantly reducing the gas supply to the central 10 pc. Although our analysis currently lacks kinematic confirmation due to the face-on orientation of IC 342, the described scenario is supported by the generally observed repetitive nature of star formation in the nuclear star clusters of late-type spiral galaxies.

Subject headings: galaxies: individual (IC 342) — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: nuclei

1. INTRODUCTION

Any “activity” found in a galactic nucleus—be it due to massive star formation, an accreting supermassive black hole, or a combination of both—requires the inflow of gas into the central few pc. On scales of kpc, the gas flow is regulated by the response to asymmetries in the gravitational potential, e.g., stellar bar or tidal interactions (Sakamoto et al. 1999; Sheth et al. 2005). Numerical models (e.g., Athanassoula 1992; Sellwood & Wilkinson 1993) have demonstrated that large-scale stellar bars are especially efficient in moving gas into the central kpc. However, no clear picture is yet available for the gas flow inside a few 100 pc from the nucleus (García-Burillo et al. 2003; Wada 2004).

Arguably the simplest galaxies to observationally test these models are the latest type spirals, because they have bulgeless disks. However, even these objects have rather complex central star formation histories. About 75% of late-type disks host distinct nuclear star clusters (Böker et al. 2002), most of which have experienced multiple discrete star formation events in their history (Rossa et al. 2006; Walcher et al. 2006). So far, it is unclear whether the repetitive star formation in these nuclear clusters is due to variability of the gravitational potential (e.g., dissolution/formation of a stellar bar) or the clumpy nature of the molecular gas (e.g., inflow of discrete giant molecular complexes [GMCs]), or whether nuclear massive star formation itself is disrupting the gas supply.

The Scd spiral IC 342 is one of the nearest examples of a late-type spiral harboring a well-studied nuclear star cluster. The nuclear cluster has a stellar mass of $\sim 10^7 M_{\odot}$ and its luminosity is dominated by a recent, 4–30 Myr old, short-lived

star formation event (after correction for a revised distance of 3.0 Mpc; Böker et al. 1997, 1999; Fingerhut et al. 2007). Previous studies of the molecular gas in IC 342, with single-dish and interferometric millimeter instruments (Turner & Hurt 1992; Turner et al. 1993; Ishizuki et al. 1990; Downes et al. 1992; Meier & Turner 2001), lack sufficient spatial resolution (58–72 pc) to resolve the structure of the GMCs, thus hampering accurate comparisons with the nuclear star formation. The spiral geometry of the molecular gas in the central 500 pc is due to the response of the gas to the large-scale stellar bar (Ishizuki et al. 1990). A comprehensive study (Meier & Turner 2005) of the molecular chemistry in IC 342 has demonstrated that the molecular gas in the central few hundred pc is subject to a number of different excitation mechanisms. Recent OVRO observations of the $^{12}\text{CO}(2-1)$ line showed evidence for molecular gas being associated with the nuclear star cluster itself (Schinnerer et al. 2003).

2. OBSERVATIONS AND ABSOLUTE ASTROMETRY

The $^{12}\text{CO}(2-1)$ and HCN(1–0) lines tracing the total and dense molecular gas content were observed with the IRAM Plateau de Bure Interferometer (PdBI) in 2005 January/February and 2004 January, respectively. For calibration and mapping, we used the standard IRAM GILDAS software packages CLIC and MAPPING (Guilloteau & Lucas 2000). The observations resulted in data cubes of $0.67'' \times 0.51''$ and $1.64'' \times 1.29''$ resolution with an rms of 10 and 3.6 mJy beam⁻¹ for the CO(2–1) and HCN(1–0) line. Intensity maps were derived using a 3σ cut for line emission present over at least two channels of 3.0 (6.0) km s⁻¹ width.

For a direct comparison of the (dense) molecular gas to the stellar light and the ionized gas (as observed with *HST*), the *HST* data need to have an absolute astrometry of better than at least $0.5''$. To achieve this, we first aligned a newly obtained *HST* Pa α image (PI Calzetti, PID 11080) to a deep 6 cm continuum VLA image (PI Schinnerer) as both exhibit a very similar geometry at comparable angular resolution ($0.4''$ vs. $0.75''$). Archival *HST* F656N and F606W images (PID 8581, 5446) were then aligned to the Pa α map using a number of stellar clusters. To obtain the continuum-subtracted H α map, we subtracted a scaled version of the F606W image from

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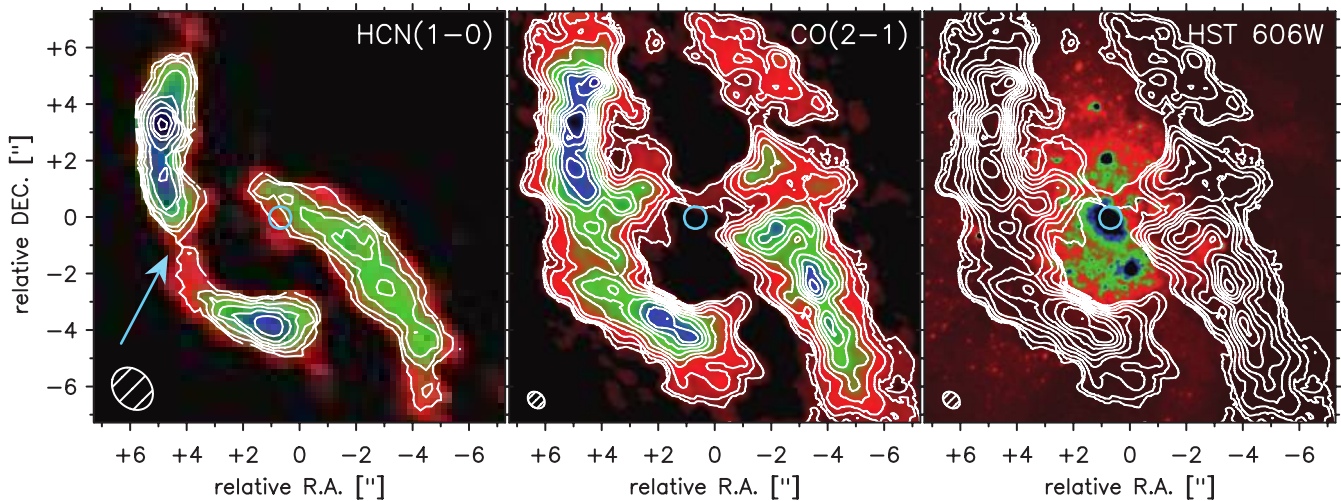


FIG. 1.—Distribution of the cold molecular gas as traced by the $^{12}\text{CO}(2-1)$ line emission (*middle*; color and contours starting at $0.9 \text{ Jy beam}^{-1} \text{ km}^{-1} \text{ s}^{-1}$ in uneven steps) in the central 225 pc of the late-type spiral galaxy IC 342 at a resolution of $0.6''$ (9.6 pc). A narrow faint gas bridge connecting the two spiral arms can be seen just north of the nuclear cluster (marked by a circle in all panels). The dense molecular gas as traced by the $\text{HCN}(1-0)$ line emission (*left*; color and contours starting at $0.45 \text{ Jy beam}^{-1} \text{ km}^{-1} \text{ s}^{-1}$ in steps of $0.15 \text{ Jy beam}^{-1} \text{ km}^{-1} \text{ s}^{-1}$) shows a very similar distribution, although the western spiral arm extends farther toward the nucleus. The break (marked by the arrow) about $4''$ east and $1''$ south of the center in the eastern spiral arm is also more prominent in the HCN map. The molecular gas also coincides well with the regions of high extinction in the optical continuum image (*right*; *HST* F606W filter in color), while the underlying stellar disk is less obscured inside the molecular gas cavity.

F656N. No astrometric corrections are required for radio interferometric data as the observations provide an absolute astrometric reference frame. This resulted in very well aligned optical/NIR and radio images, solving the ambiguities that plagued our previous study which relied on the geometry of the dust lanes (Schinnerer et al. 2003).

3. GAS DISTRIBUTION SHAPED BY STAR FORMATION

3.1. Distribution of the Molecular Gas

In the new $\text{CO}(2-1)$ and $\text{HCN}(1-0)$ maps (Fig. 1), the eastern spiral arm exhibits a prominent break at $3^{\text{h}}46^{\text{m}}49.0^{\text{s}}$ and $+68^{\circ}5'45.5''$ (J2000.0), about $4''$ east and $1''$ south of the galaxy center. At this break the eastern spiral arm stops continuing inward and stays at a roughly constant distance from the nucleus whereas the western spiral arm reaches close (within $1''$) to the nucleus itself. The nuclear $\text{CO}(2-1)$ gas clump identified earlier (Schinnerer et al. 2003) is now resolved into a faint, narrow gas lane running east-west just north of the nucleus. In addition, the southern portion of the eastern spiral arm exhibits a sharp edge on the side facing the nucleus. The geometry of the HCN emission closely resembles that of the $\text{CO}(2-1)$, except for the western spiral arm which extends farther toward the nucleus in HCN while the emission north of it is too diffuse to be detected in HCN. The central “cavity” in the molecular gas distribution is displaced from the nucleus to the southeast and offers a relatively unobscured view onto the stellar disk, as demonstrated by the comparison to the optical continuum (Fig. 1): the stellar disk is substantially fainter wherever molecular gas is present. Both $\text{CO}(2-1)$ and HCN emission trace very well the prominent dust lanes in the central 250 pc. This dramatic change in extinction causes an elongation of the isophotes even at NIR wavelengths, which might be misinterpreted as a small-scale bar. A comparison of the $\text{CO}(2-1)$ and $\text{H}\alpha$ distribution (Fig. 2) shows that the ionized gas fills the central cavity of the molecular gas. In particular, the $\text{H}\alpha$ shells (or arcs) delineating the southeast edge of the cavity suggest an ionized outflow that coincides with the inner edge of the

southeastern $\text{CO}(2-1)$ spiral arm. Due to IC 342’s almost face-on orientation, the gas motions are difficult to interpret, as we start to observe a blend of several smaller molecular clouds plus streaming motions due to the stellar bar and a mix of the diffuse and dense gas component in the $\text{CO}(2-1)$ emission.

3.2. Impact of Nuclear Star Formation on a Bar-Induced Gas Flow

While the overall molecular gas distribution in the center of IC 342 is governed by the gravitational influence of a large-scale stellar bar (Ishizuki et al. 1990) (also as evidenced by the presence of shocks seen in CH_3OH and SiO ; Meier & Turner 2005; Usero et al. 2006), the asymmetries in the molecular gas properties within the inner 50 pc can be explained by the impact of nuclear star formation onto this gas flow. The comparison of the molecular gas distribution to the $\text{H}\alpha$ image suggests that the expanding ionized gas is “running” into the molecular gas, particularly in the southeastern portion of the spiral arm (hereafter: segment). As we will show in § 4, the displacement of this arm segment is in agreement with mechanical energy input into the total and dense molecular gas, leading to it being compressed and pushed out, or at least “halted” by the pressure of the ionized gas.

Meier & Turner (2005) have shown that this part of the spiral (GMC-A) is the one most excited by UV photons and more diffuse than the rest of the dense GMCs. Radiative excitation by the nucleus can be excluded as it is not an AGN or a UV source (Böker et al. 1999). The discontinuity in the eastern spiral arm as well as the different chemical properties of this arm segment argue against a simple offset of the gas spiral from the dynamical center. Taken together, this suggests an impact from stellar winds and supernova explosions on the morphology of circumnuclear molecular gas as well as altering its chemical composition.

Some evidence for a corresponding discontinuity along the northern portion of the western arm (thin dotted line in Fig. 3) is observed in $\text{CO}(2-1)$. However the weak $\text{H}\alpha$ emission, the lack

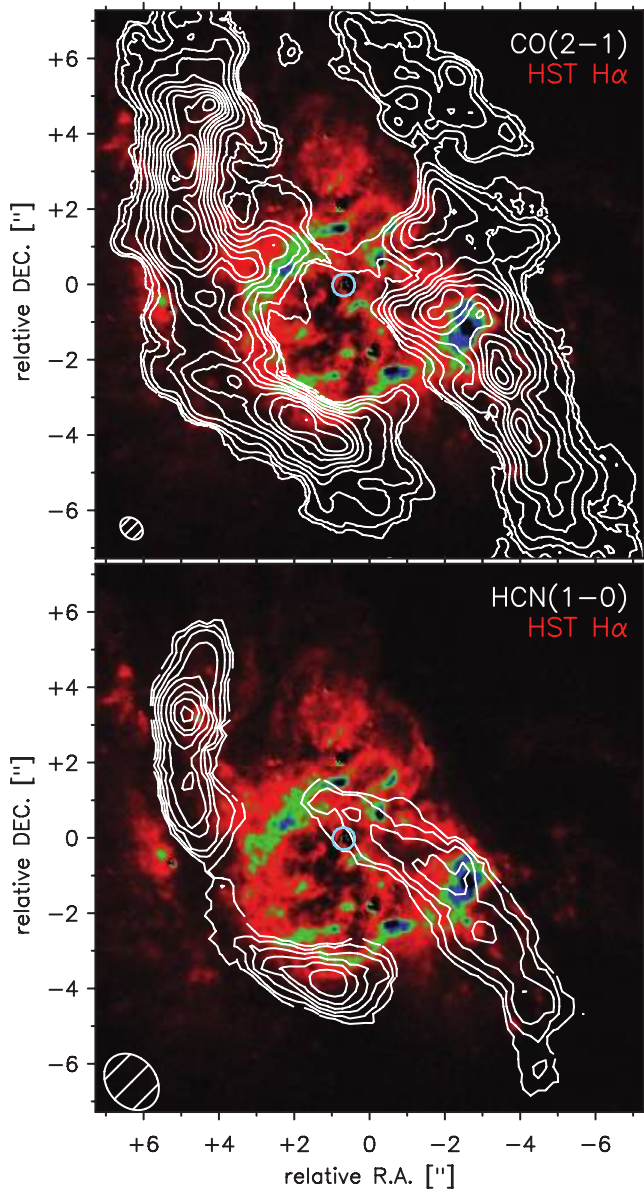


FIG. 2.—CO(2–1) (top) and HCN(1–0) (bottom) intensity maps (contours from Fig. 1) are overlaid onto the continuum-subtracted H α image from HST (color). The ionized gas bubble shows a shell-like structure in the southeast that fits well into the cavity of the molecular gas distribution. Most of the arcs outlining the bubble appear to have originated from the nuclear stellar cluster.

of an altered chemistry, and the HCN morphology make the case for direct impact of stellar winds and SNe less clear here. The exact reasons for the asymmetry manifested by the outflow from the nuclear starburst (as seen in the H α line) are unclear, but such a behavior is not unusual for large-scale outflows from central star formation (e.g., M82; Ohyama et al. 2002). Potentially the northern portion of the western spiral arm might lack these signs because it is composed of more dispersed molecular material. In addition, the higher extinction on the near-side (western side) of the galaxy can cause some differences as well.

Although the dynamical timescale in the nuclear region is very small (~ 10 Myr), the spiral pattern itself is rotating slower. As nuclear spirals can easily be excited by large-scale bars (e.g., Maciejewski 2004; Englmaier & Shlosman 2000), we can use the pattern speed of the stellar bar of $\Omega_{\text{bar}} = 0.4 \text{ km s}^{-1} \text{ arcsec}^{-1}$ (Crosthwaite et al. 2000). At a radius of $3.3''$ (50 pc)

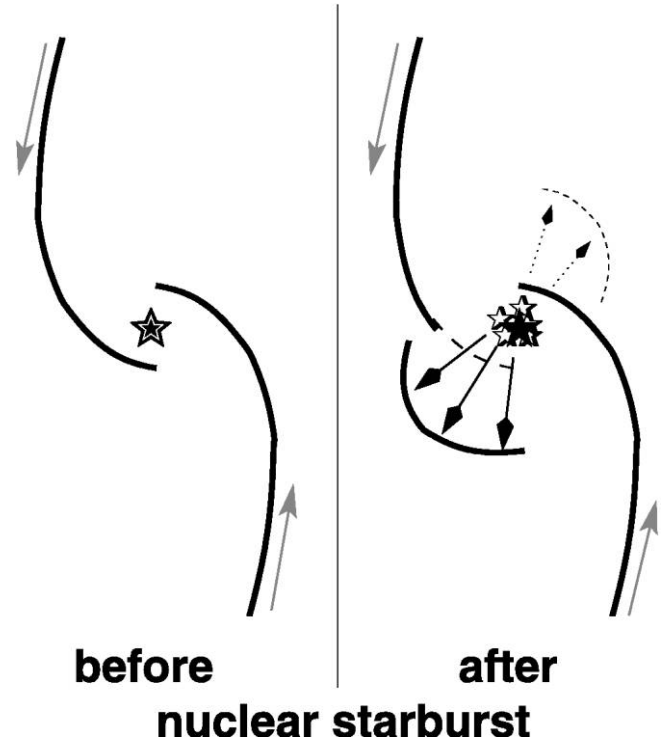


FIG. 3.—Schematic figure outlining the proposed scenario for the self-regulation of the fueling of the nuclear stellar cluster in IC 342. *Left*: In the absence of massive star formation the molecular gas moves toward the nucleus (star) along the gas lanes (black arcs) due to the gravitational influence of a large-scale stellar bar. *Right*: The mechanical energy (indicated by black arrows) released by stellar winds and supernovae of the recent massive star formation in the nucleus is sufficient to alter the flow of the molecular gas (from the dashed to the solid position), so that molecular gas from the eastern spiral arm can no longer reach close to the nucleus, thus significantly reducing the fuel available for future star formation events. The effect on the western arm is less dramatic (thin dotted line and arrows). After the stellar winds and SN explosions have ceased, it is expected that the force of the gravitational bar potential takes over again and the gas flow will be similar to the situation shown in the left panel.

this corresponds to a velocity of 8 km s^{-1} ; thus one revolution of the spiral pattern itself takes about 40 Myr. For a 10 Myr old starburst the spiral has moved by a quarter. This is consistent with the arm segment which covers about a quarter of a circle and also the age for the most recent star formation event in the nuclear cluster.

To summarize, the ionizing outflow produced by stellar winds and supernovae from the recent nuclear star forming event appears to have changed the location of the southern part of the eastern spiral arm, while the western spiral arm appears less effected. If the gas flow along the western arm is less disturbed by the nuclear bubble, this may explain why the youngest star formation episode is also asymmetrically stronger toward the western arm (e.g., Tsai et al. 2006).

4. EVIDENCE FOR FEEDBACK

We now investigate whether the timescale and required energy are indeed compatible with the scenario outlined above. The dislocation is either due to an actual movement of individual molecular clouds against the gravitational potential or the ionized gas is acting as a barrier altering the orbits of the molecular gas. In both scenarios, some kind of force is required to counterbalance the gravitational potential; thus the following estimates should be valid in either case.

The deprojected distance from the nuclear cluster to the H α rim is about 3.3" or 50 pc. A shell with a typical expansion velocity of 20–40 km s⁻¹ (Martin 1998) can travel this distance in about (2.4–1.2) Myr, which is less than the age of the last nuclear star formation episode (4–30 Myr). To first order, it is therefore possible that the H α shells were produced in this event. Assuming that the southeastern arm segment has been “pushed” to a larger radius, we can derive a rough estimate for the required cumulative energy using the mass of the molecular gas and reasonable assumptions about the gravitational potential.

We assume a virial gas mass of $1.6 \times 10^6 M_{\odot}$ for the southeastern segment (Meier & Turner 2001). To estimate the kinetic and potential energy required, we use the rotation curve of Turner & Hurt (1992) after correcting for the new distance to estimate velocities of $v(r_2 = 50 \text{ pc}) \approx 25 \text{ km s}^{-1}$ and $v(r_1 = 22 \text{ pc}) \approx 12 \text{ km s}^{-1}$. A total energy of $E_{\text{tot}} = E_{\text{kin}} + E_{\text{pot}} = 3E_{\text{kin}} = 3m_{\text{GMC-A}}[v(r_2)^2 - v(r_1)^2]/2 \cong 2.2 \times 10^{52} \text{ erg}$ is required to move the molecular gas mass from a radius of 18 pc (the location of the unaffected western spiral arm) to 50 pc, the current distance of the southeastern segment (inclination effects are neglected given the low inclination of $\sim 31^\circ$; Crosthwaite et al. 2000).

A cluster with a stellar mass of $1 \times 10^7 M_{\odot}$ releases a mechanical luminosity of $3 \times 10^{41} \text{ erg s}^{-1}$ at an age of 4–30 Myr (assuming an instantaneous burst with solar metallicity; see STARBURST99 models [Leitherer et al. 1999]). Since the flux-calibrated continuum-subtracted *HST* Pa α image suffers less dust extinction than the H α image (Fig. 2), we use the former for a consistency check. The Pa α line flux of the ionized gas bubble ($\sim 7 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$) can be converted into a H α luminosity of $5.4 \times 10^{39} \text{ erg s}^{-1}$ using a H α /Pa α ratio of 7.82 appropriate for a metal-rich region (without extinction correction). Assuming that about 3% of the mechanical energy is converted into H α luminosity (Binette et al. 1985) and a filling factor of about 0.5 for the bubble (from the flux present inside the bubble), this translates into a mechanical luminosity of about $3.6 \times 10^{41} \text{ erg s}^{-1}$. This is consistent with the above value derived from the cluster mass and age.

Thus over the course of the derived travel time of 2 Myr a total mechanical energy of $2 \times 10^{55} \text{ erg}$ will be produced. However, this mechanical energy is distributed over the entire sphere and subject to radiative losses. Assuming a filling factor of only 3% for GMC-A and radiative losses of 90%, plus taking into account that likely only a fraction of 20% of the nuclear stellar mass was produced in the last event, an energy of $1.2 \times 10^{52} \text{ erg}$ is expected to be available for mechanical inter-

action. Even this rather conservative estimate for the available mechanical energy is sufficient to explain the gas morphology. We conclude that, based on time and energetic arguments, mechanical feedback from nuclear star formation is a plausible explanation for the observed molecular gas distribution.

5. SELF-REGULATED FUELING

The following picture for the gas flow in IC 342 emerges (Fig. 3): The large-scale stellar bar moves gas toward the center via two gas spiral arms. The stellar winds and supernova shocks released by the most recent nuclear star formation event have significantly altered the path of the molecular gas toward the center on the last few 10 pc, thus currently preventing efficient fueling of the nucleus. This is the first time strong evidence has been found for mechanical feedback of nuclear star formation onto the (disk) gas *flow* in an extragalactic nucleus. As the large-scale stellar bar continues to move gas toward the center, it is likely that the gas resumes its old path once the mechanical energy has been dispersed. Presumably, the nucleus will then again collect molecular gas until the next star formation episode. This feedback between nuclear activity and fueling efficiency appears to self-regulate the rate of nuclear star formation and offers a natural explanation for the repetitive star formation found in nuclear star clusters (Rossa et al. 2006; Walcher et al. 2006).

If correct, this scenario implies that models for the gas fueling mechanism (over the innermost 1–100 pc) cannot rely on the shape of the gravitational potential alone but need to take the effect of mechanical energy released by nuclear activity onto the gas flow into account. The impact of this feedback process will be strongly variable in time and will critically depend on the amount of energy released as well as its geometry. Although mechanical feedback has long been suspected to be important for galactic nuclei, so far no observations have existed to directly support this. In a broader sense, these results also have implications for the evolution of any central massive object (be it a stellar cluster or a black hole) that requires occasional fueling. Nuclear activity appears to have the potential to significantly reduce or even (temporarily) shut off fueling, thus self-regulating the growth of the central mass.

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